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Optical waveguide structure with partially overlapping loops in direction dependent material

Abstract

An optical waveguide structure comprises a nonlinear optical waveguide comprising a set of segments, a set of extension optical waveguides, and a set of wavelength selective couplers that couples light between set of segments in the nonlinear optical waveguide and the set of extension optical waveguides based on a wavelength of light.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application is a continuation in part application of U.S. patent application Ser. No. 17/450,038, U.S. Pat. No. 11,561,454, filed Oct. 5, 2021, and entitled “Optical Waveguide Structure With Partially Overlapping Loops In Direction Dependent Material,” which is related to and claims the benefit of priority of provisional U.S. Patent Application Ser. No. 63/088,220, entitled

"Directional Phase Matching (DPM) Optical Waveguide", filed on Oct. 6, 2020; provisional U.S. Patent Application Ser. No. 63/201,661, entitled "Directional Phase Matching Optical Waveguide", filed on May 7, 2021; and provisional U.S. Patent Application Ser. No. 63/201,664, entitled "Nonlinear Optical Waveguide Structures for Light Generation and Conversion", filed on May 7, 2021, all of which are hereby incorporated herein by reference. (2) This application is related to U.S. patent application Ser. No. 17/450,031 filed on Oct. 5, 2021, entitled "Optical Waveguide Structure With Triple Partially Overlapping Loops," and U.S. patent application Ser. No. 18/059,605 filed on Nov. 29, 2022, entitled "Optical Waveguide Structure With Partially Overlapping Loops In Direction Dependent Material," assigned to the same assignee, and incorporated herein by reference in their entirety.

BACKGROUND INFORMATION

1. Field

(1) The present disclosure relates generally to optical waveguide structures and, in particular, to phase matching optical waveguide structures with partially overlapping loops to generate light using non-linear optical processes.

2. Background

(2) Optical waveguides are physical structures that guide electromagnetic waves in an optical spectrum. Optical waveguides can be used as components in integrated optical circuits. With respect to quantum communications and processing, nonlinear optical material structures can be used to create photon transmitters, repeaters, and other quantum devices for communications. Nonlinear optical structures can be used to change the light passing through them depending on factors such as orientation, temperature, wavelength of light, polarization of light, and other factors. For example, a waveguide with light of a blue wavelength passing through the waveguide can generate one or more photons of light that has a longer wavelength, such as green or red, and a correspondingly lower photon energy. This type of conversion can be performed using waveguides that incorporate a material having a second order nonlinear optical susceptibility or a third order nonlinear optical susceptibility.

(3) Current waveguides and structures that implement second order nonlinear optical processes are not as efficient as desired. Therefore, it would be desirable to have a method and apparatus that take into account at least some of the issues discussed above, as well as other possible issues. For example, it would be desirable to have a method and apparatus that overcome a technical problem with increasing efficiency in generating light in nonlinear optical waveguide structures.

SUMMARY

(4) In one illustrative embodiment, an optical waveguide structure comprises a nonlinear optical waveguide comprising a set of segments, a set of extension optical waveguides, and a set of wavelength selective couplers couples light between set of segments in the nonlinear optical waveguide and the set of extension optical waveguides based on a wavelength of light.

(5) In another illustrative embodiment, an optical waveguide structure comprises a nonlinear optical waveguide comprising a first segment having a first starting point and a first ending point, wherein a nonlinear optical interaction results in a generation of a second wavelength light from a first wavelength light traveling through the first segment; a second segment having a second starting point and a second ending point; a third segment having third starting point and third ending point. The optical waveguide structure further comprises an extension optical waveguide, a first wavelength selective coupler that couples the second wavelength light from the first segment at the first ending point into the extension optical waveguide, and a second wavelength selective coupler that couples the second wavelength light from the extension optical waveguide into the third segment at the third starting point. Wherein, the first wavelength light travels from the first ending point to the third starting point through the second segment; the second wavelength light travels from the first ending point to the third starting point through the extension optical waveguide; both the first wavelength light and the second wavelength light travel from the third starting point of the third segment to the third ending point.

(6) In yet another illustrative embodiment, a method facilitates a non-linear optical process. A first wavelength light traveling through a first segment is routed in a nonlinear optical waveguide having a first starting point and a first ending point. A second wavelength light and a third wavelength light are generated by a nonlinear optical interaction of the first wavelength light between the starting point and the first ending point in the first segment. A first wavelength selective coupler couples the first wavelength light from the first ending point to a second starting point for a second segment in the nonlinear optical waveguide. The first wavelength selective coupler couples the second wavelength light and the third wavelength light from the first ending point to an extension starting point for an extension optical waveguide. A second wavelength selective coupler couples the second wavelength light and the third wavelength light from the extension ending point for the extension optical waveguide to a third starting point for a third segment in the nonlinear optical waveguide. The second wavelength selective coupler couples the first wavelength light from the second segment in the nonlinear optical waveguide to the third starting point for the third segment in the nonlinear optical waveguide.

(7) The features and functions can be achieved independently in various embodiments of the present disclosure or may be combined in yet other embodiments in which further details can be seen with reference to the following description and drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) The novel features believed characteristic of the illustrative embodiments are set forth in the appended claims. The illustrative embodiments, however, as well as a preferred mode of use, further objectives and features thereof, will best be understood by reference to the following detailed description of an illustrative embodiment of the present disclosure when read in conjunction with the accompanying drawings, wherein:

(2) FIG. **1** is an illustration of a high level block diagram of an optical waveguide structure in accordance with an illustrative embodiment;

(3) FIG. **2** is another illustration of an optical waveguide structure in accordance with an illustrative embodiment;

(4) FIG. **3** is an illustration of a block diagram of optical waveguides in accordance with an illustrative example;

(5) FIG. **4** is an illustration of loops in optical waveguides in accordance with an illustrative embodiment;

(6) FIG. **5** is an illustration of a block diagram of a configuration for nonlinear optical waveguides in accordance with an illustrative embodiment;

(7) FIG. **6** is an illustration of phase shifters used to obtain at least one of resonance matching or roundtrip phase matching in accordance with an illustrative embodiment;

(8) FIG. **7** is an illustration of a cross-section of an optical waveguide in accordance with an illustrative embodiment;

(9) FIG. **8** is an illustration of light coupling by a wavelength-selective coupler in accordance with an illustrative embodiment;

(10) FIG. **9** is an illustration of light coupling by a wavelength-selective coupler in accordance with an illustrative embodiment;

(11) FIG. **10** is an illustration of light coupling by a wavelength-selective coupler in accordance with an illustrative embodiment;

(12) FIG. **11** is an illustration of simulation results of light coupling by a wavelength-selective coupler in accordance with an illustrative embodiment;

(13) FIG. **12** is an illustration of simulation results of light coupling by a wavelength-selective coupler is in accordance with an illustrative embodiment;

(14) FIG. **13** is an illustration of an optical waveguide structure with five optical waveguides in accordance with an illustrative embodiment;

(15) FIG. **14** is an illustration of an optical waveguide structure with five optical waveguides in accordance with an illustrative embodiment;

(16) FIG. **15** is an illustration of an optical waveguide structure with five optical waveguides in accordance with an illustrative embodiment;

(17) FIG. **16** is an illustration of an optical waveguide structure with five optical waveguides in accordance with an illustrative embodiment

(18) FIG. **17** is an illustration of an optical waveguide structure with five optical waveguides in accordance with an illustrative embodiment;

(19) FIG. **18** is an illustration of an optical waveguide structure with ten optical waveguides in accordance with an illustrative embodiment;
(20) FIG. **19** is an illustration of a flowchart of a process for a non-linear optical process in accordance with an illustrative embodiment;
(21) FIG. **20** is an illustration of a flowchart of additional operations for a process for a non-linear optical process in accordance with an illustrative embodiment;
(22) FIG. **21** is an illustration of a flowchart of additional operations for a process for a non-linear optical process in accordance with an illustrative embodiment;
(23) FIG. **22** is an illustration of a flowchart of an additional operation for a process for a non-linear optical process in accordance with an illustrative embodiment;
(24) FIG. **23** is an illustration of a flowchart of additional operation for a process for a non-linear optical process in accordance with an illustrative embodiment;
(25) FIG. **24** is an illustration of a flowchart of an additional operation for a process for a non-linear optical process in accordance with an illustrative embodiment;
(26) FIG. **25** is an illustration of a flowchart of an additional operation for a process for a non-linear optical process in accordance with an illustrative embodiment;
(27) FIG. **26** is an illustration of a flowchart of an additional operation for a process for a non-linear optical process in accordance with an illustrative embodiment;
(28) FIG. **27** is an illustration of a block diagram of a product management system in accordance with an illustrative embodiment;
(29) FIG. **28** is an illustration of a block diagram of an optical waveguide structure in accordance with an illustrative embodiment;
(30) FIG. **29** is an illustration of an optical waveguide structure in accordance with an illustrative embodiment;
(31) FIG. **30** is an illustration of an optical waveguide structure using optical waveguides in accordance with an illustrative embodiment;
(32) FIG. **31** is an illustration of a graph of the amplitude of the idler light in an optical waveguide structure in accordance with an illustrative embodiment;
(33) FIG. **32** is an illustration of an optical waveguide structure having two sets of nonlinear optical waveguides and extension optical waveguides connected by an optical waveguide in accordance with an illustrative embodiment;
(34) FIG. **33** is an illustration of an optical waveguide structure with square-shaped aspect ratio obtained by having extension optical waveguides and segments displaced or offset laterally in accordance with an illustrative embodiment;
(35) FIG. **34** is an illustration of an optical waveguide structure in accordance with an illustrative example;
(36) FIG. **35** is an illustration of an optical waveguide structure with three coupled micro-rings for an extension optical waveguide in accordance with an illustrative example;
(37) FIG. **36** is an illustration of a cross-section of an optical waveguide in accordance with an illustrative embodiment;
(38) FIG. **37** is an illustration of a cross-section of an optical waveguide in accordance with an illustrative embodiment; and
(39) FIG. **38** is an illustration of a cross-section an optical waveguide in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

(40) The illustrative embodiments recognize and take into account one or more different considerations. For example, the illustrative embodiments recognize and take into account that a nonlinear optical structure can function as a resonator such that light of a particular wavelength in resonance with the resonator can travel over a longer distance in a nonlinear optical waveguide of the nonlinear optical structure as compared to light of other wavelengths that are not in resonance with the resonator.

(41) The illustrative embodiments recognize and take into account that the loss of light from a resonator occurs when some of the light exits the resonator instead of continuing to travel in the resonator. The resonator selects certain wavelengths of light to continue traveling in the resonator. The illustrative embodiments recognize and take into account that different resonators can have different resonances that match to different wavelengths of light. The illustrative embodiments recognize and take into account that the same resonator can have multiple resonances, with different resonances matching to different wavelengths of the light.

(42) The illustrative embodiments recognize and take into account that currently used nonlinear optical waveguide structures employ a resonator that implements three-wave mixing and four-wave mixing processes to generate light of one wavelength from light of a different wavelength. In other words, the process changes the wavelength of the light. The illustrative embodiments recognize and take into account that spontaneous parametric down conversion (SPDC) is an example of a three-wave mixing process for generating certain wavelengths of light, such as a signal light and an idler light, in response to the introduction of source light of a different wavelength, such as a pump light, into the nonlinear optical waveguide structure. The illustrative embodiments recognize and take into account that spontaneous parametric down conversion can generate a pair of photons, such as a signal photon and an idler photon, from a pump photon.

(43) The illustrative embodiments recognize and take into account that the nonlinear optical waveguide structure, in forming a ring-shaped route for the travel by the light, can employ a nonlinear optical waveguide in which light of three wavelengths involved in spontaneous parametric down conversion and spontaneous four-wave mixing propagates within the nonlinear optical waveguide structure. The illustrative embodiments recognize and take into account that the ring-shaped route formed from the nonlinear optical waveguide structure can be a closed path of a ring resonator. The illustrative embodiments recognize and take into account that for current nonlinear optical waveguides structures, different wavelengths of the light must match resonances of the same resonator. The illustrative embodiments recognize and take into account that this requirement results in severe limitation on allowable wavelengths for the signal light and the idler light that are generated.

(44) The illustrative embodiments recognize and take into account that current optical waveguide structures can have optical structures to input and output light from the ring resonator. The illustrative embodiments recognize and take into account that the addition of these input and output optical structures is unhelpful for achieving the resonance match because the three wavelengths for the pump light, the signal light, and the idler light propagate through the ring resonator and are constrained to match the modes of the same ring resonator.

(45) The illustrative embodiments recognize and take into account that current nonlinear optical waveguide structures can employ two coupled ring resonators having different values for their circumferences. The illustrative embodiments recognize and take into account that these different values can result in different sets of resonance modes for the two resonators. The illustrative embodiments recognize and take into account that a first resonator can have all three wavelengths for the pump light, the signal light, and the idler light matched to the modes for the first resonator. The illustrative embodiments recognize and take into account that the second resonator can have modes matched to the wavelengths of the signal light and the idler light. The illustrative embodiments recognize and take into account that these two coupled resonators still have the same limitations on resonance matching as a single ring resonator since wavelengths of the signal light and of the idler light must match with resonances of both resonators. The illustrative embodiments recognize and take into account that the use of three coupled ring resonators may provide some improvement, but still have limitations because at least some of the light from all of the three wavelengths travels through all three rings in the current nonlinear optical waveguide structures.

(46) The illustrative embodiments recognize and take into account that current nonlinear optical waveguide structures employ multiple resonators that are coupled together directly through common wavelengths and not through a nonlinear optical process. The illustrative embodiments recognize and take into account that at least some light for all of the wavelengths travel through all of these multiple resonators. In other words, the illustrative embodiments recognize and take into account that the light with different wavelengths and traveling through all of the resonators is resonant with each of the individual resonators that are coupled together.

(47) With currently used spontaneous parametric down conversion or spontaneous four-wave mixing, all three wavelengths involved in the nonlinear optical process are adjusted to match resonances of the same ring resonator or to match common resonances of multiple coupled rings. However, this type of adjustment of the wavelengths may not be possible if an entangled photon pair, such as entangled pair of idler and signal photons, is used in a quantum photonic circuit that also contains other sources of such photon pairs. The need in quantum photonics to perform optical interference functions involving photons produced by different sources of entangled photons may require those photons to have the same wavelength, so that photons can be indistinguishable.
(48) As a result, adjusting the wavelengths associated with a first ring resonator whose output photons are involved in an optical interference function can cause a need to also adjust the wavelengths associated with a second ring resonator whose output photons are interfered with the photons from the first ring resonator. However, if those two ring resonators are not identical, such adjustment may be beyond what is permitted by the spectral width of the resonances of the two ring resonators.
(49) For example, a departure of a dimension of the fabricated waveguide, such as the waveguide width, by only 1-2 nm would shift the resonance wavelength beyond the spectral width associated with a quality factor (Q) of 10.sup.3. Resonators with a higher Q have resonances with narrower spectral width, thereby making them impractical for use in quantum photonic circuits. Thus, if multiple currently available ring resonators are used in a quantum photonic circuit, those resonators would need to have a low Q.
(50) As a result, the nonlinear optical interaction distance for producing the entangled photon pairs by spontaneous parametric down conversion or spontaneous four-wave mixing would be much shorter and the photon-pair generation rates would be much lower.
(51) The optical waveguide structure in the illustrative examples provides design flexibility to enable three loops through the waveguides to have resonances that correspond to three pre-specified wavelengths. Also, if multiple optical waveguide structures are used together in a quantum photonic circuit, these optical waveguide structures can be adjusted to make the resonances of the optical waveguide structures correspond to specified wavelengths. This type of adjustment is in contrast to having all of the wavelengths adjusted to correspond to one resonator. Thus, the loops in the optical waveguide structures in a quantum photonic circuit can have a higher Q, enabling those optical waveguide structures to generate photon pairs at higher generation rates.
(52) In an illustrative example, the optical waveguide structure can be a triple partially overlapping loops for entanglement (TriPOLE) optical waveguide structure that is used in illustrative examples to produce entangled photon pairs by nonlinear optical (NLO) processes. These nonlinear optical processes can be, for example, spontaneous parametric down conversion and spontaneous four-wave mixing. The two entangled photons produced by spontaneous parametric down conversion can be entangled when those photons are produced from the same pump photon. In a similar fashion, the two entangled photons produced by spontaneous four-wave mixing can be entangled when those photons are produced from the same two degenerate pump photons.
(53) In this illustrative example, nonlinear optical waveguides in the form of ring resonators can be used to increase the generation rate of these entangled photon pairs, comprising a signal photon and an idler photon. In a high-Q ring resonator, light can travel many times around the circumference of the ring resonator. Thus, the interaction length of a ring resonator can be many times greater than its physical size. In implementing spontaneous parametric down conversion or spontaneous four-wave mixing with three partially overlapping ring resonators as in this example, all three wavelengths of light involved in the nonlinear optical process correspond to resonances of their individual resonators.
(54) In an illustrative example, the optical waveguide structure is configured such that light of a particular wavelength can travel on a particular loop through the optical waveguide structure in which the loop is present for that particular wavelength of the light. In the illustrative examples, the loops are partially overlapping such that light of two different wavelengths are not required to travel along the same exact loop.
(55) In one illustrative example, an optical waveguide structure comprises a main nonlinear optical waveguide; an extension optical waveguide; a secondary optical waveguide; a first wavelength-selective coupler; and a second wavelength-selective coupler. The first wavelength-selective coupler optically couples a first main location in the main nonlinear optical waveguide and a primary location in the extension optical waveguide to each other. The second wavelength-selective coupler optically couples a second main location in the main nonlinear optical waveguide and a secondary location in the extension optical waveguide to each other. The first wavelength-selective coupler also optically couples a first main location in the main nonlinear optical waveguide and a first location in the secondary optical waveguide to each other. The second wavelength-selective coupler also optically couples a second main location in the main nonlinear optical waveguide and a second location in the secondary optical waveguide to each other.
(56) With this example, light of different wavelengths travels on different loops in the optical waveguide structure. A route is a path in which the light travels. In this illustrative example, a loop is a closed route. For example, a first loop can be present in which light of a first wavelength (a first-wavelength light) travels on a first loop having a first length. This first loop can extend through the main nonlinear optical waveguide and a portion of an extension optical waveguide. A second loop can extend through a portion of the main nonlinear optical waveguide and a portion of a secondary optical waveguide. Light of a second wavelength (a second-wavelength light) can travel in the second loop having a second length. The second length can be different from the first length.
(57) In this example, the first wavelength-selective coupler and the second wavelength-selective coupler can be selected to cause light of a particular wavelength to travel from one optical waveguide to another optical waveguide. For example, the first wavelength-selective coupler can cause the second-wavelength light to be coupled from the main nonlinear optical waveguide to the secondary optical waveguide. The second wavelength-selective coupler can cause the second-wavelength light to be coupled from the secondary optical waveguide back to the main nonlinear optical waveguide. The second length is determined by the first-main and second-main locations and by the first-secondary and second-secondary locations as well as by the length of the secondary optical waveguide portion (or portions) between these first-secondary and second-secondary locations. The length of the secondary optical waveguide portion (or portions) between the first-secondary and second-secondary locations can be selected to obtain a desired value for the second length.
(58) The length of the portions of secondary optical waveguide are selected to achieve a desired value for the second length. This desired value can be selected to achieve a resonance condition for a particular wavelength of light.
(59) In this example, the first wavelength-selective coupler also can cause the first-wavelength light to be coupled from the main nonlinear optical waveguide to the extension optical waveguide. The second wavelength-selective coupler can cause the first-wavelength light to be coupled from the extension optical waveguide back to the main nonlinear optical waveguide. The first length is determined by first main location and the second main location in the main nonlinear optical waveguide, the primary-extension location and secondary-extension location in the extension waveguide as well as by the length of the primary optical waveguide portion between these primary-extension and secondary-extension locations. The length of the primary optical waveguide portion between these primary-extension and secondary-extension locations can be selected to obtain a desired value for the first length.
(60) In the illustrative example, with this optical waveguide structure, the loops for the different light of different wavelengths in the optical waveguides can have lengths that can be selected such that at least one of resonance or round-trip phase matching is present for the different light of different wavelengths traveling on the different routes.
(61) As used herein, the phrase “at least one of,” when used with a list of items, means different combinations of one or more of the listed items can be used, and only one of each item in the list may be needed. In other words, “at least one of” means any combination of items and number of items may be used from the list, but not all of the items in the list are required. The item can be a particular object, a thing, or a category.
(62) For example, without limitation, “at least one of item A, item B, or item C” may include item A, item A and item B, or item B. This example also may include item A, item B, and item C or item B and item C. Of course, any combinations of these items can be present. In some illustrative

examples, “at least one of” can be, for example, without limitation, two of item A; one of item B; and ten of item C; four of item B and seven of item C; or other suitable combinations.

(63) In other words, the length can be selected for a loop such that resonance is achieved for the light traveling in a loop. This type of selection of the length can be made for each loop independently of the lengths for other loops in the optical waveguide structure. In the illustrative example, resonance occurs for each wavelength of the light separately from the other wavelengths of the light.

(64) Round-trip phase matching can be achieved for the combination of three loops in which three wavelengths of light travel. Round-trip phase matching involves all three wavelengths of the light. In the illustrative example, the lengths of all three loops are selected jointly such that round-trip phase matching is achieved for the nonlinear optical interaction between the three wavelengths of the light.

(65) In some illustrative examples, an optical waveguide structure can be a resonator-enhanced structure for nonlinear optical (NLO) three-wave mixing processes. These nonlinear optical three-wave mixing processes can include difference frequency generation, sum frequency generation, and spontaneous parametric down conversion (SPDC). In other illustrative examples, an optical structure can be a resonator-enhanced structure for degenerately pumped or degenerate output nonlinear optical (NLO) four-wave mixing processes. These degenerate output nonlinear optical four-wave mixing processes can be, for example, difference frequency generation, sum frequency generation, and spontaneous four-wave mixing (SFWM). In these illustrative examples, degenerate means at least two of the waves participating in the nonlinear optical process have the same wavelength. Further, a degenerate three-wave mixing process, such as second harmonic generation, can be used. With second harmonic generation, the two input waves have the same wavelength and produce an output wave of a different wavelength.

(66) In the illustrative examples, the nonlinear optical processes can involve three distinct wavelengths of light, a first wavelength, a second wavelength, and a third wavelength. The nonlinear optical waveguide structure in the different illustrative examples comprises triple partially overlapping loops for entanglement (TriPOLE). This optical waveguide structure comprises a main nonlinear optical waveguide, a first extension optical waveguide, a second extension optical waveguide, and a third extension optical waveguide in which light of different wavelengths travels in loops that extend through different combinations of these different optical waveguides. A first loop extends through the main nonlinear optical waveguide and a first extension optical waveguide. This first loop is overlapped by parts of two other loops, which are a second loop and a third loop. A second loop extends through the main nonlinear optical waveguide and a second extension optical waveguide. A third loop extends through the main nonlinear optical waveguide and a third extension optical waveguide. These loops can be closed routes that define optical resonators having resonances at specific sets of wavelengths.

(67) The parts of the first loop, the second loop and the third loop that are in common with or that extend through the main nonlinear optical waveguide in the optical waveguide structure are the portions of the optical waveguide structure in which the nonlinear optical three-wave mixing or four-wave mixing processes can occur. In the illustrative examples, the first extension optical waveguide is physically separate from the main nonlinear optical waveguide and is connected to the main nonlinear optical waveguide by a first wavelength-selective coupler that selectively couples only the first-wavelength light into that first extension optical waveguide, but does not couple the second-wavelength light or the third-wavelength light into that first extension optical waveguide. In other words, the first wavelength-selective coupler optically connects the first extension optical waveguide to the main nonlinear optical waveguide only for the first-wavelength light. A second wavelength-selective coupler can couple the first-wavelength light from the first extension optical waveguide back into the main nonlinear optical waveguide.

(68) In this illustrative example, the second extension optical waveguide and the third extension optical waveguide are connected to the main nonlinear optical waveguide through a segment of a secondary optical waveguide. In this example, the first wavelength-selective coupler couples the second-wavelength light and the third-wavelength light into a first segment of the secondary optical waveguide. A third wavelength-selective coupler selectively couples the second-wavelength light into the second extension optical waveguide, but the third wavelength-selective coupler does not couple the third-wavelength light into that second extension optical waveguide.

(69) In other words, the third wavelength-selective coupler optically connects the second extension optical waveguide to the secondary optical waveguide. The third wavelength-selective coupler also selectively couples the third-wavelength light into the third extension optical waveguide, but the third wavelength-selective coupler does not couple the second-wavelength light into that third extension optical waveguide. In other words, this third wavelength-selective coupler optically connects the third extension optical waveguide to the secondary optical waveguide. As a result, the selection is between the second wavelength and the third wavelength. The first wavelength is assumed to not be present in the secondary optical waveguide in this example.

(70) In an illustrative example, the first wavelength-selective coupler couples the second-wavelength light from the main nonlinear optical waveguide to travel in the second extension optical waveguide of the second loop, via a third wavelength-selective coupler, but does not couple light of the first wavelength from the main nonlinear optical waveguide to travel in the second extension optical waveguide. The first wavelength-selective coupler also couples the third-wavelength light from the main nonlinear optical waveguide to travel in the third extension optical waveguide of the third loop, via the third wavelength-selective coupler, but does not couple light of the first wavelength from the main nonlinear optical waveguide to travel in the third extension optical waveguide.

(71) The third wavelength-selective coupler couples the light of the second wavelength from the main nonlinear optical waveguide, via the first waveguide-selective coupler, to the second extension optical waveguide of the second loop but does not couple light of the first or third wavelengths into the second extension optical waveguide. The third wavelength-selective coupler also couples the light of the third wavelength from the main nonlinear optical waveguide, via the first wavelength-selective coupler, to travel in the third extension optical waveguide of the third loop but does not couple the light of the first or second wavelengths into the third extension optical waveguide. Thus, only the second-wavelength light travels a second length through the entire second loop. Also, only the third-wavelength light travels a third length through the entire third loop. The first-wavelength light travels only a first length through the first loop that includes the main nonlinear optical waveguide and the first extension optical waveguide, but does not include the second extension optical waveguide or the third extension optical waveguide.

(72) The main nonlinear optical waveguide is common to all three loops. The first-wavelength light travels in a first loop that includes the main nonlinear optical waveguide and the first extension optical waveguide. In this example, the first loop also can include the first wavelength-selective coupler and the second wavelength-selective coupler. The second-wavelength light travels in a loop that includes the main nonlinear optical waveguide and the second extension optical waveguide. The third-wavelength light travels in a third loop that includes the main nonlinear optical waveguide and the third extension optical waveguide. Each of the three loops has a length that is designed to be resonant for the light that travels in the loop. The three loops can have different lengths.

(73) The length of the first loop for the light of the first wavelength can be selected such that the first-wavelength light is at a resonance of a first resonator comprising the main nonlinear optical waveguide and the first extension optical waveguide. The length of the second loop for the light of the second wavelength can be selected such that the second-wavelength light is at a resonance of a second resonator comprising the main nonlinear optical waveguide and the second extension optical waveguide. The length of the third loop for the light of the third wavelength can be selected so that the third-wavelength light is at a resonance of a third resonator formed by the main nonlinear optical waveguide and the third extension nonlinear optical waveguide.

(74) In the illustrative example, a loop may traverse one or more of these optical waveguides. The loops through these optical waveguides can partially overlap with each other. In other words, the different loops are not identical to each other but may have overlaps within the optical waveguide structures.

(75) Thus, although the propagation constants or wave vectors for the three wavelengths may be different from each other, the light at the three different wavelengths can still be at resonances when propagating in their respective loops in the optical waveguide structure. The propagation can

occur such that the light of the three wavelengths can propagate constructively over many cycles through loops within the optical waveguide structure. This type of propagation can occur because the three loops have different lengths. Furthermore, the relative lengths of the three loops can be selected to meet the phase-matching requirement to sustain the nonlinear optical process over an interaction distance that is greater than the length of the main nonlinear optical waveguide in the optical waveguide structure.

(76) The phase matching can be a feature distinct from the resonance that occurs for a resonator in the optical waveguide structure. Thus, five constraints may be applied to the nonlinear optical interaction that occurs in the optical waveguide structure. One constraint is on “energy conservation” which constrains the relationship between the three wavelengths. The other four constraints relate to the propagation constants or wave vectors of the light of the three different wavelengths.

(77) The phase-matching condition for the nonlinear optical process occurring in the main nonlinear optical waveguide can be described by a phase walk-off and by a constructive interaction distance. The constructive interaction distance is the distance at which a phase walk-off for the nonlinear optical interaction between the light of the three wavelengths equals 180 degrees or π radians.

(78) When the phase walk-off has a value between 0 and π radians, the nonlinear optical interaction is “constructive” and transfers power from the pump into the signal and idler. This transfer of power increases the generation of signal and idler light. However, when the phase walk-off has a value between n and 2π radians, the nonlinear optical interaction is “destructive” and transfers power from the signal and idler back to the pump, thereby reducing the generation of signal and idler light.

(79) Constructive generation of signal and idler light occurs for values of the phase walk-off between 0 and π, between 2 π and 3 π, between 4 π and 5 π, etc. Destructive generation of signal and idler occurs for values of the phase walk-off between π and 2 π, between 3 π and 4 π, between 5 π and 6 π, etc.

(80) Whether the nonlinear optical generation is constructive or destructive can also depend on the sign of the nonlinear optical coefficient of the nonlinear optical material involved in that nonlinear optical process. For the same value of the phase walk-off, if the sign of the nonlinear optical coefficient changes, the generation can change from being constructive to being destructive, and vice versa.

(81) In some illustrative examples, the length of the main nonlinear optical waveguide, in which all three wavelengths of light travel, can be set to be no greater than the constructive interaction distance. This length of the main nonlinear optical waveguide can be the length of multiple separate segments.

(82) The length of the first extension optical waveguide, the length of the second extension optical waveguide, and the length of the third extension optical waveguide (when present) can be set such that that the roundtrip phase walk-off for the nonlinear optical interaction between the light of the three wavelengths is a specified value. This round-trip phase walk-off can be set equal to zero or as close to being zero as possible, or can be set as close as possible to being a multiple of 2π radians or 360 degrees.

(83) In some examples, tuning electrodes can be located at optical waveguides. For example, the first extension optical waveguide can have a set of tuning electrodes that operates to adjust the roundtrip phase of the light of the first wavelength. The second extension optical waveguide can have a set of tuning electrodes that operate to adjust the roundtrip phase of the light of the second wavelength. The third extension optical waveguide can have a set of tuning electrodes that operate to adjust the roundtrip phase of the light of the third wavelength. The main nonlinear optical waveguide can have a set of phase shifters, such as a set of tuning electrodes, that operate to adjust the roundtrip phase of the light of all three wavelengths, and in particular of the first wavelength. Thus, these tuning electrodes can enable adjusting the resonance conditions to compensate for changes in at least one of the wavelengths of the light, the cross-sectional dimensions of the optical waveguides, and environmental conditions, such as temperature, or other factors. These tuning electrodes can also allow the optical waveguide structure to adjust the phase walk-off for the nonlinear optical interaction occurring in the main nonlinear optical waveguide.

(84) For example, a structure for spontaneous parametric down conversion can have the light such as, the pump light, supplied to the main nonlinear optical waveguide through an input optical coupler and travel in the first loop. The optical coupler can be connected to an input optical waveguide that receives the pump light. The signal light and the idler light generated by the spontaneous parametric down conversion process would travel in the second loop and the third loop, respectively.

(85) A nonlinear optical generation process such as spontaneous parametric down conversion can result in generation of lower intensity light from higher intensity light. A nonlinear optical generation process also can result in the generation of a higher intensity light from a lower intensity light. However, since the efficiency of a nonlinear optical generation process depends on the intensity of the input or source light for that process, which typically is the pump light, a nonlinear optical process typically results in generation of additional lower intensity light from the higher intensity light. Typically, the pump light has an intensity that is at least twice the intensity of the signal light and at least twice the intensity of the idler light. In some examples, such as many examples as spontaneous parametric down conversion, the intensity of the pump light is at least ten times greater than the intensity of the signal light or of the idler light. Thus, even when a phase-matched condition is present, if the pump light is absent from an optical waveguide comprising nonlinear optical material, and only signal and idler light are present, there is much less generation of pump light from that weaker signal and idler light.

(86) In the illustrative examples, an optical waveguide structure can comprise a first nonlinear optical waveguide segment, a second nonlinear optical waveguide segment, an extension optical waveguide, a first wavelength-selective coupler, and a second wavelength-selective coupler. A first-wavelength light and a second-wavelength light travel in the first nonlinear optical waveguide segment. A second-order nonlinear optical process such as spontaneous parametric down conversion can occur in the first and second nonlinear optical waveguide segments. The first nonlinear optical waveguide segment has a nonlinear optical coefficient of a first sign. The second nonlinear optical waveguide segment has a nonlinear optical coefficient of a second sign, which is opposite from the first sign. In this illustrative example, this second nonlinear optical segment is part of the second extension waveguide or the third extension waveguide. It is desirable to divert the pump light away from these extension segments for the signal and idler light. In this example these extension segments comprise electro-optic material to enable them to provide voltage-controlled phase shifts.

(87) The first wavelength-selective coupler can optically couple a first location in the first nonlinear optical waveguide segment and a primary extension location in the extension optical waveguide to each other such that the first-wavelength light is coupled from the first nonlinear optical waveguide at the first location to the extension optical waveguide at the primary extension location. The second wavelength-selective coupler can optically couple a second location in the first nonlinear optical waveguide segment and a secondary extension location in the extension optical waveguide to each other such that the first-wavelength light is coupled from the extension optical waveguide at the secondary extension location to the main nonlinear optical waveguide at a location in the first nonlinear optical waveguide segment. Thus, the first-wavelength light bypasses the second nonlinear optical waveguide segment that has a nonlinear optical coefficient of a second sign, which is opposite from the first sign. Instead, the first-wavelength light travels only through the first nonlinear optical waveguide segment that has a nonlinear optical coefficient of the first sign.

(88) In the illustrative examples, the wavelength-selective couplers enable selective coupling of light in a manner that directs light of different wavelengths to either travel through or to bypass two different nonlinear optical waveguide segments that have nonlinear optical coefficients of opposite sign.

(89) Some examples of the optical waveguide structures can avoid undesired effects of the sign reversal in the nonlinear optical coefficient by removing the pump light or by having an absence of a non-linear optical material in part of the loop traversed by the pump light. Other examples of the optical waveguide structures can take advantage of a sign reversal in the nonlinear optical coefficient by adjusting the phase walk-off to compensate for the sign reversal in the nonlinear optical coefficient for two different segments of nonlinear optical waveguide.

(90) With reference now to the figures and, in particular, with reference to FIG. **1**, an illustration of a high level block diagram of an optical

waveguide structure is depicted in accordance with an illustrative embodiment. In this illustrative example, optical waveguide structure **100** comprises optical waveguides **102** in which at least one of optical waveguides **102** is comprised of nonlinear optical material **104**. One or more other optical waveguides in optical waveguides **102** can be comprised of at least one of nonlinear optical material **104** or non-nonlinear optical material **105**. In this example, nonlinear optical material **104** can have first sign **107** and second sign **109** for nonlinear optical coefficient **112** for a nonlinear optical interaction of light with nonlinear optical material **104**. As depicted, first sign **107** is opposite of second sign **109**. Nonlinear optical coefficient **112** is a coefficient that quantifies the strength of the nonlinear optical interaction. Nonlinear optical coefficient **112** can be a second order nonlinear optical coefficient or a third order nonlinear optical coefficient depending on the type of optical process implemented in optical waveguide structure **100**. One or more optical waveguides in optical waveguides **102** also can be comprised of an electro-optic material **103**. The refractive index of an electro-optic material **103** can be changed by applying a DC or low-frequency (as compared to the optical frequency) electric field to the material. In some cases, a material can be both a nonlinear optical material **104** as well as an electro-optic material **103**.
(91) In this illustrative example, optical waveguide structure **100** can also include at least one of input optical waveguides **164** or output optical waveguides **166**. In this illustrative example, input optical waveguides **164** and output optical waveguides **166** are connected to one or more of optical waveguides **102** using optical couplers **130**.
(92) For example, a set of input optical waveguides **164** can input input light **168** into one or more of optical waveguides **102**. As another example, a set of output optical waveguides **166** can output output-light **170** from one or more of optical waveguides **102**. The input of input light **168** and output of output light **170** can be facilitated by a set of optical couplers **130** that connect the set of input optical waveguides or the set of output optical waveguides to one or more of optical waveguides **102**.
(93) As used herein, a “set of” when used with reference items means one or more items. For example, a set of input optical waveguides **164** is one or more of input optical waveguides **164**.
(94) In this illustrative example, light generation can be improved for optical waveguide structure **100** using optical waveguides **102** arranged as loops **116** through optical waveguides **102**. In the illustrative example, loops **116** are defined as the course of travel of light **118** within one or more of optical waveguides **102**. In other words, loops **116** are defined as where light **118** travels within optical waveguides **102**.
(95) The manner in which optical waveguides **102** are coupled to each other is through mechanisms such as wavelength-selective couplers **114**, which can be used to define loops **116** along which light **118** can travel within optical waveguides **102**. In the illustrative example, loops **116** can use different portions of optical waveguides **102** and wavelength-selective couplers **114** in optical waveguide structure **100**.
(96) As depicted, optical waveguide structure **100** also includes wavelength-selective couplers **114** that can be used to define routes **115** in the form of loops **116** for light **118** traveling within optical waveguide structure **100**. These wavelength-selective couplers can selectively direct light **118** from one optical waveguide to another optical waveguide in optical waveguides **102**.
(97) Wavelength-selective couplers **114** can take a number of different forms. For example, wavelength-selective couplers **114** can be selected from at least one of a two-waveguide coupler, a multi-mode interference coupler, a pulley coupler, a Mach-Zehnder interferometer, a 4-port micro-ring resonator coupler, or some other suitable wavelength-selective coupler that can couple light and determine which wavelengths of light are directed through coupling from one optical waveguide to another optical waveguide.
(98) As used herein, a “number of” when used with reference items means one or more items. For example, a number of different forms is one or more different forms.
(99) In this illustrative example, optical waveguides **102** in optical waveguide structure **100** can support the propagation of light **118** through routes **115** in the form of loops **116**, which are closed routes. Light **118** travels within optical waveguides **102** along routes **115**. In the illustrative example, a closed route is a route for which a starting point and ending point are common or for which no distinct starting point that is separate from an ending point is present. The closed route is also referred to as a loop.
(100) In this illustrative example, loops **116** can traverse multiple optical waveguides **102** in optical waveguide structure **100**. Loops **116** also can traverse one or more of wavelength-selective couplers **114** in optical waveguide structure **100**. Loops **116** can comprise multiple loops that overlap each other in portions of some of optical waveguides **102** in optical waveguide structure **100** but do not overlap each other for other optical waveguides **102** traversed by a loop of loops **116**. Different wavelengths of light **118** can travel through different loops. In other words, overlap is present between portions of loops **116** for the different wavelengths of light **118** traveling through optical waveguides **102**.
(101) As depicted, wavelength-selective couplers **114** can operate to define different loops in loops **116** for the different wavelengths of light **118**, with these different loops having different lengths.
(102) As depicted in this illustrative example, nonlinear optical material **104** has nonlinear optical coefficient **112**. In the illustrative example, nonlinear optical coefficient **112** can be a second order nonlinear optical coefficient or a third order nonlinear optical coefficient depending on the type of optical process implemented in optical waveguide structure **100**.
(103) Nonlinear polarization can occur in nonlinear optical material **104** in which the material polarization no longer varies linearly with the electric field amplitude. This nonlinear relationship can be expressed as follows:
$P=\chi$.sup.(1)$E+\chi$.sup.(2)$EE+\chi$.sup.(3)$EEE+\dots$
(104) where E is the electric field, χ(1) is the linear optical susceptibility, χ(2) is the second order nonlinear optical susceptibility, etc. The nonlinear susceptibilities, such as χ(2) and χ(3), represent the nonlinear parts of the material dipolar characteristics.
(105) In this example, the electric field amplitude is the electric field amplitude of the light wave, which is an electromagnetic field. An electromagnetic field has a traveling (or propagating) electric field and a traveling (or propagating) magnetic field.
(106) In this illustrative example, nonlinear optical process **140** can be nonlinear optical mixing processes that can occur within optical waveguide structure **100**. These nonlinear optical mixing processes can be used to generate light **118**. For example, the propagation of first-wavelength light **132** can result in the generation of at least one of second-wavelength light **134** or third-wavelength light **136** using one or more nonlinear optical waveguides employing nonlinear optical mixing processes in optical waveguides **102**.
(107) In the illustrative example, nonlinear optical mixing processes can include nonlinear optical three-wave mixing processes and nonlinear optical four-wave mixing processes. In this illustrative example, the nonlinear optical three-wave mixing processes and the nonlinear optical four-wave mixing processes can include difference frequency generation (DFG) and sum frequency generation (SFG). The nonlinear optical three-wave mixing processes can also include spontaneous parametric down conversion (SPDC). The nonlinear optical four-wave mixing can also include spontaneous four-wave mixing (SFWM).
(108) In this illustrative example, nonlinear optical wave-mixing processes can include three types of light with three distinct wavelengths such as first-wavelength light **132**, second-wavelength light **134**, and third-wavelength light **136**.
(109) For example, nonlinear optical process **140** such as spontaneous three-wave mixing is a second-order nonlinear optical process that can occur in an optical waveguide having nonlinear optical material **104** in optical waveguides **102**. In this process, pair of generated photons **142** are generated from source photons **144** in optical waveguides **102** that have nonlinear optical material **104**. Generated photons **142** of a pair can have different wavelengths from each other, such as of second-wavelength light **134** and third-wavelength light **136** and have wavelengths different from the wavelength, such as first-wavelength light **132** of source photons **144**.
(110) In this illustrative example, “resonance matching” means a given wavelength is matched to a resonance of a resonator. A resonator can have many resonances. Also, a resonator can be designed such that different lengths can still produce resonance matching for a particular wavelength of light. Resonance is achieved every time the round-trip phase is a multiple of 2π. In this illustrative example, lengths for loops **116** can be selected such that at least one of resonance matching or roundtrip phase matching is present for different wavelengths of light **118**.

(111) The lengths for loops **116** can be selected based on the locations where wavelength-selective couplers **114** connect to optical waveguides **102**.
(112) Thus, optical waveguide structure **100** can have multiple optical waveguides in optical waveguides **102** that are configured or constructed to enable the propagation of light **118** of different wavelengths to travel within optical waveguide structure **100** in a constructive manner. In one illustrative example, the light **118** of the different wavelengths can travel on loops **116** in which each loop is selected to enable light **118** of a particular wavelength to travel in a constructive manner. For example, a loop in loops **116** can traverse through both a main nonlinear optical waveguide and extension optical waveguides in optical waveguides **102** that extend the length of the loop in loops **116** for different wavelengths of light beyond that provided by the main nonlinear optical waveguide.
(113) Additionally, some loops in loops **116** can extend through both the main nonlinear optical waveguide and one or more parts of a secondary waveguide in addition to or in place of the extension optical waveguides. As a result, a loop in loops **116** for a light of a particular wavelength can traverse one or more of optical waveguides **102**.
(114) Thus, although the propagation constants or wave vectors for the light of three wavelengths may be different from each other, the light at the three different wavelengths can still be at resonances when propagating on their respective loops in optical waveguides **102**. The propagation can occur such that light **118** of the three wavelengths can propagate constructively over many cycles through loops **116** within the optical waveguide structure **100**. This type of propagation can occur because loops **116** have different lengths that are selected to be constructive for light of a particular wavelength.
(115) Turning next to FIG. **2**, another illustration of an optical waveguide structure is depicted in accordance with an illustrative embodiment. In the illustrative examples, the same reference numeral may be used in more than one figure. This reuse of a reference numeral in different figures represents the same element in the different figures.
(116) As depicted in this illustrative example, optical waveguide structure **100** comprises optical waveguides **102**. As depicted, optical waveguides **102** include main nonlinear optical waveguide **106**, first extension optical waveguide **108**, secondary optical waveguide **113**, and first wavelength-selective coupler **120**, and second wavelength-selective coupler **122**. In this example, main nonlinear optical waveguide **106** comprises a nonlinear optical material **104**. Main nonlinear optical waveguide **106** also can comprise an electro-optic material **103**. First extension optical waveguide **108** and secondary optical waveguide **113** can comprise a nonlinear optical material **104**, a non-nonlinear optical material **105**, or a combination of a nonlinear optical material and one or more non-nonlinear optical materials. Main nonlinear optical waveguide **106** can comprise a single optical waveguide segment or can comprise multiple optical waveguide segments that are physically separate from each other. Secondary optical waveguide **113** likewise can comprise a single optical waveguide segment or can comprise multiple optical waveguide segments that are physically separate from each other.
(117) In this example, first-wavelength light **512** of a first wavelength and second-wavelength light **518** of a second wavelength travel in the main nonlinear optical waveguide **106**. As an example, first-wavelength light **512** can be a pump light with second-wavelength light **518** being at least one of a signal light or an idler light.
(118) In this illustrative example, first wavelength-selective coupler **120** optically couples first main location **520** in main nonlinear optical waveguide **106** and primary extension location **522** in first extension optical waveguide **108** to each other. First wavelength-selective coupler **120** optically couples these two optical waveguides such that first-wavelength light **512** is coupled from main nonlinear optical waveguide **106** at first main location **520** to first extension optical waveguide **108** at primary extension location **522**.
(119) Second wavelength-selective coupler **122** optically couples second main location **524** in main nonlinear optical waveguide **106** and secondary extension location **526** in first extension optical waveguide **108** to each other. In this example, second wavelength-selective coupler **122** optically couples these two optical waveguides such that first-wavelength light **512** is coupled from first extension optical waveguide **108** at secondary extension location **526** to main nonlinear optical waveguide **106** at second main location **524**.
(120) In this example, first-wavelength light **512** travels in first loop **528** that traverses through portions of main nonlinear optical waveguide **106**, portions of first extension optical waveguide **108**, first wavelength-selective coupler **120** and second wavelength-selective coupler **122**. In this example, first loop **528** has first length **530**.
(121) In this illustrative example, first wavelength-selective coupler **120** also optically couples first main location **520** in main nonlinear optical waveguide **106** and first secondary location **511** in secondary optical waveguide **113** to each other. First wavelength-selective coupler **120** optically couples these two optical waveguides such that second-wavelength light **518** is coupled from main nonlinear optical waveguide **106** at first main location **520** to secondary optical waveguide **113** at first secondary location **511**.
(122) In this example, second wavelength-selective coupler **122** also optically couples second main location **524** in main nonlinear optical waveguide **106** and second secondary location **513** in secondary optical waveguide **113** to each other. In this example, second wavelength-selective coupler **122** optically couples these two optical waveguides such that second-wavelength light **518** is coupled from secondary optical waveguide **113** at second secondary location **513** to main nonlinear optical waveguide **106** at second main location **524**.
(123) In this illustrative example, second-wavelength light **518** travels in main nonlinear optical waveguide **106** and is coupled from main nonlinear optical waveguide **106** at first main location **520** to secondary optical waveguide **113** at first secondary location **511** and travels in secondary optical waveguide **113** to second secondary location **513**. Second-wavelength light **518** is coupled from secondary optical waveguide **113** at second secondary location **513** to main nonlinear optical waveguide **106** at second main location **524** by second wavelength-selective coupler **122** such that second-wavelength light **518** travels in second loop **534** having second length **536** for second-wavelength light **518**.
(124) Second loop **534** includes portions of main nonlinear optical waveguide **106**, portions of secondary optical waveguide **113**, first wavelength-selective coupler **120** and second wavelength-selective coupler **122**.
(125) With reference next to FIG. **3**, an illustration of a block diagram of optical waveguides is depicted in accordance with an illustrative embodiment. In this illustrative example, optical waveguides **102** comprise main nonlinear optical waveguide **106**, secondary optical waveguide **113**, first extension optical waveguide **108**, second extension optical waveguide **110**, and third extension optical waveguide **119**. Each of these waveguides, main nonlinear optical waveguide **106**, secondary optical waveguide **113**, first extension optical waveguide **108**, second extension optical waveguide **110**, and third extension optical waveguide **119** can comprise one or more segments.
(126) As depicted in this example, main nonlinear optical waveguide **106** is an optical waveguide in the set of optical waveguides **102** and is comprised of nonlinear optical material **104**. Additionally, secondary optical waveguide **113** is another optical waveguide in the set of optical waveguides **102** and can be comprised of nonlinear optical material **104** or non-nonlinear optical material **105**. Secondary optical waveguide **113** can comprise a single optical waveguide segment or can comprise multiple optical waveguide segments that are physically separate from each other. First extension optical waveguide **108** is an example of first extension optical waveguide **108** depicted in FIG. **2**.
(127) In this example, light **118** of three different wavelengths can travel through main nonlinear optical waveguide **106**. For example, first-wavelength light **132**, second-wavelength light **134**, and third-wavelength light **136** can travel in main nonlinear optical waveguide **106**.
(128) Light of two different wavelengths can travel through secondary optical waveguide **113**. For example, second-wavelength light **134** and third-wavelength light **136** can travel in secondary optical waveguide **113**.
(129) As depicted in this example, light **118** traveling through optical waveguides **102** can comprise at least one of first-wavelength light **132**, second-wavelength light **134**, or third-wavelength light **136**. In this particular example, first-wavelength light **132**, second-wavelength light **134**, and third-wavelength light **136** can refer to a pump light **161**, a signal light **163**, and an idler light **165**, but not necessarily in any particular order.
(130) For example, first-wavelength light **132** can also be the signal light **163**, second-wavelength light **134** can be the pump light **161**, and third-wavelength light **136** can be idler light **165**. As another example, first-wavelength light **132** can also be pump light **161**, second-wavelength light **134**

can be signal light **163**, and third-wavelength light **136** can be idler light **165**.

(131) Typically, pump light **161** has an intensity that is at least twice the intensity of signal light **163** and at least twice the intensity of idler light **165**. In some examples, the intensity of pump light **161** is at least ten times greater than the intensity of signal light **163** or of idler light **165**. Typically, pump light **161** is supplied as an input to optical waveguide structure **100**. In some cases, either of signal light **163** and idler light **165** also can be supplied as a second input to optical waveguide structure **100**. Either or both of signal light **163** and idler light **165** can be generated through nonlinear optical process **140** that occurs in portions of optical waveguide structure **100** that comprise a nonlinear optical material **104**.

(132) First extension optical waveguide **108** can be comprised of one at least one of nonlinear optical material **104** or a non-nonlinear optical material **105**. In this example, a light such as a pump light **161** can travel through first extension optical waveguide **108**.

(133) Second extension optical waveguide **110** can be comprised of at least one of nonlinear optical material **104** or non-nonlinear optical material **105**. A light such as signal light **163** can travel through second extension optical waveguide **110**.

(134) Third extension optical waveguide **119** can also be comprised of one of nonlinear optical material **104** and a non-nonlinear optical material **105**. In this example, a light such as idler light **165** can travel through third extension optical waveguide **119**, which can be a nonlinear optical waveguide.

(135) In one illustrative example, first extension optical waveguide **108**, second extension optical waveguide **110**, and third extension optical waveguide **119** are not constructed using nonlinear optical material **104**. In another illustrative example, at least one of first extension optical waveguide **108**, second extension optical waveguide **110** and third extension optical waveguide **119** can be constructed using nonlinear optical material **104**. In yet another illustrative example, at least one of first extension optical waveguide **108**, second extension optical waveguide **110** and third extension optical waveguide **119** can be constructed using electro-optic material **103**. Main nonlinear optical waveguide **106** also can be constructed using electro-optic material **103**.

(136) In this illustrative example, wavelength-selective couplers **114** include first wavelength-selective coupler **120**, second wavelength-selective coupler **122**, third wavelength-selective coupler **133**, and fourth wavelength-selective coupler **131**. Wavelength-selective couplers **114** can couple light **118** of different wavelengths to different optical waveguides based on the wavelengths in light **118**. For example, wavelength-selective couplers **114** can be configured to couple first-wavelength light **132**, second-wavelength light **134** and third-wavelength light **136** to selected different routes for travel of light **118** through optical waveguides in optical waveguides **102** based on the wavelengths of the light. For another example, wavelength-selective couplers **114** can be configured to couple at least one of second-wavelength light **134** or third-wavelength light **136** to different selected optical waveguides in optical waveguides **102** based on the wavelengths of the light.

(137) For example, first wavelength-selective coupler **120** optically couples first main location **146** in main nonlinear optical waveguide **106** and primary first extension location **148** in first extension optical waveguide **108** to each other such that first-wavelength light **132** is coupled from main nonlinear optical waveguide **106** at the first main location **146** to first extension optical waveguide **108** at primary first extension location **148**.

(138) First-wavelength light **132** can travel from primary first extension location **148** to secondary first extension location **150** through first extension segment **141**. In this illustrative example, locations at which first wavelength-selective coupler **120** and second wavelength-selective coupler **122** connect to main nonlinear optical waveguide **106** define the extent of main segment **143** of main nonlinear optical waveguide **106**. Further, main nonlinear optical waveguide **106** also can include additional segments. These additional segments can be defined by additional locations in main nonlinear optical waveguide **106** at which those segments are coupled to wavelength-selective couplers.

(139) In this example, second wavelength-selective coupler **122** optically couples second main location **152** in main nonlinear optical waveguide **106** and secondary first extension location **150** in first extension optical waveguide **108** to each other such that first-wavelength light **132** is coupled from first extension optical waveguide **108** at secondary first extension location **150** to main nonlinear optical waveguide **106** at second main location **152**.

(140) First-wavelength light **132** can travel from second main location **152** to first main location **146** through main segment **143** in main nonlinear optical waveguide **106**.

(141) In this illustrative example, first main location **146** and second main location **152** define main segment **143**, which is the portion of main nonlinear optical waveguide **106** through which first-wavelength light **132**, second-wavelength light **134**, and third-wavelength light **136** can travel. In this example, main segment **143** is comprised of a nonlinear optical material **104** and nonlinear optical processes can occur within main segment **143**.

(142) In this example, third wavelength-selective coupler **133** optically couples third secondary location **123** in secondary optical waveguide **113** and primary second extension location **156** in second extension optical waveguide **110** to each other such that second-wavelength light **134** is coupled from secondary optical waveguide **113** at third secondary location **123** to second extension optical waveguide **110** at primary second extension location **156**.

(143) In this example, second-wavelength light **134** can travel from primary second extension location **156** to secondary second extension location **158** through second extension segment **145** in second extension optical waveguide **110**.

(144) Illustration of waveguide configurations for optical waveguides **102** in FIG. **1**, FIG. **2** and FIG. **3** are presented as illustrations of some configurations for optical waveguides **102**. These illustrations are not meant to limit the manner in which other illustrative examples can be implemented. For example, one or more waveguide segments can be present in addition to or in place of main segment **143**. As yet another example, additional ones of wavelength-selective couplers **114** can be connected to additional segments of main nonlinear optical waveguide **106**, additional segments of secondary optical waveguide **113** and additional extension optical waveguides in optical waveguide **102**. In other illustrative examples, optical waveguide **102** can omit at least one of second extension optical waveguide **110** or third extension optical waveguide **119**.

(145) Turning to FIG. **4**, fourth wavelength-selective coupler **131** optically couples fourth secondary location **125** in the secondary optical waveguide **113** and secondary second extension location **158** in second extension optical waveguide **110** to each other such that second-wavelength light **134** is coupled from second extension optical waveguide **110** at secondary second extension location **158** to secondary optical waveguide **113** at fourth secondary location **125**. Second-wavelength light **134** can travel from primary second extension location **156** to secondary second extension location **158** through second extension segment **145** in second extension optical waveguide **110**.

(146) Second-wavelength light **134** can travel from first secondary location **124** to third secondary location **123** through first secondary segment **147** (in FIG. **4**). Second-wavelength light **134** can travel from fourth secondary location **125** to second secondary location **129** through second secondary segment **127** (in FIG. **4**). Similarly, third-wavelength light **136** can travel from first secondary location **124** to third secondary location **123** through second secondary segment **127** (in FIG. **4**). Third-wavelength light **136** can travel from fourth secondary location **125** to second secondary location **129** through second secondary segment **127** (in FIG. **4**). In this illustrative example, first-wavelength light **132** can be pump light **161**, second-wavelength light **134** can be one of signal light **163** and idler light **165**.

(147) Additionally, third wavelength-selective coupler **133** can optically couple third secondary location **123** in secondary optical waveguide **113** and primary third extension location **171** in third extension optical waveguide **119** to each other such that third-wavelength light **136** is coupled from secondary optical waveguide **113** at third secondary location **123** to third extension optical waveguide **119** at primary third extension location **171**.

(148) Furthermore, fourth wavelength-selective coupler **131** can optically couple fourth secondary location **125** in secondary optical waveguide **113** and secondary third extension location **173** in the third extension optical waveguide **119** to each other such that third-wavelength light **136** is coupled from third extension optical waveguide **119** at secondary third extension location **173** to secondary optical waveguide **113** at fourth secondary location **125**. Third-wavelength light **136** can travel from primary third extension location **171** to secondary third extension location **173** through third extension segment **175** in third extension optical waveguide **119**. Third-wavelength light **136** can travel from third secondary location **123** to fourth secondary location **125** through second secondary segment **127** (in FIG. **4**).

(149) When second extension optical waveguide **110** and third extension optical waveguide **119** are present and coupled to secondary optical waveguide **113**, both second-wavelength light **134** and third-wavelength light **136** can travel through secondary optical waveguide **113**. In this example, first-wavelength light **132** can be pump light **161**, second-wavelength light **134** can be signal light **163**, and third-wavelength light **136** can be idler light **165**.
(150) With reference now to FIG. **4**, an illustration of loops in optical waveguides is depicted in accordance with an illustrative embodiment. In this example, first loop **200**, second loop **202**, and third loop **204** are examples of loops **116** in FIG. **1**.
(151) In this illustrative example, first-wavelength light **132** travels in first loop **200** through main segment **143** between first main location **146** and second main location **152** within the main nonlinear optical waveguide **106** and first extension segment **141** between primary first extension location **148** and secondary first extension location **150** in the first extension optical waveguide **108**. In this example, first loop **200** has first length **191**.
(152) Second-wavelength light **134** travels in second loop **202** through first secondary segment **147** between first secondary location **124** and third secondary location **123** in secondary optical waveguide **113**, second extension segment **145** between primary second extension location **156** and secondary second extension location **158** in second extension optical waveguide **110**, second secondary segment **127** between third secondary location **123** and second secondary location **129** in secondary optical waveguide **113**, and main segment **143** in main nonlinear optical waveguide **106**. In this illustrative example, second loop **202** has second length **193** for second-wavelength light **134**.
(153) Third-wavelength light **136** travels in third loop **204** through first secondary segment **147** between first secondary location **124** and third secondary location **123** in secondary optical waveguide **113**, third extension segment **175** between primary third extension location **171** and secondary third extension location **173** in third extension optical waveguide **119**, second secondary segment **127** between fourth secondary location **125** and second secondary location **129** in secondary optical waveguide **113**, and main segment **143** in main nonlinear optical waveguide **106**. In this example, third loop **204** as third length **195**.
(154) As depicted, first-wavelength light **132** travels within main segment **143** in main nonlinear optical waveguide **106** and first extension segment **141** in first extension optical waveguide **108** in first loop **200**. In this example, first loop **200** has first length **191**.
(155) As depicted, first length **191** can also comprise the length of first wavelength-selective coupler **120** and the length of second wavelength-selective coupler **122**. Second length **193** can also comprise the lengths of third wavelength-selective coupler **133** and fourth wavelength-selective coupler **131** as well as the lengths of first wavelength-selective coupler **120** and second wavelength-selective coupler **122**. Third length **195** of third loop **204** can also comprise the lengths of third wavelength-selective coupler **133** and the length of fourth wavelength-selective coupler **131** as well as the lengths of first wavelength-selective coupler **120** and second wavelength-selective coupler **122**.
(156) The lengths of first loop **200**, second loop **202**, and third loop **204** can be selected based on the locations where wavelength-selective couplers **114** connect optical waveguides **102** to each other. First length **191** for first loop **200**, second length **193** for second loop **202**, and third length **195** for third loop **204** can have different lengths from each other.
(157) For example, first length **191** of first loop **200** can be selected based on a selection of first main location **146** and primary first extension location **148** for first wavelength-selective coupler **120** connecting main nonlinear optical waveguide **106** to first extension optical waveguide **108** and based on a selection of secondary second extension location **158** and second main location **152** for second wavelength-selective coupler **122** connecting first extension optical waveguide **108** to main nonlinear optical waveguide **106**.
(158) As another example, second length **193** of second loop **202** can be selected based on a selection of first secondary location **124** in secondary optical waveguide **113**, and second secondary location **129** and primary second extension location **156** for third wavelength-selective coupler **133** connecting secondary optical waveguide **113** to second extension optical waveguide **110**; and based on a selection of secondary second extension location **158** and third secondary location **123** for fourth wavelength-selective coupler **131** connecting second extension optical waveguide **110** to secondary optical waveguide **113**, and fourth secondary location **125** in secondary optical waveguide **113**.
(159) As yet another example, third length **195** of third loop **204** can be selected based on a selection of first secondary location **124** in secondary optical waveguide **113**, and second secondary location **129** and primary third extension location **171** for third wavelength-selective coupler **133** connecting secondary optical waveguide **113** to third extension optical waveguide **119** and based on a selection of secondary third extension location **173** and third secondary location **123** for fourth wavelength-selective coupler **131** connecting third extension optical waveguide **119** to secondary optical waveguide **113**, and fourth secondary location **125** in secondary optical waveguide **113**.
(160) With reference next to FIG. **5**, an illustration of a block diagram of a configuration for nonlinear optical waveguides is depicted in accordance with an illustrative embodiment. In illustrative example, at least one of resonance matching **300** or roundtrip phase matching **302** for optical waveguides **102** can be achieved through the selection of dimensions **304** for optical waveguides **102**. This selection of dimensions **304** can be made in addition to the selection of lengths, such as first length **191**, second length **193**, and second length **193** for loops **116** optical waveguides **102** to achieve at least one of resonance matching **300** or roundtrip phase matching **302** for optical waveguides **102**.
(161) For example, main nonlinear optical waveguide **106** can have main cross-section **308** with a set of dimensions **310** in dimensions **304** selected to achieve resonance condition **306** for first-wavelength light **132** traveling in main nonlinear optical waveguide **106**. In this example, secondary optical waveguide **113** can have secondary cross-section **301** with secondary dimensions **303** selected to achieve resonance condition **306** for one of first-wavelength light **132** and second-wavelength light **134** traveling in secondary optical waveguide **113**.
(162) As another example, first extension optical waveguide **108** can have first cross-section **312** with first dimensions **314** selected to achieve resonance condition **306** for first-wavelength light **132** traveling in first extension optical waveguide **108**. Further, second extension optical waveguide **110** can have second cross-section **316** with a set of second dimensions **318** selected to achieve resonance condition **306** for second-wavelength light **134** traveling in second extension optical waveguide **110**. Also, third extension optical waveguide **119** can have third cross-section **317** with a set of third dimensions **319** selected to achieve resonance condition **306** for third-wavelength light **136** traveling in second extension optical waveguide **110**.
(163) With reference now to FIG. **6**, an illustration of phase shifters used to obtain at least one of resonance matching or roundtrip phase matching is depicted in accordance with an illustrative embodiment. At least one of manufacturing deviations from specifications, environmental factors, or other influences can affect whether a resonance condition is present during the operation of optical waveguide structure **100**.
(164) When roundtrip phase matching **302** in FIG. **5** is not present during operation of optical waveguide structure **100**, a set of phase shifters **400** can be used to adjust a set of phases **402** for light **118** propagating within optical waveguides **102**. In one illustrative example, the set of phase shifters **400** can be structures that are located adjacent to one or more of optical waveguides **102**; connected to one or more of optical waveguides **102**; include part of one or more of optical waveguides **102**; or a combination thereof.
(165) The set of phase shifters **400** can operate to ensure a desired level of roundtrip phase matching **302** is achieved for light **118** that is generated within optical waveguides **102** in optical waveguide structure **100**. As depicted, light **118** can be generated in an optical waveguide in optical waveguides **102** that is comprised of nonlinear optical material **104**. In the illustrative example, main nonlinear optical waveguide **106** is comprised of nonlinear optical material **104**. Optionally, at least one of first extension optical waveguide **108**, second extension optical waveguide **110** or third extension optical waveguide **119** can be comprised of nonlinear optical material **104**. In an illustrative example, at least one of first extension optical waveguide **108**, second extension optical waveguide **110** or third extension optical waveguide **119** can be comprised of electro-optic material **103**.
(166) In one illustrative example, a set of phase shifters **400** can be connected to a set of optical waveguides **102** comprising at least one of main nonlinear optical waveguide **106**, first extension optical waveguide **108** second extension optical waveguide **110**, or third extension optical waveguide **119**. The set of phase shifters **400** can apply a set of activations **404** to achieve a change or shift in the phase of at least one of first-wavelength light **132**, second-wavelength light **134**, or third-wavelength light **136** in light **118** traveling in the set of optical waveguides **102** to which

the set of activations **404** is applied.
(167) In one illustrative example, the set of phase shifters **400** comprises a set of elements that can be located adjacent to a waveguide. The set of phase shifters **400** can take a number of different forms. For example, the set of phase shifters **400** can be selected from at least one of a tuning electrode, a thermal element, shape memory alloy element, piezo electric element, or some other element that can change the phase of light of a particular wavelength propagating through the optical waveguide. These elements for the set of phase shifters **400** can be at least one of adjacent to part of an optical waveguide, connected to part of an optical waveguide, or include part of an optical waveguide.
(168) The set of activations **404** can take a number of different forms. For example, the set of activations **404** can be selected from at least one of a voltage, a current, a thermal energy, an electrically induced strain, or some other type of energy that can be applied to an optical waveguide to affect the manner in which light propagates through the optical waveguide. In particular, the energy can be used to affect the phase of light of a particular wavelength propagating through the optical waveguide.
(169) In other words, the set of phase shifters **400** can selectively apply the set of activations **404** to adjust the phase for a particular wavelength of light **118** traveling within loops **116** in optical waveguides **102**. This adjustment can be made by applying the activations **404** using a particular phase shifter located adjacent to an optical waveguide in the set of optical waveguides **102** in a loop in loops **116** for a particular wavelength of light to maintain or reach resonance matching **300** for that particular wavelength of light.
(170) For example, a phase shifter, such as main phase shifter **406**, can be located adjacent to a portion of main nonlinear optical waveguide **106**. Main phase shifter **406** can apply an activation in activations **404** such that a phase shifts in first-wavelength light **132** to achieve resonant condition **306** for first-wavelength light **132** for light traveling in first loop **200**.
(171) Another phase shifter, such as secondary phase shifter **408** can be located adjacent to a portion of secondary optical waveguide **113**. Secondary phase shifter **408** can apply an activation in activations **404** such that a phase shifts in one or both of second-wavelength light **134** and third-wavelength light **136** to achieve a roundtrip phase matching **302** for the nonlinear optical process.
(172) A phase shifter, such as first phase shifter **410**, can be located adjacent to a portion of first extension optical waveguide **108**. First phase shifter **410** can apply an activation in activations **404** such that a phase shifts in first-wavelength light **132** to achieve a resonance condition **306** for first-wavelength light **132** in first loop **200**. First phase shifter **410** also can apply an activation in activations **404** such that a phase shifts in first-wavelength light **132** to achieve a roundtrip phase matching **302** for the nonlinear optical process.
(173) In another illustrative example, a phase shifter, such as second phase shifter **412**, can be located adjacent to a portion of second extension optical waveguide **110**. Second phase shifter **412** can apply an activation in activations **404** such that a phase shifts in second-wavelength light **134** to achieve a resonance condition **306** for second-wavelength light **134** in second loop **202**.
(174) As another illustrative example, a phase shifter, such as third phase shifter **414**, can be located adjacent to a portion of third extension optical waveguide **119**. Third phase shifter **414** can an activation in activations **404** such that a phase shifts in third-wavelength light **136** to achieve resonance condition **306** for third-wavelength light **136** in third loop **204**.
(175) In one illustrative example, the set of phase shifters **400** can be a set of tuning electrodes that apply a set of activations **404** as a set of voltages **418**. With this type of phase shifters in the form of tuning electrodes that apply activations **404** in the form of voltages **418**, the optical waveguides associated with the tuning electrodes can be comprised of an electro-optic material **103**. One example of an electro-optical material **103** is lithium niobate. This material does not have to be use throughout the entire optical waveguide. Lithium niobate can be used in the sections that are associated with or adjacent to the tuning electrodes.
(176) Lithium niobate is an electro-optic material for which the material refractive index can be changed by applying an electric field to the lithium niobate material. Lithium niobate has a second order nonlinear optical coefficient that is large enough to result in undesired light generation. As a result, in some illustrative examples the regions in a nonlinear optical waveguide containing the lithium niobate containing regions used for electro-optic tuning from the lithium niobate can be separated from regions containing lithium niobate used for the nonlinear optical generation of signal photons and idler photons.
(177) With this example, main phase shifter **406** in the set of phase shifters **400** can be main tuning electrode **420** located adjacent to a portion of main nonlinear optical waveguide **106**. Secondary phase shifter **408** in the set of phase shifters **400** can be secondary tuning electrode **422** located adjacent to a portion of secondary optical waveguide **113**.
(178) In this illustrative example, first phase shifter **410** can be first tuning electrode **424** located adjacent to a portion of first extension optical waveguide **108**. Second phase shifter **412** can be second tuning electrode **426** located adjacent to a portion of second extension optical waveguide **110**, and third phase shifter **414** in the set of phase shifters **400** can be third tuning electrode **428** located adjacent to a portion of third extension optical waveguide **119**.
(179) First tuning electrode **424**, second tuning electrode **426**, and third tuning electrode **428** can apply the set of activations **404** in the form of a set of voltages **418** to adjust the set of phases **402** in at least one of first-wavelength light **132**, second-wavelength light **134**, or third-wavelength light **136** traveling in a set of loops **116** through optical waveguides **102**. This shift in the set of phases **402** can be made to maintain or reach resonance condition **306** for one or more of the wavelengths of light **118**. These wavelengths of light can be for example, at least one of first-wavelength light **132**, second-wavelength light **134**, or third-wavelength light **136**. This shift in the set of phases **402** also can be made to achieve or maintain roundtrip phase matching **302**.
(180) In the illustrative example, when an optical waveguide in the set of optical waveguides **102** comprises an electro-optic material **103**, the activation can take the form of a voltage. When the optical waveguide does not comprise an electro-optic material, other forms of energy such as, for example, thermal energy, such as heat, or strain can be used as the set of activations **404**. In this illustrative example, heat can be generated by applying electrical current to a resistor that forms a phase shifter in the set of phase shifters **400** such that heat is generated. As another example, a voltage can be applied to a piezo electric element for phase shifter in the set of phase shifters **400** to change the dimensions of the tuning electrode to cause strain in the portion of the optical waveguide adjacent to the phase shifter in the set of phase shifters **400**.
(181) The illustration of optical waveguide structure **100** and the different components in FIGS. **1-6** is not meant to imply physical or architectural limitations to the manner in which an illustrative embodiment may be implemented. Other components in addition to or in place of the ones illustrated may be used. Some components may be unnecessary. Also, the blocks are presented to illustrate some functional components. One or more of these blocks may be combined, divided, or combined and divided into different blocks when implemented in an illustrative embodiment.
(182) For example, additional extension waveguides can be present in optical waveguide structure **100**. For example, another extension waveguide can be optically coupled to second extension optical waveguide **110**. This coupling can be performed using another pair of wavelength-selective couplers to form a third extension segment for third-wavelength light.
(183) In another illustrative example, fewer components can be present than depicted in optical waveguide structure **100** in FIGS. **1-6**. In another illustrative example, third extension optical waveguide **119** can be omitted from optical waveguides **111**. In other illustrative examples, phase shifters **400** may be used with some but not all of optical waveguides **102**. In one example, only main phase shifter **406** may be present.
(184) With reference now to FIG. **7**, an illustration of a cross-section of an optical waveguide is depicted in accordance with an illustrative embodiment. In this illustrative example, optical waveguide **700** is shown in a cross-sectional view. This cross-section can be used in the optical waveguides in optical waveguide structure **100** in FIGS. **1-6**.
(185) As depicted, optical waveguide **700** comprises core region **702** and cladding region **704**. Core region **702** can be comprised of a material such as silicon nitride (Si.sub.3N.sub.4), silicon (Si) or silicon carbide (SiC) for optical processes based on four wave mixing. Core region **702** can be comprised of a material such as lithium niobate (LiNbO.sub.3), gallium phosphide (GaP), aluminum nitride (AlN), aluminum gallium arsenide

(AlGaAs), or silicon carbide (SiC) for optical processes based on three-wave mixing. Cladding region **704** can be comprised of silicon dioxide (SiO.sub.2) or other material whose refractive index is lower than the refractive index of the material comprising core region **702**. The particular material used in optical waveguide **700** can vary in other illustrative examples depending on the optical process used.

(186) In this illustrative example, core region **702** has width w **706** and height tw **708**. Cladding region **704** has height tox **710**. Cladding region **704** can cover any combination of the top, the two sides and the bottom of core region **702**.

(187) Optical waveguide **700** can be adjusted to achieve values for the effective refractive indices (neff) of the wavelengths of light **118** traveling through optical waveguide **700**. The effective refractive indices can be adjusted through the selection of the material refractive index at a specific wavelength and varying the waveguide dimensions such as width w **706**, height tw **708**, and top oxide thickness, height tox **710**.

(188) The selection of at least one of the material and dimensions for optical waveguide **700** can be based on the conditions for momentum conservation and phase matching. In the illustrative example, momentum conservation is an automatic consequence of the nonlinear optical interaction. Whether the phase matching associated with the particular waveguide structure is consistent with momentum conservation determines the degree of phase walk-off that results as the light travels in the waveguide over some distance.

(189) For example, an effective refractive index can be a function of the height and width of core region **702**. The constructive nonlinear generation length is the propagation length at which the phase walk-off equals π radians. The constructive nonlinear generation length is inversely proportional to the phase mismatch. In an illustrative example, the length of the main nonlinear optical waveguide should be no larger than the constructive nonlinear generation length that can be achieved for the main nonlinear optical waveguide. In illustrative examples, the nonlinear optical interaction occurs in all three loops.

(190) Additionally, the cross-section shown for optical waveguide **700** is provided as an example and is not meant to limit the manner in which other illustrative examples can implement cross-sections for waveguides. For example, optical waveguide **700** is shown with side **720** and side **722** that are angled for core region **702**. In other illustrative examples, these two sides can be parallel to each other rather than angled. As another example, other components may be present in this cross-section such as side regions that may be located adjacent to side **720** and side **722**. In yet another illustrative example, the cross-section of optical waveguide **700** may also include a phase shifter such as a tuning electrode. As another example, optical waveguide **700** can include a second core region in addition to core region **702** when optical waveguide **700** is used to implement a two-waveguide optical coupler.

(191) Turning to FIG. **8**, an illustration of light coupling by a wavelength-selective coupler is depicted in accordance with an illustrative embodiment. In this illustrative example, pump light **802**, signal light **804**, and idler light **806** travel through optical waveguide **808** and are input into wavelength-selective coupler **810**. Signal light **804** and idler light **806** also travel through optical waveguide **808** and are input into wavelength-selective coupler **810**. As depicted, at the output of wavelength-selective coupler **810**, pump light **802** continues through to optical waveguide **828**. In this example, signal light **804** and idler light **806** cross over from optical waveguide **808** to optical waveguide **822** at the output of wavelength-selective coupler **810**. Signal light **804** and idler light **806** also cross over from optical waveguide **812** at the input of wavelength-selective coupler **810** to optical waveguide **828** at the output of wavelength-selective coupler **810**. Wavelength-selective coupler **810** is an illustration of an implementation for first wavelength-selective coupler **1220** and second wavelength-selective coupler **1222** in optical waveguide structure **1200** in FIG. **16** and for first wavelength-selective coupler **1320** and second wavelength-selective coupler **1322** in optical waveguide structure **1300** in FIG. **17**.

(192) With reference next to FIG. **9**, an illustration of light coupling by a wavelength-selective coupler is depicted in accordance with an illustrative embodiment. In this illustrative example, pump light **902**, signal light **904**, and idler light **906** travel through optical waveguide **908** into wavelength-selective coupler **910**. Pump light **912** also travels through optical waveguide **914** and is input into wavelength-selective coupler **910**.

(193) As depicted, at the output of wavelength-selective coupler **910**, signal light **904** and idler light **906** continues through into optical waveguide **928**. Pump light **902** traveling into wavelength-selective coupler **910** from optical waveguide **908** crosses over to optical waveguide **924** at the output of wavelength-selective coupler **910**. In a similar fashion, pump light **912** traveling through optical waveguide **914** into wavelength-selective coupler **910** crosses over to optical waveguide **928** at the output of wavelength-selective coupler **910**. Wavelength-selective coupler **910** is illustrative of first wavelength-selective coupler **1120** and second wavelength-selective coupler **1122** in optical waveguide structure **1100** in FIG. **13**, first wavelength-selective coupler **1020** and second wavelength-selective coupler **1022** in optical waveguide structure **1000** in FIG. **14**, first wavelength-selective coupler **1420**, second wavelength-selective coupler **1422** in optical waveguide structure **1400** in FIG. **15**, and first wavelength-selective coupler **1580**, second wavelength-selective coupler **1586**, third wavelength-selective coupler **1584** and fourth wavelength-selective coupler **1582** in optical waveguide structure **1500** in FIG. **18**, described below.

(194) With reference to FIG. **10**, an illustration of light coupling by a wavelength-selective coupler is depicted in accordance with an illustrative embodiment. In this illustrative example, signal light **3902** and idler light **3904** travel through optical waveguide **3906** and are input into wavelength-selective coupler **3908**. In this depicted example, light is not input into optical waveguide **3910** which is connected to wavelength-selective coupler **3908**. As depicted, at the output of wavelength-selective coupler **3908**, idler light **3904** continues through into optical waveguide **3926** and signal light **3902** crosses over into optical waveguide **3920**.

(195) This crossover of signal light **3902** is caused by the design of wavelength-selective coupler **3908**. In illustrative examples, wavelength-selective coupler **3908** can be used for a signal wavelength-selective coupler to selectively couple signal light from a secondary optical waveguide to a signal extension optical waveguide. Wavelength-selective coupler **3908** can also be used to selectively couple signal light from a signal extension optical waveguide to the secondary optical waveguide. Wavelength-selective coupler **3908** is illustrative of wavelength-selective couplers used in optical waveguide structure **1500** in FIG. **18**.

(196) In FIG. **11**, an illustration of simulation results of light coupling by a wavelength-selective coupler is depicted in accordance with an illustrative embodiment. As depicted, simulation results **4000** comprises plots and. Simulation results **4000** comprise signal extraction plot **4002** for a signal extraction result and idler retention plot **4004** for an idler retention result. These plots are of the optical-field distributions for a signal light and an idler light having different wavelengths from each other.

(197) Simulation results **4000** are generated using a wavelength-selective coupler such as wavelength-selective coupler **3908** in FIG. **10**. This wavelength-selective coupler can be implemented as a two-waveguide optical coupler. In this illustrative example, simulation results **4000** are for a case in which signal light **3902**, that is coupled and exits from the “cross” output of wavelength-selective coupler **3908**, has a larger guided-mode effective index of refraction n.sub.eff and is confined more strongly than the idler light **3904**, that exits from the “through” output of wavelength-selective coupler **3908**.

(198) As depicted, signal extraction plot **4002** depicts the electric-field magnitude of the signal light. Plot **4002** has x-axis **4006** that represents the longitudinal direction of the two-guide wavelength-selective coupler structure and y-axis **4008** that represents the transverse direction of the two-guide wavelength-selective coupler structure. Signal extraction plot **4002** in simulation results **4000** shows that signal light is coupled from the lower left waveguide to the upper right waveguide and is illustrative of the cross-state of a coupler.

(199) In this illustrative example, idler retention plot **4004** depicts the electric-field magnitude of the idler light. Idler retention plot **4004** has x-axis **4010** that represents the longitudinal direction of the two-guide wavelength-selective coupler structure and y-axis **4012** that represents the transverse direction of the two-guide wavelength-selective coupler structure. As depicted, idler retention plot **4004** shows that the idler light couples from the lower waveguide to the upper waveguide in a few portions of the coupling region but eventually remains in the lower waveguide away from that coupling section and exits from the lower right waveguide, illustrative of the thru-state of a coupler.

(200) In this example, these simulation results can be obtained using a wavelength-selective coupler that comprises two curved waveguides that are coupled by a section of a straight waveguide of a length and a gap for wavelength-selective coupler that are selected to result in the coupling of the

signal light from a first optical waveguide to a second optical waveguide when passing through the wavelength-selective coupler.
(201) Thus, if light of both signal light **3902** and idler light **3904** are supplied to wavelength-selective coupler **3908** through optical waveguide **3906**, signal light **3902** exits wavelength-selective coupler **3908** via optical waveguide **3920** and idler light **3904** exits wavelength-selective coupler **3908** via optical waveguide **3926**.
(202) For this example, an example length d.sub.s|i for the coupling section for wavelength-selective coupler **3908** can be described by the following relation: κ.sub.s|i(λ.sub.S).Math.d.sub.s|i=π, where κ.sub.s|i is the coupling coefficient. To achieve the desired wavelength selectivity, wavelength-selective coupler **3908** can also be constrained by another relation: κ.sub.s|i(λ.sub.I).Math.d.sub.s|i=2.Math.π.Math.X, where λ.sub.I is the longer wavelength and X is an integer. In the illustrative example, the value of X is 2, such that the photons of signal light wavelength λ.sub.S have approximately 100% coupling between the two waveguides being coupled, while the photons of idler light wavelength λ.sub.I are coupled back again to the starting waveguide.
(203) With reference now to FIG. **12**, an illustration of simulation results of light coupling by a wavelength-selective coupler is depicted in accordance with an illustrative embodiment. Simulation results **4100** comprise plots that illustrate light coupling using a wavelength-selective coupler such as a two-waveguide optical coupler.
(204) As depicted, simulation results **4100** are for pump light in pump plot **4118**, signal light in signal plot **4110**, and idler light in idler plot **4114**. These simulation results are plots of the electric field magnitude distributions of light at the pump, signal and idler wavelengths. Pump plot **4118** is a plot for field magnitude distribution in linear scale. As depicted, pump plot **4118** has x-axis **4108** that represents the longitudinal direction of the two-guide wavelength-selective coupler structure and y-axis **4102** that represents the transverse direction of the two-guide wavelength-selective coupler structure.
(205) In this illustrative example, signal plot **4110** and idler plot **4114** are plots for the signal and idler field magnitude distributions in a logarithmic scale. As depicted, signal plot **4110** has x-axis **4112** that represents the longitudinal direction of the two-guide wavelength-selective coupler structure and y-axis **4105** that represents the transverse direction of the two-guide wavelength-selective coupler structure. Idler plot **4114** has x-axis **4116** that represents the longitudinal direction of the two-guide wavelength-selective coupler structure and y-axis **4107** that represents the transverse direction of the two-guide wavelength-selective coupler structure.
(206) In this depicted example, the optical waveguide at the lower portion of the plots for simulation results **4100** has a smaller radius of curvature than the optical waveguide at the upper portion of those plots. The light travels from left to right in these plots for simulation results **4100**. Pump light enters in the upper guide from the upper left of pump plot **4118**. Signal light and idler light enter in the lower, curved guide from the lower left of signal plot **4104** and idler plot **4106**.
(207) In this example, the pump light experiences primarily the “cross” state of this coupler and is coupled into the curved, lower guide and exits from the lower right of the plot. The signal and idler light experience the “through” state of this coupler and remain in the curved guide to also exit from the lower right of the plots. For this example, the pump light is carried by a higher-order transverse mode of the lower, curved guide. Thus, the field magnitude distribution of the pump light in that curved guide has several brighter regions. The signal and idler light, however, are carried by the fundamental transverse modes at those wavelengths. Thus, the intensity distributions for the signal and idler light have just one bright region that is brighter near the center of the guide. In this illustrative example, the pump light is carried in the upper guide by the fundamental transverse mode at the pump wavelength. Thus, the intensity distribution for the pump light in the upper waveguide has just one bright region that is brighter near the center of that upper guide. The simulation results **4100** can be examples of the performance of some implementations of wavelength-selective coupler **910** illustrated in FIG. **9**.
(208) The examples of FIGS. **13**-**18** illustrate different aspects of optical waveguide structure **100** as shown in FIGS. **1**-**6**. These illustrations are intended to be inclusive rather than exclusive. Thus, although only some features are illustrated in one example and other features are illustrated in another example, this difference in features in different figures is used only for the purpose of clarity and to simplify the description of features in the illustrative examples.
(209) With reference to FIG. **13**, an illustration of an optical waveguide structure with five optical waveguides is depicted in accordance with an illustrative embodiment. In this illustrative example, optical waveguide structure **1100** is an example of an implementation for optical waveguide structure **100** as shown in FIGS. **1**-**6**. More specifically, FIG. **13** is an implementation for optical waveguides **102** as depicted in FIG. **3**.
(210) In this illustrative example, optical waveguide structure **1100** can be designed to achieve the concurrent requirements that the three wavelengths are at resonances of their respective resonator loops and also that the phase match condition is met for sustaining the nonlinear optical process over many cycles of travel through the loops.
(211) In this illustrative example, optical waveguide structure **1100** comprises optical waveguides in the form of main nonlinear optical waveguide **1110**, segment **1107** in secondary optical waveguide **1108**, segment **1109** in secondary optical waveguide **1108**, pump loop extension **1102**, signal loop extension **1104**, and idler loop extension **1106**. Main nonlinear optical waveguide **1110** is an example of main nonlinear optical waveguide **106** in FIG. **3** and main nonlinear optical waveguide **106** in FIG. **2**. Pump loop extension **1102** is an example of an implementation for first extension optical waveguide **108** in FIG. **3** and first extension optical waveguide **108** in FIG. **2**. Signal loop extension **1104** and idler loop extension **1106** are optical waveguides that can be coupled to segments of secondary optical waveguide **113** in FIG. **3** or secondary optical waveguide **113** in FIG. **2**. Signal loop extension **1104** and idler loop extension **1106** are examples of second extension optical waveguide **110** and third extension optical waveguide **119**, respectively, in FIGS. **3**-**6**.
(212) In these illustrative examples, the individual optical waveguides can be portions or segments from which loops can be established through the use of wavelength selective optical couplers to connect those segments or portions to other segments or portions.
(213) In this illustrative example, main nonlinear optical waveguide **1110** of optical waveguide structure **1100** is comprised of a nonlinear optical material **104**. For some second-order nonlinear optical materials, such as x-cut lithium niobate, the nonlinear optical coefficient is much larger for light whose electric-field vector is aligned parallel to one crystallographic axis than for light whose electric-field vector is aligned perpendicular to that crystallographic axis. Thus, for x-cut lithium niobate, a larger second-order nonlinear optical coefficient applies for a nonlinear optical waveguide aligned parallel to the material Y-axis, with the electric-field vector of the propagating transverse-electric (TE) polarized light aligned parallel to the material Z-axis. In this illustrative example, main nonlinear optical waveguide **1110** has a linear shape and is aligned parallel to the lithium niobate material Y-axis. Thus, the propagation direction would be in the +y direction or the −y direction of the lithium niobate crystalline material.
(214) In this illustrative example, pump loop extension **1102** is comprised of a non-nonlinear optical material **105**. As depicted, idler loop extension **1106** is comprised of an electro-optic material **103**. As depicted, signal loop extension **1104** is comprised of a nonlinear optical material **104** as well as an electro-optic material **103**. An electro-optic material is a material with a large electro-optic coefficient. Examples of electro-optic materials that can be used are lithium niobate, gallium arsenide, gallium phosphide and silicon carbide.
(215) In an illustrative example, the use of an electro-optic material can provide desired propagation properties for light. Electro-optical materials often also are nonlinear optical materials having nonlinear optical coefficient.
(216) As depicted, optical waveguide structure **1100** also includes pump input optical waveguide **1132** that inputs pump light **1112**. Optical waveguide structure **1100** also includes signal output optical waveguide **1134** and idler output optical waveguide **1136**. Signal output optical waveguide **1134** can output signal light **1114**. Idler output optical waveguide **1136** can output idler light **1116**.
(217) As depicted, first wavelength-selective coupler **1120** and second wavelength-selective coupler **1122** connect pump loop extension **1102** to main nonlinear optical waveguide **1110**. In this illustrative example, third wavelength-selective coupler **1124** and fourth wavelength-selective coupler **1126**

connect signal loop extension **1104** and idler loop extension **1106** to segment **1107** and segment **1109** of secondary optical waveguide **1108**.

(218) In this illustrative example, pump optical coupler **1131** couples pump input optical waveguide **1132** to pump loop extension **1102**. Signal optical coupler **1135** couples signal output optical waveguide **1134** to signal loop extension **1104**. Idler optical coupler **1137** couples idler output optical waveguide **1136** to idler loop extension **1106**.

(219) In this illustrative example, pump light **1112** travels in pump loop **1152** which extends through main nonlinear optical waveguide **1110** and pump loop extension **1102**. Signal light **1114** travels in signal loop **1154** which extends through main nonlinear optical waveguide **1110**, secondary optical waveguide **1108** and signal loop extension **1104**. Idler light **1116** travels in idler loop **1156** which extends through main nonlinear optical waveguide **1110**, secondary optical waveguide **1108** and idler loop extension **1106**.

(220) As depicted, optical waveguide structure **1100** also includes phase shifters in the form of tuning electrodes. In this illustrative example, tuning electrode **1160** is located adjacent to a portion of main nonlinear optical waveguide **1110**. Tuning electrode **1164** is located adjacent to a portion of signal loop extension **1104**. Tuning electrode **1166** is located adjacent to a portion of idler loop extension **1106**.

(221) In this illustrative example, each wavelength-selective coupler in optical waveguide structure **1100** produces a phase shift for each given wavelength of light at its “thru” state output and a possibly different phase shift for each given wavelength of light at its “cross” state output. For example, first wavelength-selective coupler **1120** extracts pump light **1112** from main nonlinear optical waveguide **1110** into pump loop extension **1102**. First wavelength-selective coupler **1120** also extracts signal light **1114** and idler light **1116** from main nonlinear linear optical waveguide **1110** into segment **1107** of secondary optical waveguide **1108**.

(222) In this illustrative example, first wavelength-selective coupler **1120** produces a phase shift of ϕ_{M1p} for the pump light **1112** coupled from main nonlinear optical waveguide **1110** to pump loop extension **1102** via a “cross” state output of first wavelength-selective coupler **1120**. First wavelength-selective coupler **1120** produces a phase shift of ϕ_{1s} for signal light **1114** that is coupled from main nonlinear optical waveguide **1110** into segment **1107** of secondary optical waveguide **1108**, and a phase shift of P for idler light **1116** that is coupled from main nonlinear optical waveguide **1110** into segment **1107** of secondary optical waveguide **1108** via a “thru” state output of first wavelength-selective coupler **1120**.

(223) Furthermore, second wavelength-selective coupler **1122** causes a phase shift of ϕ_{1Mp} for pump light **1112** coupled from pump loop extension **1102** back to main nonlinear optical waveguide **1110**. Second wavelength-selective coupler **1122** produces a phase shift of ϕ_{1s} for signal light **1114** that is coupled from segment **1109** of secondary optical waveguide **1108** into main nonlinear optical waveguide **1110** and produces a phase shift of ϕ_{1i} for idler light **1116** that is coupled from segment **1109** of secondary optical waveguide **1108** into main nonlinear optical waveguide **1110**.

(224) In this illustrative example, third wavelength-selective coupler **1124** and fourth wavelength-selective coupler **1126** between the secondary optical waveguide **1108** and idler loop extension **1106** produce phase shifts of ϕ_{2i} and ϕ_{2i} for idler light **1116** coupled in their “cross” state output. Third wavelength-selective coupler **1124** and fourth wavelength-selective coupler **1126** between the secondary optical waveguide **1108** and signal loop extension **1104** produce phase shifts of ϕ_{2s} and ϕ_{2s} for signal light **1114** that exits from their “thru” state outputs.

(225) The light propagating in a waveguide can experience a phase shift associated with the length of the waveguide and with the effective refractive index of the wave-guided mode. For transverse-electric (TE) polarized light in x-cut lithium niobate, the material index depends on the direction of propagation. Thus, the phase shift can be estimated by performing a numerical simulation. The phase shifters, such as tuning electrodes, can contribute an additional phase shift that can either advance the phase or retard the phase, depending on the sign of the applied voltage, for an electro-optic phase shifter.

(226) For the example in optical waveguide structure **1100** in FIG. **13**, tuning electrode **1164** for signal loop extension **1104** in signal loop **1154** and tuning electrode **1166** for idler loop extension **1106** in idler loop **1156** can contribute additional phase shifts of $\Delta\phi_{Es}$ and $\Delta\phi_{Ei}$, respectively. These phase shifts can have a positive or negative value.

(227) In this illustrative example, tuning electrode **1160** for main nonlinear optical waveguide **1110** affects pump light **1112**, signal light **1114**, and idler light **1116** and can produce additional phase shifts of $\Delta\phi_{MEp}$, $\Delta\phi_{MEs}$, and $\Delta\phi_{MEi}$ to the pump light **1112**, signal light **1114**, and idler light **1116**, respectively.

(228) The resonator for pump light **1112** is comprised of components of optical waveguide structure **1100** in pump loop **1152**. This pump loop comprises main nonlinear optical waveguide **1110**, the cross-state of first wavelength-selective coupler **1120**, the cross-state of second wavelength-selective coupler **1122**, and pump loop extension **1102**. The round-trip phase shift ϕ_{RTp} for pump light **1112** at the pump wavelength should be equal to a multiple of 2π for pump light **1112** to remain circulating for many round-trips through pump loop **1152** and thus circulate for many passes through main nonlinear optical waveguide **1110**.

(229) In this illustrative example, the phase shift of the pump light **1112** due to propagation in the pump loop extension **1102** can be described by the expression:

$\phi_{1p}=2\pi n_{1p}L_{1}/\lambda_{p}$,

where n_{1p} is a net or equivalent effective refractive index of the wave-guided pump light in the pump loop extension **1102**; L_{1} is the length of pump loop extension **1102**; and λ_{p} is the wavelength of pump light **1112**.

(230) The phase shift of pump light **1112** from propagation through the main nonlinear optical waveguide **1110** can be described as follows:

$\phi_{Mup}=2\pi n_{Mp}L_{M}/\lambda_{p}$

where n_{Mp} is the effective refractive index of the wave-guided pump mode in main nonlinear optical waveguide **1110**, L_{M} is the length of main nonlinear optical waveguide **1110**, which is located between first wavelength-selective coupler **1120** and second wavelength-selective coupler **1122**; and λ_{p} is the wavelength of pump light **1112**.

(231) Next, the resonance requirement for pump light **1112** can be given by the expression:

$\phi_{RTp}=\phi_{1p}+\phi_{1Mp}+\phi_{Mup}+\phi_{M1p}+\Delta\phi_{MEp}=2\pi P$

(232) where P is an integer. In an illustrative example, P can have values that also result in phase matching to maintain constructive generation of signal and idler from pump light.

(233) This resonance requirement can be met by designing optical waveguide structure **1100** to have suitable values for the length L_{1} and the phase shift ϕ_{1p}. The phase shift ϕ_{M1p} is due to the first wavelength-selective coupler and the phase shift ϕ_{1Mp} is due to the second wavelength-selective coupler.

(234) In this illustrative example, signal loop **1154** extends through main nonlinear optical waveguide **1110**. More specifically signal loop **1154** extends through main nonlinear optical waveguide **1110**, first wavelength-selective coupler **1120** (in its thru state) and second wavelength-selective coupler **1122** (in its thru state); segment **1107** and segment **1109** of secondary optical waveguide **1108**, in which both signal light **1114** and idler light **1116** propagate; third wavelength-selective coupler **1124** (in its thru state) and fourth wavelength-selective coupler **1126** (in its thru state); and signal loop extension **1104**. As depicted, only signal light **1114** propagates through signal loop extension **1104**.

(235) In this example, main nonlinear optical waveguide **1110** can have length L_{Mu}. Pump light **1112**, signal light **1114**, and idler light **1116** propagate through main nonlinear optical waveguide **1110**. Segment **1107** and segment **1109** have a total length of L_{Mc}. In this illustrative example, signal loop extension **1104** has a total length of L_{2}.

(236) Signal loop **1154** is a resonator loop in which the signal light **1114** travels. The round-trip phase shift ϕ_{RTs} of signal light **1114** traveling in signal loop **1154** can be given by:

$\phi_{RTs}=2\phi_{1s}+\phi_{Mus}+\Delta\phi_{MEs}+2\phi_{2s}+\phi_{MCs}+\phi_{Ss}+\Delta\phi_{SEs}=2\pi S$.

(237) For signal light **1114** to remain circulating for many round-trips in signal loop **1154** and thus circulate for many passes through main nonlinear

optical waveguide **1110**, the round-trip phase shift should be as close as possible to a multiple of 2π, that is, with S being an integer.
(238) The phase shift of signal light **1114** propagating in main nonlinear optical waveguide **1110** can be described by the expression:
$\phi_{Mus}=2\pi n_{Ms} L_{Mu}/\lambda_s$
where n_{Ms} is the effective refractive index of signal light **1114** in the main nonlinear optical waveguide **1110**; L_{Mu} is the length of main nonlinear optical waveguide **1110**; and λ_s is the wavelength of signal light **1114**.
(239) Each of the two wavelength-selective couplers coupled to main nonlinear optical waveguide **1110**, first wavelength-selective coupler **1120** and second wavelength-selective coupler **1122**, in signal loop **1154** operate in its "cross" state for the signal wavelength and produces a phase shift of ϕ_{1s} for the signal wavelength. In a similar fashion, each of the two wavelength-selective couplers coupled to signal loop extension **1104**, third wavelength-selective coupler **1124** and fourth wavelength-selective coupler **1126**, in signal loop **1154** operate in its "thru" state for the signal wavelength and produces a phase shift of ϕ_{2s} for the signal light **1114.** The net phase shift from the two corner portions, segment **1107** and segment **1109** of the secondary optical waveguide **1108** in signal loop **1154**, in which both signal light **1114** and idler light **1116** propagate can be given by ϕ_{Mcs}. The phase shift from signal loop extension **1104** in signal loop **1154**, in which only the signal light propagates, can be given by ϕ_{Ss}.
(240) In an illustrative example, tuning electrode **1160** used to adjust the phase shift for pump light **1112** in its resonator loop also produces a phase shift for signal light **1114** of $\Delta\phi_{MEs}$. However, tuning electrode **1164** in signal loop extension **1104** affects only signal light **1114**. Tuning electrode **1166** produces a phase shift of $\Delta\phi_{SEs}$.
(241) Idler loop **1156** in which idler light **1116** extends through main nonlinear optical waveguide **1110** and idler loop extension **1106**. In this depicted example, idler loop **1156** comprises segment **1107** in secondary optical waveguide **1108**, first wavelength-selective coupler **1120** and third wavelength-selective coupler **1124**; segment **1109** in secondary optical waveguide **1108**, fourth wavelength-selective coupler **1126** and second wavelength-selective coupler **1122**; and idler loop extension **1106**.
(242) Each of the two wavelength-selective couplers, first wavelength-selective coupler **1120** and second wavelength-selective coupler **1122**, in idler loop **1156** have a "cross" state for the pump wavelength and a "thru" state for the idler wavelength and produces a phase shift of ϕ_{1i} at the "thru" state output of the wavelength-selective coupler. Likewise, each of the two wavelength-selective couplers, third wavelength-selective coupler **1124** and fourth wavelength-selective coupler **1126**, have a "cross" state for the idler wavelength and produces a phase shift of ϕ_{2i} at its "cross" state output for idler light **1116**.
(243) The total phase shift of idler light **1116** from the two corner portions, segment **1107** and segment **1109**, in which both signal light **1114** and idler light **1116** propagate, can be given by ϕ_{Mci}. The phase shift from idler loop extension **1106**, in which only idler light **1116** propagates, can be given by ϕ_{lei}.
(244) In this illustrative example, tuning electrode **1160** for main nonlinear optical waveguide **1110** used to adjust the phase shift for pump light **1112** will also produce a phase shift for idler light **1116** of $\Delta\phi_{MEi}$. Tuning electrode **1166** for idler loop extension **1106** affects only idler light **1116**. Tuning electrode **1166** can produce a phase shift of $\Delta\phi_{IEi}$.
(245) Thus, the round-trip phase shift ϕ_{RTi} of idler light **1116** can be given by:
$\phi_{RTi}=2\phi_{1i}+\phi_{Mui}+\Delta\phi_{MEi}=2\phi_{2i}+\phi_{Mci}+\phi_{Ii}+\Delta\phi_{IEi}=2\pi I.$
(246) For idler light **1116** to remain circulating for many round-trips in idler loop **1156** extending through main nonlinear optical waveguide **1110** and thus making many passes through main nonlinear optical waveguide **1110**, the round-trip phase shift should be a close as possible to a multiple of 2π, that is, with I being an integer. The length and waveguide cross-sectional structure in main nonlinear optical waveguide **1110** can be designed to achieve phase matching for the nonlinear optical interaction.
(247) Thus, the value for ϕ_{Mui} can be determined by the design of the waveguide cross-sectional structure in main nonlinear optical waveguide **1110**. However, the length L_3 of idler loop extension **1106** can be selected to achieve the desired resonance condition for the idler wavelength in its resonator loop, idler loop **1156**. Also, the additional phase shift $\Delta\phi_{IEi}$ produced by the tuning electrode **1166** in the idler loop extension **1106** can be used to further adjust that round-trip phase shift for idler light **1116**.
(248) In the illustrative example, main nonlinear optical waveguide **1110** is the location where the desired nonlinear optical photon generation occurs in optical waveguide structure **1100**. Main nonlinear optical waveguide **1110** can be designed to achieve a phase matched condition for the nonlinear optical process. This phase matched condition can be achieved through the selection of dimensions of the cross-sectional waveguide structure.
(249) The cross-sectional structure of main nonlinear optical waveguide **1110** as well as the propagation direction of the light determines the effective refractive index of the pump light **1112**, signal light **1114** and idler light **1116** in a given portion of main nonlinear optical waveguide **1110**. The propagation direction for light guided in main nonlinear optical waveguide **1110**, in which the desired nonlinear optical interaction occurs, can be chosen to increase the nonlinear optical generation. For example, a waveguide comprising x-cut lithium niobate could be aligned parallel to the material Y-axis. Thus, the propagation direction would be in the +y direction or the −y direction of the lithium niobate crystalline material.
(250) For the nonlinear optical process to occur constructively over a long interaction distance so that the generation rate or generation efficiency of the signal photons and idler photons from the pump photons continues to increase as the physical interaction distance is increased, the phase matching condition of the nonlinear optical process also should be maintained. This condition includes the round-trip phase shift of pump light **1112** traveling in the main nonlinear optical waveguide **1110** as well as in pump loop extension **1102**, the round-trip phase shift of signal light **1114** traveling in main nonlinear optical waveguide **1110**, in segment **1107** and segment **1109** of secondary optical waveguide **1108**, as well as in signal loop extension **1104**, and the round-trip phase shift of idler light **1116** traveling in main nonlinear optical waveguide **1110**, in segment **1107** and segment **1109** of secondary optical waveguide **1108**, as well as in idler loop extension **1106**.
(251) Thus:
$\phi_{RTp}-\phi_{RTs}-\phi_{RTi}=2\pi A$
where A is an integer and can be zero.
(252) Furthermore, to increase the nonlinear optical generation of signal and idler light that occurs in a given round-trip, meeting another phase matching condition is desirable for propagation of the three wavelengths of light through main nonlinear optical waveguide **1110**, which is the portion where the nonlinear optical generation occurs. This phase matching condition can be described as follows:
(253) $0\leq\phi_{Mup}-\phi_{Mus}+\phi_{Mui}\leq\pi$, or $-\pi\leq\phi_{Mup}-\phi_{Mus}-\phi_{Mui}\leq 0$, and is close to zero.
(254) The additional phase shifts that can be achieved by applying bias voltages to the tuning electrodes for optical waveguide structure **1100** can be used to adjust the round-trip phase shifts for pump light **1112** (by adjusting $\Delta\phi_{MEp}$), for the signal light **1114** (by adjusting $\Delta\phi_{SEs}$) and for idler light **1116** (by adjusting $\Delta\phi_{IEi}$). These adjustments can be used to correct or to compensate for departures of the other parameters from their as-designed values in actually fabricated and operating devices.
(255) The phase shift that can be obtained for a given electric field in the electro-optic material (due to a voltage applied to a set of tuning electrodes) can be described by the relation:
$\Delta\phi_{KEj}=2\pi r_j n_j^3 E\Gamma_j L_E/\lambda_j$
where j=p, s, i, and where p indicates pump light **1112**, s indicates signal light **1114**, and i indicates idler light **1116**. Also, K=M, S or P and indicates the optical waveguide with the tuning electrode, such as K=M for main nonlinear optical waveguide **1110**, K=S for signal loop extension **1104** and K=I for idler loop extension **1106**. Other parameters in this expression are: the electric field E, the electro-optic coefficient, r_j, the refractive index n_j, the overlap of the optical field of pump light **1112**, signal light **1114**, or idler light **1116** with the electro-optic material Γ_j, the electrode length (or electro-optic interaction distance) L_E, and the wavelength λ_j of the pump light **1112**, signal light **1114**, or idler light

1116. As an example, for an electro-optic material such as lithium niobate and for an electric field applied across the waveguide of 10.sup.6 V/m, the electrode length needed to achieve a phase shift of 2π is about 3-10 mm.

(256) Turning to FIG. **14**, an illustration of an optical waveguide structure with five optical waveguides is depicted in accordance with an illustrative embodiment. In this illustrative example, optical waveguide structure **1000** is an example of an implementation for optical waveguide structure **100** as shown in FIGS. **1**-**6**.

(257) In this illustrative example, optical waveguide structure **1000** comprises optical waveguides. These waveguides include main nonlinear optical waveguide **1010**, secondary optical waveguide **1008** having segment **1007** and segment **1009**, pump loop extension **1002**, signal loop extension **1004**, and idler loop extension **1006**.

(258) Main nonlinear optical waveguide **1010** is an example of main nonlinear optical waveguide **106** in FIG. **3** and main nonlinear optical waveguide **106** in FIG. **2**. Secondary optical waveguide **1008** is an example of an implementation for secondary optical waveguide **113** in FIG. **3** and secondary optical waveguide **113** in FIG. **2**.

(259) Pump loop extension **1002** is an example of an implementation for first extension optical waveguide **108** in FIG. **3** and first extension optical waveguide **108** in FIG. **2**. Signal loop extension **1004** and idler loop extension **1006** are examples of second extension optical waveguide **110** and third extension optical waveguide **119**, respectively, in FIGS. **3**-**6**.

(260) In this illustrative example, main nonlinear optical waveguide **1010** is comprised of a nonlinear optical material, such as nonlinear optical material **104**. Secondary optical waveguide **1008** can be comprised of a nonlinear optical material, such as nonlinear optical material **104** or a non-nonlinear optical material, such as non-nonlinear optical material **105**.

(261) As depicted, pump loop extension **1002** is comprised of a non-nonlinear optical material. Signal loop extension **1004** is comprised of both a nonlinear optical material and an electro-optic material, such as electro-optic material **103**, in this illustrative example. Idler loop extension **1006** has portions comprised of a nonlinear optical material **104** and other portions comprised of a non-nonlinear optical material. In this example, a taper **1049** can join an optical waveguide portion comprising nonlinear optical material and an optical waveguide portion comprising a non-nonlinear optical material. In this illustrative example, section **1043** and section **1045** of idler loop extension **1006** are comprised of a non-nonlinear optical material. Section **1046** of idler loop extension **1006** is comprised of a nonlinear optical material that also is an electro-optic material. Examples of material that have a large second-order nonlinear optical coefficient as well as a large electro-optic coefficient include lithium niobate and gallium arsenide.

(262) In this illustrative example, segment **1007** and segment **1009** of secondary optical waveguide **1008** is comprised of a nonlinear optical material that also is an electro-optic material. In this example, signal loop extension **1004** likewise is comprised of a nonlinear optical material that also is an electro-optic material.

(263) As depicted, optical waveguide structure **1000** also includes pump input optical waveguide **1032** that inputs pump light **1012**. Optical waveguide structure **1000** also includes signal output optical waveguide **1034** and idler output optical waveguide **1036**. Signal output optical waveguide **1034** can output signal light **1014**. Idler output optical waveguide **1036** can output idler light **1016**.

(264) As shown in this figure, first wavelength-selective coupler **1020** and second wavelength-selective coupler **1022** connect pump loop extension **1002** to main nonlinear optical waveguide **1010**. In this illustrative example, third wavelength-selective coupler **1024** and fourth wavelength-selective coupler **1026** connect idler loop extension **1006** to segment **1007** and segment **1009** of secondary optical waveguide **1008**. Third wavelength-selective coupler **1024** and fourth wavelength-selective coupler **1026** also connect signal loop extension **1004** to segment **1007** and segment **1009** of secondary optical waveguide **1008**.

(265) In this illustrative example, pump optical coupler **1031** couples pump input optical waveguide **1032** to pump loop extension **1002**. Signal optical coupler **1035** couples signal output optical waveguide **1034** to signal loop extension **1004**. Idler optical coupler **1037** couples idler output optical waveguide **1036** to idler loop extension **1006**.

(266) In this illustrative example, pump light **1012** travels in pump loop **1052** which extends through main nonlinear optical waveguide **1010** and pump loop extension **1002**. Signal light **1014** travels in signal loop **1054** which extends through main nonlinear optical waveguide **1010**, segment **1007** and segment **1009** in secondary optical waveguide **1008**, and signal loop extension **1004**. Idler light **1016** travels in idler loop **1056**, which extends through main nonlinear optical waveguide **1010**, segment **1007** and segment **1009** of secondary optical waveguide **1008**, and idler loop extension **1006**.

(267) As depicted, optical waveguide structure **1000** also includes phase shifters in the form of tuning electrodes. In this illustrative example, tuning electrode **1060** is located adjacent to a portion of main nonlinear optical waveguide **1010**. In this example, the portion of main nonlinear optical waveguide **1010** is segment **1040**. Tuning electrode **1064** is located adjacent to a portion of signal loop extension **1004**. As depicted, the portion of signal loop extension **1004** is segment **1044**. Tuning electrode **1066** is located adjacent to section **1046** of idler loop extension **1006**. These tuning electrodes can apply voltages to obtain a desired level of resonance to achieve a resonant condition for the three wavelengths of light traveling within optical waveguide structure **1000**. For example, tuning electrode **1060** can adjust the phase for pump light **1012**. Tuning electrode **1064** can adjust the phase of signal light **1014**. Tuning electrode **1066** can adjust the phase of idler light **1016**.

(268) A nonlinear optical process for the generation of photons for signal light **1014** and idler light **1016** from photons of pump light **1012** occurs in main nonlinear optical waveguide **1010** in optical waveguide structure **1000**. In this example, the nonlinear optical process does not occur, or negligibly occurs, in other parts of optical waveguide structure **1000**. In this depicted example, pump light **1012** supplied through pump input optical waveguide **1032** travels only through main nonlinear optical waveguide **1010**, first wavelength-selective coupler **1020**, second wavelength-selective coupler **1022** and pump loop extension **1002**. Nonlinear optical generation of signal photons and idler photons from pump photons occurs only where pump light travels and interacts with nonlinear optical material in a waveguide. Thus, both pump light and nonlinear optical material must be present for nonlinear optical generation of signal photons and idler photons from pump photons to occur.

(269) In this illustrative example, pump loop extension **1002** is comprised of a material having a negligible second order nonlinear optical coefficient such as Si.sub.3N.sub.4 and SiO.sub.2. The other portions of optical waveguide structure **1000** through which pump light **1012** does not propagate can contain a material such as lithium niobate, which has a large electro-optic coefficient and also has a large second-order nonlinear optical coefficient. This material is useful for electro-optic tuning.

(270) Additionally, signal light **1014** travels in signal loop **1054** that traverses through main nonlinear optical waveguide **1010**, segment **1007** and segment **1009** of secondary optical waveguide **1008** and signal loop extension **1004**, as well as through first wavelength-selective coupler **1020** and second wavelength-selective coupler **1022** and third wavelength-selective coupler **1024** and fourth wavelength-selective coupler **1026**. In this example, this combination of optical waveguides can also serve as a resonator for signal light **1014**. Tuning electrode **1064** for signal loop extension **1004** is located along signal loop **1054** and can operate to achieve electrically controlled optical phase shifting for signal light **1014**.

(271) In this depicted example, idler light **1016** travels in idler loop **1056**. Idler loop **1056** extends through idler loop extension **1006**, and tuning electrode **1066** for idler loop extension **1006** can operate to achieve an electrically controlled optical phase shifting for idler light **1016**. Lithium niobate is an electro-optic material for which the material refractive index can be changed by applying an electrical field. A material such as lithium niobate can be used in the segment **1044** of signal loop extension **1004** adjacent to tuning electrode **1064** and in the section **1046** of idler loop extension **1006** adjacent to tuning electrode **1066**.

(272) In this illustrative example, pump loop extension **1002** does not have a tuning electrode. Tuning electrode **1060** can be used adjacent to main nonlinear optical waveguide **1010** and can operate to achieve some electrical control of the optical phase shift for pump light **1012**. However, the use of tuning electrode **1060** can affect the round-trip phase shift of pump light **1012**, as well as the round-trip phase shifts of signal light **1014** and idler

light **1016**.
(273) These tuning electrodes in optical waveguide structure **1000** can apply voltages to obtain desired levels of phase shifts for the pump light **1012**, signal light **1014** and idler light **1016** to achieve resonance matching **300** in FIG. **5** for those three wavelengths of light traveling within optical waveguide structure **1000**. These tuning electrodes in optical waveguide structure **1000** also can apply voltages to obtain desired levels of phase shifts for the pump light **1012**, signal light **1014** and idler light **1016** to achieve roundtrip phase matching **302** for the combination of those three wavelengths of light traveling within optical waveguide structure **1000**.
(274) With reference now to FIG. **15**, an illustration of an optical waveguide structure with five optical waveguides is depicted in accordance with an illustrative embodiment. In this illustrative example, optical waveguide structure **1400** is an example of an implementation for optical waveguide structure **100** as shown in FIGS. **1**-**6**. As depicted, optical waveguide structure **1400** comprises optical waveguides in the form of main nonlinear optical waveguide **1410**, segments of secondary optical waveguide **1408**, pump loop extension **1402**, signal loop extension **1404**, and idler loop extension **1406**.
(275) In this illustrative example, main nonlinear optical waveguide **1410** is comprised of a nonlinear optical material **104**.
(276) As depicted, pump loop extension **1402** is comprised of a non-nonlinear optical material, such as non-nonlinear optical material **105**. In this example, idler loop extension **1406** is comprised of an electro-optic material **103** that also can have a large second-order nonlinear optical coefficient. In this example, signal loop extension **1404** is comprised of a nonlinear optical material, such as nonlinear optical material **104**, that also has a large electro-optic coefficient.
(277) As depicted, optical waveguide structure **1400** includes pump input optical waveguide **1432** that inputs pump light **1412**. Optical waveguide structure **1400** also includes signal output optical waveguide **1434** and idler output optical waveguide **1436**. Signal output optical waveguide **1434** can output signal light **1414**. Idler output optical waveguide **1436** can output idler light **1416**.
(278) As depicted, first wavelength-selective coupler **1420** and second wavelength-selective coupler **1422** connect pump loop extension **1402** to main nonlinear optical waveguide **1410**. In this illustrative example, third wavelength-selective coupler **1424** and fourth wavelength-selective coupler **1426** connect idler loop extension **1406** to segment **1407** and segment **1409** of secondary optical waveguide **1408**. In this illustrative example, third wavelength-selective coupler **1424** and fourth wavelength-selective coupler **1426** also connect signal loop extension **1404** to segment **1407** and segment **1409** of secondary optical waveguide **1408**.
(279) In this illustrative example, pump input coupler **1431** couples pump input optical waveguide **1432** to pump loop extension **1402**. Signal output coupler **1435** couples signal output optical waveguide **1434** to signal loop extension **1404**. Idler output coupler **1437** couples idler output optical waveguide **1436** to idler loop extension **1406**.
(280) In this depicted example, pump loop **1452** is present for pump light **1412**. This pump loop **1452** is a resonator loop in which pump light **1412** travels in pump loop extension **1402** and in main nonlinear optical waveguide **1410**.
(281) In this example, signal light **1414** travels in signal loop **1454**. As depicted, signal loop **1454** extends through main nonlinear optical waveguide **1410**, through segments **1407** and **1409** of secondary optical waveguide **1408**, and through signal loop extension **1404**. As shown in the figure, idler light **1416** travels in idler loop **1456**. Further, in this example, idler loop **1456** extends through main nonlinear optical waveguide **1410**, through segments **1407** and segment **1409** of secondary optical waveguide **1408**, and through idler loop extension **1406**.
(282) As depicted, optical waveguide structure **1400** also includes phase shifters in the form of tuning electrodes. In this illustrative example, tuning electrode **1460** is located adjacent to main nonlinear optical waveguide **1410**. Tuning electrode **1464** is located adjacent to signal loop extension **1404**. Tuning electrode **1466** is located adjacent to idler loop extension **1406**.
(283) In this illustrative example, a nonlinear optical process occurs in main nonlinear optical waveguide **1410** in optical waveguide structure **1400**. Main nonlinear optical waveguide **1410** is constructed using a material such as x-cut lithium niobate, which can have both a large second order nonlinear optical coefficient and a large electro-optic coefficient.
(284) As depicted, main nonlinear optical waveguide **1410** has a straight segment **1470** and two corner segments, corner segment **1471** and corner segment **1473**. In this illustrative example, straight segment **1470** is aligned parallel to the y-axis of the x-cut lithium niobate crystal. Segment **1407** and segment **1409** are part of secondary optical waveguide **1408**. In this illustrative example, segment **1407** and segment **1409** are aligned parallel to the z-axis of the x-cut lithium niobate crystal.
(285) In this depicted example, transverse-electric (TE) polarized light propagating in main nonlinear optical waveguide **1410** can encounter the largest electro-optic coefficient r.sub.33 when the light travels in straight segment **1470** in main nonlinear optical waveguide **1410**. TE polarized light also encounters the largest electro-optic coefficient r.sub.33 of x-cut lithium niobate when the light travels in segment **1474** of signal loop extension **1404** adjacent to tuning electrode **1464** and when the light travels in the portion of idler loop extension **1406** adjacent to tuning electrode **1466**.
(286) As depicted, light travels in a clockwise direction through main nonlinear optical waveguide **1410**, pump loop extension **1402**, signal loop extension **1404**, and idler loop extension **1406**. This direction is selected by the configuration of the input and output couplers, such as pump input coupler **1431**, signal output coupler **1435**, and idler output coupler **1437**. However, these three input and output couplers could be configured to have the light travel in a counter-clockwise direction through main nonlinear optical waveguide **1410**, pump loop extension **1402**, signal loop extension **1404**, and idler loop extension **1406**, and by where pump light **1412** is supplied to pump input optical waveguide **1432**. Counter-clockwise travel is established by supplying pump light into the opposite end of pump input coupler **1431**, extracting signal light out from the opposite end of signal output coupler **1435**, and extracting idler light out from the opposite end of idler output coupler **1437**.
(287) As depicted, first wavelength-selective coupler **1420** connects corner segment **1471** of main nonlinear optical waveguide **1410** to segment **1407** of secondary optical waveguide **1408**. Second wavelength-selective coupler **1422** connects segment **1409** of secondary optical waveguide **1408** to corner segment **1473** of main nonlinear optical waveguide **1410**.
(288) As depicted, third wavelength-selective coupler **1424** and fourth wavelength-selective coupler **1426** operate to establish a resonator loop, idler loop **1456**, for idler light **1416** and also to establish a resonator loop, signal loop **1454**, for signal light **1414**. In this illustrative example, third wavelength-selective coupler **1424** extracts idler light **1416** away from segment **1407** of secondary optical waveguide **1408** and into the idler loop extension **1406**. Fourth wavelength-selective coupler **1426** returns idler light **1416** back into segment **1409** of secondary optical waveguide **1408** after idler light **1416** has propagated through idler loop extension **1406** while traveling in idler loop **1456**.
(289) In this illustrative example, third wavelength-selective coupler **1424** also extracts signal light **1414** away from segment **1407** of secondary optical waveguide **1408** and into the signal loop extension **1404**. Fourth wavelength-selective coupler **1426** also returns signal light **1414** back into segment **1409** of secondary optical waveguide **1408** after signal light **1414** has propagated through signal loop extension **1404** while traveling in idler loop **1456**. Signal light **1414** travels to a thru-state output of third wavelength-selective coupler **1424** and travels to a thru-state output of fourth wavelength-selective coupler **1426**. Idler light **1416** travels to a cross-state output of third wavelength-selective coupler **1424** and travels to a cross-state output of fourth wavelength-selective coupler **1426**, as discussed before with reference to FIG. **10**.
(290) In this illustrative example, first wavelength-selective coupler **1420** and second wavelength-selective coupler **1422** operate to establish a resonator loop, pump loop **1452** for pump light **1412**. As depicted, first wavelength-selective coupler **1420** extracts pump light **1412** away from main nonlinear optical waveguide **1410** and into pump loop extension **1402** to travel in pump loop **1452**. Second wavelength-selective coupler **1422** returns pump light **1412** to main nonlinear optical waveguide **1410** after pump light **1412** has propagated through pump loop extension **1402** while traveling in pump loop **1452**.
(291) In this illustrative example, the material for idler loop extension **1406** and the material for signal loop extension **1404** can be a material such as lithium niobate for which the electro-optic coefficient is large. The large electro-optic coefficient allows the phase shifters in the signal loop

extension and the idler loop extension to be more efficient, producing a larger phase shift for a given applied voltage. But for lithium niobate, the second order nonlinear optical coefficient also is large. However, pump light **1412** is not supplied to these portions of optical waveguide structure **1400**, resulting in an absence of undesired nonlinear optical generation of additional signal or idler photons in these portions. In this illustrative example, pump loop extension **1402** is comprised of a non-nonlinear optical material.

(292) As depicted, pump light **1412** propagates primarily only in main nonlinear optical waveguide **1410** and pump loop extension **1402**. The second order nonlinear optical coefficient is largest d.sub.33 for light propagating in straight segment **1470** of main nonlinear optical waveguide **1410** and is smaller for light propagating in corner segment **1471** and corner segment **1473**. Also, the sign of a component d.sub.22 of the second order nonlinear optical coefficient in corner segment **1471** is opposite from the sign of that component of the second order nonlinear optical coefficient in corner segment **1473**. As a result, the generation of signal light **1414** and idler light **1416** occurs mainly in straight segment **1470** and occurs much less in other portions of optical waveguide structure **1400** because of the manner in which pump light **1412** is introduced and removed from main nonlinear optical waveguide **1410**.

(293) In this illustrative example, pump light **1412** can be extracted from main nonlinear optical waveguide **1410** before idler light **1416** is extracted from main nonlinear optical waveguide **1410** through secondary optical waveguide **1408** into idler loop extension **1406**. Also in this example, pump light **1412** is re-supplied to main nonlinear optical waveguide **1410** from pump loop extension **1402** after idler light **1416** is re-supplied to main nonlinear optical waveguide **1410** from idler loop extension **1406** through secondary optical waveguide **1408**. A similar arrangement applies for the pump light **1412** in relation to the signal light **1414**.

(294) As a result, although the nonlinear optical material is present along the entire length of the signal loop **1054** for signal light **1414** and idler loop **1456** for idler light **1416**, the nonlinear optical generation of photons for signal light **1414** and idler light **1416** from photons for pump light **1412** occurs only in main nonlinear optical waveguide **1410**. Nonlinear optical generation of signal light **1414** and idler light **1416** is absent in secondary optical waveguide **1408**, idler loop extension **1406** and signal loop extension **1404**. The absence of nonlinear optical generation is because pump light **1412** is supplied only to main nonlinear optical waveguide **1410**.

(295) A nonlinear optical generation process can result in generation of lower intensity light from higher intensity light. A nonlinear optical generation process also can operate in reverse and result in the generation of a higher intensity light from a lower intensity light. The efficiency of the nonlinear optical generation process depends on the intensity of the source light involved in that generation process, or the intensities of the source light of several different wavelengths if source light of multiple wavelengths is involved in that process. For spontaneous parametric down conversion as an illustrative example of a nonlinear optical generation process, the pump light, which is the input or source light, has an intensity that is at least twice the intensity of the generated signal light and at least twice the intensity of the generated idler light.

(296) In many examples of spontaneous parametric down conversion, the intensity of the pump light is at least ten times greater than the intensity of the signal light or of the idler light. Thus, even when a phase-matched condition is present, if the pump light is absent from an optical waveguide comprising nonlinear optical material and only signal and idler light are present, the reverse process in which pump light, or light at the pump wavelength, is generated from the weaker source light at the signal and idler wavelengths is much less efficient and may produce very little or possibly even negligible light at the pump wavelength.

(297) With reference next to FIG. **16**, an illustration of an optical waveguide structure with five optical waveguides is depicted in accordance with an illustrative embodiment. In this illustrative example, optical waveguide structure **1200** is an example of an implementation for optical waveguide structure **100** as shown in FIGS. **1**-**6**.

(298) As depicted, optical waveguide structure **1200** comprises optical waveguides in the form of main nonlinear optical waveguide **1210**, pump loop extension **1202**, secondary optical waveguide **1208**, signal loop extension **1204**, and idler loop extension **1206**. Main nonlinear optical waveguide **1210** is an example of main nonlinear optical waveguide **106** in FIG. **3** and main nonlinear optical waveguide **106** in FIG. **2**. Pump loop extension **1202** is an example of an implementation for first extension optical waveguide **108** in FIG. **3** and first extension optical waveguide **108** in FIG. **2**. Idler loop extension **1206** and signal loop extension **1204** are optical waveguides that can be coupled to secondary optical waveguide **113** in FIG. **3** or coupled to secondary optical waveguide **113** in FIG. **2**.

(299) In this illustrative example, first loop **1252** through main nonlinear optical waveguide **1210** and pump loop extension **1202** has a rectangular shape with curved corners and may also be referred to as a racetrack shape. First loop **1252** for the pump light is a closed path route.

(300) As depicted in this example, first loop **1252** for pump light **1212** through main nonlinear optical waveguide **1210** and through pump loop extension **1202** traverses segments of waveguide comprised of nonlinear optical material **104** and segments of waveguide comprised of non-nonlinear optical material **105**. The nonlinear optical material is present in main nonlinear optical waveguide **1210**, which includes straight segment **1270** corner segment **1271**, and corner segments **1273**. The nonlinear optical material also is present in portions of corner segment **1275** and corner segment **1277** of pump loop extension **1202**. A non-nonlinear optical material **105** is present in segment **1272** of pump loop extension **1202**.

(301) A non-nonlinear optical material also can be present in corner segment **1275** and corner segment **1277** of pump loop extension **1202** instead of the nonlinear optical material. As depicted in this figure, a tapered transition **1247** can be present between the portion of corner segment **1275** and corner segment **1277** that contains a nonlinear optical material and the portion of corner segment **1275** and corner segment **1277** that does not contain a nonlinear optical material but rather comprises only non-nonlinear optical material.

(302) In this illustrative example, both signal loop extension **1204** and idler loop extension **1206** have portions that comprise an electro-optic material **103** that also is a nonlinear optical material **104** and other portions that comprise a non-nonlinear optical material **105**. The electro-optic material is located in section **1244** of signal loop extension **1204** and in section **1246** of idler loop extension **1206**. To reduce optical losses and reflections, there can be a tapered transition **1249** between a waveguide portion comprising an electro-optic material and a waveguide portion comprising a non-nonlinear optical material.

(303) As depicted, optical waveguide structure **1200** also includes pump input optical waveguide **1232** that inputs pump light **1212**. Optical waveguide structure **1200** also includes signal output optical waveguide **1234** and idler output optical waveguide **1236**. Signal output optical waveguide **1234** can output signal light **1214**. Idler output optical waveguide **1236** can output idler light **1216**.

(304) In this illustrative example, pump optical coupler **1231** couples pump input optical waveguide **1232** to pump loop extension **1202**. Signal optical coupler **1235** couples signal output optical waveguide **1234** to signal loop extension **1204**. Idler optical coupler **1237** couples idler output optical waveguide **1236** to idler loop extension **1206**.

(305) In this illustrative example, first wavelength-selective coupler **1220** and second wavelength-selective coupler **1222** connect pump loop extension **1202** to main nonlinear optical waveguide **1210**. Pump light **1212** is coupled via the thru-state outputs of first wavelength-selective coupler **1220** and second wavelength-selective coupler **1222**. As depicted, first wavelength-selective coupler **1220** and second wavelength-selective coupler **1222** also connect signal light **1214** and idler light **1216** between main nonlinear optical waveguide **1210** and segments of secondary optical waveguide **1208**. Signal light **1214** and idler light **1216** are coupled via the cross-state outputs of first wavelength-selective coupler **1220** and second wavelength-selective coupler **1222**. In this illustrative example, third wavelength-selective coupler **1224** and fourth wavelength-selective coupler **1226** connect idler loop extension **1206** to segment **1207** and segment **1209** of secondary optical waveguide **1208**. Third wavelength-selective coupler **1224** and fourth wavelength-selective coupler **1226** also connect signal loop extension **1204** to segment **1207** and segment **1209** of secondary optical waveguide **1208**. Signal light **1214** is coupled via the thru-state outputs of third wavelength-selective coupler **1224** and fourth wavelength-selective coupler **1226**. Idler light **1216** is coupled via the cross-state outputs of third wavelength-selective coupler **1224** and fourth wavelength-selective coupler **1226**.

(306) In this illustrative example, first loop **1252** is present for pump light **1212**. This first loop is a resonator loop in which pump light **1212** travels

in main nonlinear optical waveguide **1210** and in pump loop extension **1202**. Signal light **1214** travels in second loop **1254**. As depicted, second loop **1254** extends through main nonlinear optical waveguide **1210**, through segment **1207** and segment **1209** of secondary optical waveguide **1208** and through signal loop extension **1204**. In this illustrative example, idler light **1216** travels in third loop **1256**. As depicted, third loop **1256** extends through main nonlinear optical waveguide **1210**, through segment **1207** and segment **1209** of secondary optical waveguide **1208**, and through idler loop extension **1206**.

(307) As depicted, optical waveguide structure **1200** also includes phase shifters in the form of tuning electrodes. In this illustrative example, tuning electrode **1260** is located adjacent to section **1240** in main nonlinear optical waveguide **1210**. Tuning electrode **1264** is located adjacent to section **1244** in signal loop extension **1204** and tuning electrode **1266** is located adjacent to section **1246** in idler loop extension **1203**. These tuning electrodes can apply voltages to obtain a desired level of resonance to achieve a resonant condition for light traveling within optical waveguide structure **1200**.

(308) In this illustrative example of optical waveguide structure **1200** having triple partially overlapping loop resonators for entanglement with direction dependent material, pump light **1212**, signal light **1214**, and idler light **1216** travel in different resonator loops, first loop **1252**, second loop **1254**, and third loop **1256**, respectively. First loop **1252** is a resonator loop for the pump light **1212** and extends through main nonlinear optical waveguide **1210**, first wavelength-selective coupler **1220** (via its thru-state output), second wavelength-selective coupler **1222** (via its thru-state output), pump loop extension **1202**, and pump optical coupler **1231** (via its thru-state output).

(309) In this illustrative example, second loop **1254** is a resonator loop for signal light **1214**. Second loop **1254** extends through main nonlinear optical waveguide **1210**, first wavelength-selective coupler **1220** (via its cross-state output), segment **1207** of secondary optical waveguide **1208**, third wavelength-selective coupler **1224** (via its thru-state output), signal loop extension **1204**, and signal optical coupler **1235** (via its thru-state output) fourth wavelength-selective coupler **1226** (via its thru-state output), segment **1209** of secondary optical waveguide **1208**, and second wavelength-selective coupler **1222** (via its cross-state output), looping again to main nonlinear optical waveguide **1210**.

(310) As depicted, third loop **1256** is a resonator loop for idler light **1216**. This third loop **1256** extends through main nonlinear optical waveguide **1210**, first wavelength-selective coupler **1220** (via its cross-state output); segment **1207** of secondary optical waveguide **1208** located between first wavelength-selective coupler **1220** and third wavelength-selective coupler **1224**; third wavelength-selective coupler **1224** (via its cross-state output); idler loop extension **1206**; idler optical coupler **1237** (via its thru-state output); fourth wavelength-selective coupler **1226** (via its cross-state output); segment **1209** of secondary optical waveguide **1208** located between fourth wavelength-selective coupler **1226** and second wavelength-selective coupler **1222**; and second wavelength-selective coupler **1222** (via its cross-state output); looping back to main nonlinear optical waveguide **1210**.

(311) In this illustrative example of optical waveguide structure **1200** having triple partially overlapping loop resonators for entanglement constructed from a direction dependent material, main nonlinear optical waveguide **1210** is common to and overlaps all three loop resonators. Also, first wavelength-selective coupler **1220** and second wavelength-selective coupler **1222** are encountered by the light in all three loops. However, first loop **1252** for pump light **1212** encounters the thru-state of these couplers. In this example, second loop **1254** and third loop **1256** for signal light **1214** and idler light **1216**, respectively, encounter the cross-state of these couplers.

(312) In this illustrative example, a second-order nonlinear optical process such as spontaneous parametric down conversion occurs in optical waveguide structure **1200**. Nonlinear optical generation of signal photons and idler photons from pump photons, which is a result of spontaneous parametric down conversion, occurs when pump light propagates in an optical waveguide comprising nonlinear optical material such as lithium niobate which has a large second-order nonlinear optical coefficient. Optical waveguide structure **1200** includes main nonlinear optical waveguide **1210**. Main nonlinear optical waveguide **1210** is the primary part of optical waveguide structure **1200** for which pump light **1212** is present and propagates in a waveguide comprising nonlinear optical material. As result, most of the generation of signal photons and idler photons from pump photons occurs in main nonlinear optical waveguide **1210**. Essentially, negligible generation of signal photons and idler photons occurs in other portions of optical waveguide structure **1200**. As depicted, main nonlinear optical waveguide **1210** comprises a nonlinear optical material. Most of the pump loop extension **1202**, such as portion or segment **1272** of pump loop extension **1202** does not comprise a nonlinear optical material.

(313) The various optical waveguides in optical waveguide structure **1200** can be fabricated using x-cut lithium niobate and in particular, from x-cut thin-film lithium niobate. In this illustrative example, straight segment **1270** in main nonlinear optical waveguide **1210** and segment **1272** in pump loop extension **1202** can be considered long legs of a rectangular-shaped path with curved corners or of a racetrack shaped path. These two segments are oriented to be aligned parallel to the y-axis of the x-cut lithium niobate crystal. As depicted, corner segments **1271** and **1273** of main nonlinear optical waveguide **1210** together with corner segment **1275** and corner segment **1277** of pump loop extension **1202** are the short legs of this rectangular-shaped or racetrack shaped path. The straight portions of corner segment **1271** and corner segment **1275** closest to first wavelength-selective coupler **1220** and the straight portions of corner segment **1273** and corner segment **1277** closest to second wavelength-selective coupler **1222** are aligned parallel to the z-axis of the x-cut lithium niobate crystal. In this example, transverse-electric (TE) polarized light propagating in main nonlinear optical waveguide **1210** encounters the largest second order nonlinear optical coefficient d.sub.33 when the light travels in straight segment **1270** in main nonlinear optical waveguide **1210**.

(314) In this example, when phase matching is achieved, most of the nonlinear optical generation of signal light **1214** and idler light **1216** occurs in straight segment **1270** of main nonlinear optical waveguide **1210**. Some nonlinear optical generation of signal and idler photons also occurs in corner segments **1271** and **1273** of main nonlinear optical waveguide **1210**. Some generation of signal light **1214** and idler light **1216** also can occur in portions of corner segment **1275** and corner segment **1277** of pump loop extension **1202** because these portions comprise nonlinear optical material, as depicted in FIG. **16**. However, the second order nonlinear optical coefficient d.sub.22 for transverse-electric (TE) polarized light in these portions is more than one order of magnitude smaller than the second order nonlinear optical coefficient d.sub.33 for transverse-electric (TE) polarized light in straight segment **1270** in this illustrative example. Moreover, the nonlinear optical generation of signal and idler photons that occurs in corner segment **1275** is partially counter-acted by the nonlinear optical generation of signal and idler photons that occurs in corner segment **1277**. This is because the second order nonlinear optical coefficient d.sub.22 in these two segments have opposite sign. Segment **1272** in pump loop extension **1202** comprises a non-nonlinear optical material. Thus, no generation of signal and idler photons occurs in that segment.

(315) Turning next to FIG. **17**, an illustration of an optical waveguide structure with five optical waveguides is depicted in accordance with an illustrative embodiment. In this illustrative example, optical waveguide structure **1300** is an example of an implementation for optical waveguide structure **100** as shown in FIGS. **1-6**. As depicted, optical waveguide structure **1300** comprises optical waveguides in the form of main nonlinear optical waveguide **1310**, secondary optical waveguide **1308** having segment **1307** and segment **1309**, pump loop extension **1302**, signal loop extension **1304**, and idler loop extension **1306**.

(316) In this illustrative example, main nonlinear optical waveguide **1310** and pump loop extension **1302** form a path that has a rectangular shape with curved corners and may also be referred to as a racetrack shape. Main nonlinear optical waveguide **1310** is comprised of a nonlinear optical material **104**. Pump loop extension **1302** also is comprised of a nonlinear optical material **104**. Optical waveguide structure **1300** is similar to optical waveguide structure **1200** in FIG. **16** but with the entire length of pump loop extension **1302** being comprised of nonlinear optical material **104** rather than having a portion of its length being comprised of a non-nonlinear optical material **105**. In this example, main nonlinear optical waveguide **1310** has at least portion **1340** that comprises an electro-optic material **103**. Also, pump loop extension **1302** has at least portion **1342** that comprises an electro-optic material.

(317) As depicted in this illustrative example, both signal loop extension **1304** and idler loop extension **1306** have a portion of their length comprising a nonlinear optical material **104** and another portion of their length comprising a non-nonlinear optical material **105**. Nonlinear optical material **104** is included in these waveguides because nonlinear optical material **104** is electro-optic material **103** that is efficient with a large electro-

optic coefficient. The portion of waveguide with the electro-optic (and nonlinear optical) material is located in section **1344** of signal loop extension **1304** and in section **1346** of idler loop extension **1306**.

(318) As depicted, optical waveguide structure **1300** includes pump input optical waveguide **1332** that inputs pump light **1312**. Optical waveguide structure **1300** also includes signal output optical waveguide **1334** and idler output optical waveguide **1336**. Signal output optical waveguide **1334** can output signal light **1314**. Idler output optical waveguide **1336** can output idler light **1316**.

(319) In this illustrative example, pump optical coupler **1331** couples pump input optical waveguide **1332** to pump loop extension **1302**. Signal optical coupler **1335** couples signal output optical waveguide **1334** to signal loop extension **1304**. Idler optical coupler **1337** couples idler output optical waveguide **1336** to idler loop extension **1306**.

(320) As depicted, first wavelength-selective coupler **1320** and second wavelength-selective coupler **1322**, operated in their thru-state, connect pump loop extension **1302** to main nonlinear optical waveguide **1310**. In this illustrative example, first wavelength-selective coupler **1320** and second wavelength-selective coupler **1322** operated in their cross-state connect the segments of secondary optical waveguide **1308** to main nonlinear optical waveguide **1310**. In this illustrative example, third wavelength-selective coupler **1324** and fourth wavelength-selective coupler **1326** operated in their thru-state connect signal loop extension **1304** to segments of secondary optical waveguide **1308**. In this illustrative example, third wavelength-selective coupler **1324** and fourth wavelength-selective coupler **1326** operated in their cross-state connect idler loop extension **1306** to segments of secondary optical waveguide **1308**.

(321) In this illustrative example, first loop **1352** is present for pump light **1312**. This first loop is a resonator loop in which pump light **1312** travels in a route that extends through main nonlinear optical waveguide **1310** and pump loop extension **1302**. Signal light **1314** travels in second loop **1354**. As depicted, second loop **1354** extends through main nonlinear optical waveguide **1310**, through segments of secondary optical waveguide **1308** and through signal loop extension **1304**. In this illustrative example, idler light **1316** travels in third loop **1356**. As depicted, third loop **1356** extends through main nonlinear optical waveguide **1310**, through segments of secondary optical waveguide **1308**, and through idler loop extension **1306**.

(322) In this illustrative example, first wavelength-selective coupler **1320** operating in its thru-state connects segment **1371** of main nonlinear optical waveguide **1310** and segment **1375** of pump loop extension **1302**, and second wavelength-selective coupler **1322** connects segment **1377** of pump loop extension **1302** and segment **1373** of main nonlinear optical waveguide **1310**. As depicted, first wavelength-selective coupler **1320**, operating in its thru-state, couples pump light **1312** away from main nonlinear optical waveguide **1310** and into pump loop extension **1302** and second wavelength-selective coupler **1322**, operating in its thru-state, couples pump light **1312** away from pump loop extension **1302** and into main nonlinear optical waveguide **1310** such that pump light **1312** travels in first loop **1352**.

(323) In this illustrative example, first wavelength-selective coupler **1320**, operating in its cross-state, extracts signal light **1314** and idler light **1318** away from main nonlinear optical waveguide **1310** and into segment **1307** of secondary optical waveguide **1308** such that signal light **1314** generated in main nonlinear optical waveguide **1310** does not travel in first loop **1352** but instead travels in second loop **1354** and idler light **1316** generated in main nonlinear optical waveguide **1310** does not travel in first loop **1352** but instead travels in third loop **1356**. In this illustrative example, second wavelength-selective coupler **1322**, operating in its cross-state, returns signal light **1314** traveling in second loop **1354** and idler light **1316** traveling in third loop **1356** back through main nonlinear optical waveguide **1310**.

(324) In this illustrative example, signal light **1314** reaches signal loop extension **1304** by passing through a segment **1307** of secondary optical waveguide **1308** before being coupled by third wavelength-selective coupler **1324**, operating in its thru-state, into signal loop extension **1304**. Additionally, signal light **1314** is returned from signal loop extension **1304** into a segment **1309** of secondary optical waveguide **1308** by fourth wavelength-selective coupler **1326**, operating in its thru-state. In this example, signal light **1314** passes through another portion, segment **1309** of secondary optical waveguide **1308** before being coupled back into main nonlinear optical waveguide **1310** by second wavelength-selective coupler **1322**, operating in its cross-state.

(325) In this illustrative example, idler light **1316** reaches idler loop extension **1306** by passing through a segment **1307** of secondary optical waveguide **1308** before being coupled by third wavelength-selective coupler **1324**, operating in its cross-state, into the idler loop extension **1306**. Additionally, idler light **1316** is returned from idler loop extension **1306** into another segment **1309** of secondary optical waveguide **1308** by fourth wavelength-selective coupler **1326**, operating in its cross-state. In this example, idler light **1316** passes through another portion of secondary optical waveguide **1308** before being coupled back into main nonlinear optical waveguide **1310** by second wavelength-selective coupler **1322**, operating in its cross-state.

(326) In this illustrative example, pump light **1312**, signal light **1314**, and idler light **1316** travel in different resonator loops. In this illustrative example, first loop **1352** is a resonator loop for pump light **1312**. First loop **1352** extends through main nonlinear optical waveguide **1310**, pump loop extension **1302**, first wavelength-selective coupler **1320**, and second wavelength-selective coupler **1322**.

(327) Second loop **1354** is resonator loop for signal light **1314**. This second loop extends through main nonlinear optical waveguide **1310**, first wavelength-selective coupler **1320** and second wavelength-selective coupler **1322**; segments **1307**, **1309** of secondary optical waveguide **1308**, third wavelength-selective coupler **1324**; fourth wavelength-selective coupler **1326**; and signal loop extension **1304**.

(328) Third loop **1356** is a resonator loop for idler light **1316**. Third loop **1356** comprises main nonlinear optical waveguide **1310**; first wavelength-selective coupler **1320**; a segment **1307** of secondary optical waveguide **1308** between first wavelength-selective coupler **1320** and third wavelength-selective coupler **1324**; third wavelength-selective coupler **1324**; idler loop extension **1306**; fourth wavelength-selective coupler **1326**; a segment **1309** of secondary optical waveguide **1308** between fourth wavelength-selective coupler **1326** and second wavelength-selective coupler **1322**.

(329) As depicted, optical waveguide structure **1300** also includes phase shifters in the form of tuning electrodes. In this illustrative example, tuning electrode **1360** is located adjacent to a portion **1340** of main nonlinear optical waveguide **1310**. Tuning electrode **1362** is located adjacent to a portion **1342** of pump loop extension **1302**. Tuning electrode **1364** is located adjacent to section **1344** of signal loop extension **1304** and tuning electrode **1366** is located adjacent to section **1346** of idler loop extension **1306**. These tuning electrodes can apply voltages to obtain desired level of resonance to achieve a resonant condition for light traveling within optical waveguide structure **1300**. These tuning electrodes also can apply voltages to obtain a desired round-trip phase matching condition for the nonlinear optical generation process that occurs in optical waveguide structure **1300**.

(330) Compared to optical waveguide structure **1200** of FIG. **16**, optical waveguide structure **1300** has four tuning electrodes rather than three tuning electrodes. The additional tuning electrode (or set of tuning electrodes) provides greater flexibility for simultaneously achieving resonance conditions for all three wavelengths of light—pump light **1312**, signal light **1314**, and idler light **1316** in their respective resonator loops, first loop **1352**, second loop **1354** and third loop **1356** as well as to achieve round-trip phase matching. For example, tuning electrode **1360** can be used to adjust the round-trip phase ϕ.sub.RTp of pump light **1312** in first loop **1352**. Tuning electrode **1364** can be used to adjust the round-trip phase ϕ.sub.RTs of signal light **1314** in second loop **1354**, which is a signal loop. Tuning electrode **1366** can be used to adjust the round-trip phase ϕ.sub.RTi of idler light **1316** in third loop **1356**, which is an idler loop. Tuning electrode **1362** can be used to further adjust the round-trip phase ϕ.sub.RTp of pump light **1312** in order to achieve round-trip phase matching for the nonlinear optical process that occurs in main nonlinear optical waveguide **1310**. Using the terminology defined with reference to optical waveguide structure **1100** shown in FIG. **13**, the round-trip phase matching condition is achieved when: ϕ.sub.RTp−ϕ.sub.RTs−ϕ.sub.RTi=2π*A*

(331) where A is an integer, and can be zero. This means: P−S−I=A with the integers P, S and I defined earlier with reference to optical waveguide structure **1100** shown in FIG. **13**. Thus, for the example of optical waveguide structure **1300**, the four conditions for achieving integer values for the parameters P, S, I and A can be satisfied by adjusting the four tuning electrodes, tuning electrode **1360**, tuning electrode **1364**, tuning electrode **1366** and tuning electrode **1362**.

(332) In this illustrative example, electrically controlled phase shifts are provided in optical waveguide structure **1300**. In this illustrative example,

portions of optical waveguide structure **1300** can be fabricated in x-cut lithium niobate. As depicted, the main nonlinear optical waveguide **1310** and pump loop extension **1302** through which the first loop **1352** extends form a rectangular shape with rounded corners. The orientation of optical waveguide structure **1300** can be such that segment **1370** in main nonlinear optical waveguide **1310** and segment **1372** in pump loop extension **1302** are aligned parallel to the y-axis of the lithium niobate crystal in the x-cut lithium niobate. These two segments—segment **1370** of main nonlinear optical waveguide **1310** and segment **1372** of pump loop extension **1302**—can be referred to as the long legs of the rectangular shape.
(333) The other portions of optical waveguides in the rectangular shaped waveguide structure defined by first loop **1352** include segment **1371** and segment **1373** of main nonlinear optical waveguide **1310** as well as segment **1375** and segment **1377** of pump loop extension **1302**. These segments are part of what can be referred to as the corners and short legs of the rectangular shaped or race-track shaped path traversed by first loop **1352**. In this illustrative example, segment **1371**, segment **1373**, segment **1375** and segment **1377** together with first wavelength-selective coupler **1320** and second wavelength-selective coupler **1322** are aligned mainly parallel with the z-axis of the x-cut lithium niobate crystal.
(334) In this illustrative example, orientation for optical waveguide structure **1300**, transverse-electric (TE) polarized light propagating in the optical waveguides traversed by first loop **1352** encounters the largest electro-optic coefficient of x-cut lithium niobate when the light travels in portion **1340** and portion **1342** of main nonlinear optical waveguide **1310** and pump loop extension **1302**, respectively. Portion **1340** and portion **1342** portions in which tunable phase shifts can occur. As depicted, the light travels in a clockwise direction around first loop **1352**. Furthermore, TE polarized signal light traversing portion in section **1344** of signal loop extension **1304** and TE polarized idler light traversing portion in section **1346** of idler loop extension **1306** also encounter the largest electro-optic coefficient of x-cut lithium niobate. Thus, the orientation depicted in FIG. **17** for optical waveguide structure **1300** can achieve efficient voltage-controlled electro-optic phase shifting.
(335) In this illustrative example, a nonlinear optical light generation process occurs in main nonlinear optical waveguide **1310**. Furthermore, to increase the nonlinear optical generation of signal and idler light that occurs in a given round-trip, it is desirable to meet another phase matching condition for propagation of the three wavelengths of light through segment **1370** of main nonlinear optical waveguide **1310**, which is the portion where most of the desired nonlinear optical generation occurs. This phase matching can be as follows:
(336) 0.Math.ϕ.sub.Mup−ϕ.sub.Mus−ϕ.sub.Mui≤π, or −π≤ϕ.sub.Mup−ϕ.sub.Mus−ϕ.sub.Mui≤0, and is close to zero.
(337) Many materials such as lithium niobate that have a large electro-optic coefficient for a certain orientation also have a large second-order nonlinear optical coefficient. In this illustrative example, transverse-electric (TE) polarized light propagating in the optical waveguides traversed by first loop **1352**, which is a pump loop, encounters the largest second order nonlinear optical coefficient when the light travels in segment **1370** of main nonlinear optical waveguide **1310** and in segment **1372** of pump loop extension **1302**. In this illustrative example, the entire length of the optical waveguides traversed by the light in first loop **1352**, which includes main nonlinear optical waveguide **1310** and pump loop extension **1302**, comprises a nonlinear optical material. As a result, photons for signal light **1314** and idler light **1316** can be generated both in segment **1370** of main nonlinear optical waveguide **1310** and in segment **1372** of pump loop extension **1302**. Some, albeit typically less, generation of signal and idler light also occurs in the corner segments, segment **1371**, segment **1373**, segment **1375** and segment **1377**.
(338) In this illustrative example, the optical fields of signal light **1314** and idler light **1316** generated in an optical waveguide segment that comprises nonlinear optical material can be described by expressions such as:
(339) $A_i(L) = \frac{{}_i^2}{k_i c^2}\int_A^B \frac{2id_{eff}A_pA_s}{1}e^{i\ kz}\,dz \sim \frac{2id_{eff}\ {}_i^2 A_pA_sL}{k_ic^2}\left(\frac{e^{i(\ Mup - Mus - Mui)}-1}{i(\ Mup - Mus - Mui)}\right)$ and $A_s(L) = \frac{{}_s^2}{k_s c^2}\int_A^B \frac{2id_{eff}A_pA_i}{1}e^{i\ kz}\,dz \sim \frac{2id_{eff}\ {}_s^2 A_pA_iL}{k_sc^2}\left(\frac{e^{i(\ Mup - Mus - Mui)}-1}{i(\ Mup - Mus - Mui)}\right)$.
(340) In these expression, A and B are the starting and ending points of a segment, such as segment **1370** of main nonlinear optical waveguide **1310** or segment **1372** of pump loop extension **1302**, with L being the length of that segment. The subscripts i, s and p indicate pump, signal and idler, respectively. The second order nonlinear optical coefficient d.sub.eff in segment **1370** has the opposite sign from the second order nonlinear optical coefficient d.sub.eff in segment **1372**. As a result, the contributions to the signal and idler optical fields from segment **1370** of main nonlinear optical waveguide **1310** and segment **1372** of pump loop extension **1302** can counteract each other, or the optical fields can interfere in a destructive manner, if the optical fields from these two segments are combined together, assuming the phase matching is perfect.
(341) Optical waveguide structure **1300** avoids the interaction of signal and idler light generated in segment **1370** with signal and idler light generated in segment **1372**. First wavelength-selective coupler **1320** functions to couple signal light **1314** and idler light **1316** generated in segment **1370** away from pump loop extension **1302** and thus away from segment **1372** by diverting that light into segment **1307** of secondary optical waveguide **1308**. Similarly, second wavelength-selective coupler **1322** functions to couple signal light **1314** and idler light **1316** generated in segment **1372** away from main nonlinear optical waveguide **1310** and thus away from segment **1370**, as shown by arrow **1380** into output optical waveguide **1305**. This coupling function done by second wavelength-selective coupler **1322** is performed in addition to coupling signal light **1314** in second loop **1354** and idler light **1316** in third loop **1356** from segment **1309** of secondary optical waveguide **1308** into main nonlinear optical waveguide **1310**. Thus, the signal light **1314** and idler light **1316** coupled back into main nonlinear optical waveguide **1310** through second wavelength-selective coupler **1322** is generated in a prior pass through main nonlinear optical waveguide **1310** and is not generated in the pump loop extension **1302**.
(342) As a result, any destructive interaction between signal light **1314** and idler light **1316** generated in segment **1370** and generated in segment **1372** is absent. Thus, signal light **1314** and idler light **1316** that result from circulation through many round-trips in the optical waveguide structure **1300** are those photons for signal light **1314** and idler light **1316** generated primarily in segment **1370** in main nonlinear optical waveguide **1310**.
(343) Next, FIG. **18** is an illustration of an optical waveguide structure with ten optical waveguides is depicted in accordance with an illustrative embodiment. In this illustrative example, optical waveguide structure **1500** is an example of an implementation for optical waveguide structure **100** as shown in FIGS. **1**-**6**. More specifically, FIG. **18** is an implementation for optical waveguides **102** as depicted in FIG. **2**.
(344) As depicted, optical waveguide structure **1500** comprises optical waveguides in the form of first main nonlinear optical waveguide segment **1510**A, second main nonlinear optical waveguide segment **1510**B, first pump bypass optical waveguide **1502**A, second pump bypass optical waveguide **1502**B, first secondary optical waveguide portion **1508**A, second secondary optical waveguide portion **1508**B, first signal loop extension **1504**A, second signal loop extension **1504**B, first idler loop extension **1506**A, and second idler loop extension **1506**B. First main nonlinear optical waveguide segment **1510**A and second main nonlinear optical waveguide segment **1510**B of main nonlinear optical waveguide **1510** are examples of main nonlinear optical waveguide **106** in FIG. **2**. First pump bypass optical waveguide **1502**A and second pump bypass optical waveguide **1502**B are examples of an implementation for first extension optical waveguide **108** in FIG. **2**. First secondary optical waveguide portion **1508**A and second secondary optical waveguide portion **1508**B are examples of an implementation of secondary optical waveguide **113** in FIG. **2**.
(345) As depicted in the detailed illustrative example of FIG. **18**, main nonlinear optical waveguide **1510** comprises two separate segments, first main nonlinear optical waveguide segment **1510**A and second main nonlinear optical waveguide segment **1510**B. Secondary optical waveguide **1508** comprises multiple segments that are part of first secondary optical waveguide portion **1508**A and second secondary optical waveguide portion **1508**B. In this example, extension optical waveguide **1502** has two distinct portions, called pump bypass waveguides. In this illustrative example, first pump bypass optical waveguide **1502**A and second pump bypass optical waveguide **1502**B are connected to optical couplers at each of the two ends of each of those optical waveguides. These optical waveguides are comprised of a non-nonlinear optical material **105** in this example.
(346) First secondary optical waveguide portion **1508**A is connected to first signal loop extension **1504**A and first idler loop extension **1506**A. Second secondary optical waveguide portion **1508**B is connected to second signal loop extension **1504**B and second idler loop extension **1506**B. These connections from the secondary optical waveguide portions to the various signal loop extensions and idler loop extensions are made through wavelength-selective couplers such as first signal loop coupler **1594**A, first idler loop coupler **1596**A, second signal loop coupler **1594**B, and second idler loop coupler **15963**. Connections between first main nonlinear optical waveguide segment **1510**A and second main nonlinear optical waveguide

segment **15103** of the main nonlinear optical waveguide and first secondary optical waveguide portion **1508**A and second secondary optical waveguide portion **15083** of the secondary optical waveguide are made through wavelength selective optical couplers, such as first wavelength-selective coupler **1580**, second wavelength-selective coupler **1586**, third wavelength-selective coupler **1584**, and fourth wavelength-selective coupler **1582**.

(347) In this illustrative example, optical waveguide structure **1500** also includes pump input optical waveguide **1532**, signal output optical waveguide **1534**, and idler output optical waveguide **1536**. Pump input optical waveguide **1532** can input pump light **1512** into second pump bypass optical waveguide **15023**. Signal output optical waveguide **1534** can output signal light **1514** from second signal loop extension **15043**. Idler output optical waveguide **1536** can output idler light **1516** from second idler loop extension **15063**.

(348) In this illustrative example, pump optical coupler **1531** couples pump input optical waveguide **1532** to second pump bypass optical waveguide **15023**. Signal optical coupler **1535** couples second signal loop extension **15043** to signal output optical waveguide **1534**. Idler optical coupler **1537** couples second idler loop extension **15063** to idler output optical waveguide **1536**.

(349) As depicted, first wavelength-selective coupler **1580** and second wavelength-selective coupler **1586** connect pump bypass optical waveguide **1502**A to two different segments, first main nonlinear optical waveguide segment **1510**A and second main nonlinear optical waveguide segment **15103**, of main nonlinear optical waveguide **1510**. In this illustrative example, third wavelength-selective coupler **1584** and fourth wavelength-selective coupler **1582** connect second pump bypass optical waveguide **15023** to the opposite ends of those two segments, first main nonlinear optical waveguide segment **1510**A and second main nonlinear optical waveguide segment **15103**, of main nonlinear optical waveguide **1510**.

(350) In this illustrative example, pump light **1512** travels in pump loop **1552**. Pump loop **1552** is a resonator loop that extends through first main nonlinear optical waveguide segment **1510**A of main nonlinear optical waveguide; first wavelength-selective coupler **1580**; first pump bypass optical waveguide **1502**A; second wavelength-selective coupler **1586**; second main nonlinear optical waveguide segment **15103** of main nonlinear optical waveguide; third wavelength-selective coupler **1584**; second pump bypass optical waveguide **15023**; and fourth wavelength-selective coupler **1582**; and continues again through first main nonlinear optical waveguide segment **1510**A of main nonlinear optical waveguide **1510**. The lengths of the various waveguides through which pump light **1512** of pump wavelength travels in pump loop **1552** can be selected so that pump wavelength matches a resonance condition for pump loop **1552**.

(351) Pump light **1512**, signal light **1514** and idler light **1516** all travel through first main nonlinear optical waveguide segment **1510**A and second main nonlinear optical waveguide segment **1510**B of main nonlinear optical waveguide **1510**. As depicted, first wavelength-selective coupler **1580** couples pump light **1512** into first pump bypass optical waveguide **1502**A. First wavelength-selective coupler **1580** also couples signal light **1514** and idler light **1516** into first secondary optical waveguide portion **1508**A. Thus, only signal light **1514** and idler light **1516** travel through second secondary optical waveguide portion **1508**B. First signal loop coupler **1594**A couples signal light from segment **1571** of first secondary optical waveguide portion **1508**A into first signal loop extension **1504**A. First signal loop coupler **1594**A also couples signal light that has propagated through first signal loop extension **1504**A into segment **1573** of first secondary optical waveguide portion **1508**A. Signal light **1514** then continues to propagate through first secondary optical waveguide portion **1508**A, being coupled by first idler loop coupler **1596**A from segment **1573** to segment **1575** of first secondary optical waveguide portion **1508**A. Second wavelength-selective coupler **1586** couples signal light **1514** from first secondary optical waveguide portion **1508**A into second main nonlinear optical waveguide segment **1510**B. Second wavelength-selective coupler **1586** also couples pump light from first pump bypass optical waveguide **1502**A into second main nonlinear optical waveguide segment **1510**B.

(352) As with first main nonlinear optical waveguide segment **1510**A of main nonlinear optical waveguide **1510**, pump light **1512**, signal light **1514** and idler light **1516** all travel through second main nonlinear optical waveguide segment **1510**B of main nonlinear optical waveguide **1510**. As depicted, third wavelength-selective coupler **1584** couples pump light **1512** into second pump bypass optical waveguide **1502**B. Third wavelength-selective coupler **1584** also couples signal light **1514** and idler light **1516** into second secondary optical waveguide portion **1508**B. Thus, only signal light **1514** and idler light **1516** travel through second secondary optical waveguide portion **1508**B.

(353) Second signal loop coupler **1594**B couples signal light from segment **1576** of second secondary optical waveguide portion **1508**B into second signal loop extension **1504**B. Second signal loop coupler **1594**B also couples signal light that has propagated through second signal loop extension **1504**B into segment **1574** of second secondary optical waveguide portion **1508**B. Signal light **1514** then continues to propagate through second secondary optical waveguide portion **1508**B, being coupled by second idler loop coupler **1596**B from segment **1574** to segment **1572** of second secondary optical waveguide portion **1508**B. Fourth wavelength-selective coupler **1582** couples signal light **1514** from second secondary optical waveguide portion **1508**B again into first main nonlinear optical waveguide segment **1510**A. Fourth wavelength-selective coupler **1582** also couples pump light **1512** from first pump bypass optical waveguide **1502**A into first main nonlinear optical waveguide segment **1510**A.

(354) In this illustrative example, signal light **1514** travels in signal loop **1554**. Signal loop **1554** is a resonator loop that can be thought of as comprising two halves. One half of signal loop **1554** extends through first main nonlinear optical waveguide segment **1510**A of main nonlinear optical waveguide **106**; first wavelength-selective coupler **1580** (in its thru state); segment **1571** of first secondary optical waveguide portion **1508**A; first signal loop coupler **1594**A (in its cross state); first signal loop extension **1504**A; a second pass through first signal loop coupler **1594**A (again in its cross state); segment **1573** of first secondary optical waveguide portion **1508**A; first idler loop coupler **1596**A (in its thru state); segment **1575** of first secondary optical waveguide portion **1508**A; and second wavelength-selective coupler **1586** (in its thru state). A second half of signal loop **1554** extends through second main nonlinear optical waveguide segment **1510**B of main nonlinear optical waveguide **1510**; third wavelength-selective coupler **1584** (in its thru state); segment **1576** of second secondary optical waveguide portion **1508**B; second signal loop coupler **1594**B (in its cross state); second signal loop extension **1504**B; a second pass through second signal loop coupler **1594**B (again in its cross state); segment **1574** of second secondary optical waveguide portion **1508**B; second idler loop coupler **1596**B (in its thru state); segment **1572** of second secondary optical waveguide portion **1508**B; and fourth wavelength-selective coupler **1582** (in its thru state). The lengths of the various waveguides through which signal light **1514** of a signal wavelength travels in signal loop **1554** can be selected so that signal wavelength matches a resonance condition for signal loop **1554**.

(355) Additionally, besides coupling signal light **1514**, first wavelength-selective coupler **1580** also couples idler light **1516** into first secondary optical waveguide portion **1508**A. Thus, only signal light **1514** and idler light **1516** travel through first secondary optical waveguide portion **1508**A. Idler light **1516** then continues to propagate through first secondary optical waveguide portion **1508**A, being coupled by first signal loop coupler **1594**A from segment **1571** to segment **1573** of first secondary optical waveguide portion **1508**A.

(356) In this illustrative example, first idler loop coupler **1596**A couples idler light **1516** from segment **1573** of first secondary optical waveguide portion **1508**A into first idler loop extension **1506**A. First idler loop coupler **1596**A also couples idler light that has propagated through first idler loop extension **1506**A into segment **1575** of first secondary optical waveguide portion **1508**A. Second wavelength-selective coupler **1586** couples idler light **1516** from first secondary optical waveguide portion **1508**A into second main nonlinear optical waveguide segment **1510**B. Pump light **1512**, signal light **1514** and idler light **1516** all travel through second main nonlinear optical waveguide segment **1510**B of main nonlinear optical waveguide **1510**. Besides coupling pump light **1512** into second pump bypass optical waveguide **1502**B, third wavelength-selective coupler **1584** also couples idler light **1516** and signal light **1514** into second secondary optical waveguide portion **1508**B. Thus, only idler light **1516** and signal light **1514** travel through second secondary optical waveguide portion **1508**B. Idler light **1516** then continues to propagate through second secondary optical waveguide portion **1508**B, being coupled by second signal loop coupler **1594**B from segment **1576** to segment **1574** of second secondary optical waveguide portion **1508**B.

(357) As depicted, second idler loop coupler **1596**B couples idler light **1516** from segment **1574** of second secondary optical waveguide portion **1508**B into second idler loop extension **1506**B. Second idler loop coupler **1596**B also couples idler light that has propagated through second idler

loop extension **1506**B into segment **1572** of second secondary optical waveguide portion **1508**B. Fourth wavelength-selective coupler **1582** couples idler light **1516** from second secondary optical waveguide portion **1508**B into first main nonlinear optical waveguide segment **1510**A.
(358) In this illustrative example, idler light **1516** travels in idler loop **1556**. Idler loop **1556** is a resonator loop that can be thought of as comprising two halves. One half of idler loop **1556** extends through first main nonlinear optical waveguide segment **1510**A of main nonlinear optical waveguide **1510**; first wavelength-selective coupler **1580** (in its thru state); segment **1571** of first secondary optical waveguide portion **1508**A; first signal loop coupler **1594**A (in its thru state); segment **1573** of first secondary optical waveguide portion **1508**A; first idler loop coupler **1596**A (in its cross state); first idler loop extension **1506**A; a second pass through first idler loop coupler **1596**A (again in its cross state); segment **1575** of first secondary optical waveguide portion **1508**A; and second wavelength-selective coupler **1586** (in its thru state). A second half of idler loop **1556** extends through second main nonlinear optical waveguide segment **1510**B of main nonlinear optical waveguide **1510**; third wavelength-selective coupler **1584** (in its thru state); segment **1576** of second secondary optical waveguide portion **1508**B; second signal loop coupler **1594**B (in its thru state); segment **1574** of second secondary optical waveguide portion **1508**B; second idler loop coupler **1596**B (in its cross state); second idler loop extension **1506**B; a second pass through second idler loop coupler **1596**B (again in its cross state); segment **1572** of second secondary optical waveguide portion **1508**B; and fourth wavelength-selective coupler **1582** (in its thru state). The lengths of the various waveguides through which idler light **1516** of idler wavelength travels in idler loop **1556** can be selected so that the idler wavelength matches a resonance condition for idler loop **1556**.
(359) As depicted, the resonator loops, pump loop **1552**, signal loop **1554**, and idler loop **1556**, have portions that overlap each other and portions that do not overlap each other. All three loops include nonlinear optical waveguide segments, such as first main nonlinear optical waveguide segment **1510**A and second main nonlinear optical waveguide segment **1510**B. Signal loop **1554** and idler loop **1556** further overlap each other through portions, such as first secondary optical waveguide portion **1508**A and second secondary optical waveguide portion **1508**B. Phase shifters can be placed at the non-overlapping portions of pump loop **1552**, signal loop **1554**, and idler loop **1556** to produce phase shifts for pump light **1512**, idler light **1516**, and signal light **1514** that can be adjusted separately from each other.
(360) The signal loop **1554**, idler loop **1556**, and pump loop **1552** can each be considered as having two halves. These halves can be distinguished in the illustration of FIG. **18** by their location relative to the reference line **1595**. A first half includes the components to the right of reference line **1595**. A second half includes the components to the left of reference line **1595**.
(361) As depicted, optical waveguide structure **1500** includes phase shifters in the form of tuning electrodes. In this example, tuning electrode **1564**A and tuning electrode **1565**A are located adjacent to first signal loop extension **1504**A. These tuning electrodes enable adjustment of the phase of signal light **1514** in the first half of signal loop **1554**. Tuning electrode **1566**A and tuning electrode **1567**A are located adjacent to first idler loop extension **1506**A. These tuning electrodes enable adjustment of the phase of idler light **1516** in the first half of idler loop **1556**. Tuning electrode **1564**B and tuning electrode **1565**B are located adjacent to second signal loop extension **1504**B. These tuning electrodes enable adjustment of the phase of signal light **1514** in the second half of signal loop **1554**. Tuning electrode **1566**B and tuning electrode **1567**B are located adjacent to second idler loop extension **1506**B. These tuning electrodes enable adjustment of the phase of idler light **1516** in the second half of idler loop **1556**.
(362) Tuning electrode **1560**A is located adjacent to first main nonlinear optical waveguide segment **1510**A. Tuning electrode **1560**A can be used to adjust the phase of pump light **1512** in the first half of pump loop **1552**. Tuning electrode **1560**B is located adjacent to second main nonlinear optical waveguide segment **1510**B. Tuning electrode **1560**B can be used to adjust the phase of pump light **1512** in the second half of pump loop **1552**. Since signal light **1514** and idler light **1516** also propagate through first main nonlinear optical waveguide segment **1510**A and second main nonlinear optical waveguide segment **1510**B for main nonlinear optical waveguide **1510**, tuning electrode **1560**A and tuning electrode **1560**B also affect the phase of signal light **1514** and idler light **1516**. The use of tuning electrodes to accomplish resonance matching and round-trip phase matching was described with reference to FIG. **13**, as an example.
(363) In optical waveguide structure **1500**, nonlinear optical generation of signal light **1514** and idler light **1516** from pump light **1512** occurs only in first main nonlinear optical waveguide segment **1510**A and second main nonlinear optical waveguide segment **1510**B of main nonlinear optical waveguide **1510**. First main nonlinear optical waveguide segment **1510**A can be considered as part of the first half of optical waveguide structure **1500**. Second main nonlinear optical waveguide segment **1510**B can be considered as part of the second half of optical waveguide structure **1500**.
(364) In this example, signal light **1514** and idler light **1516** propagate in first secondary optical waveguide portion **1508**A and second secondary optical waveguide portion **1508**B of secondary optical wavelength and in first signal loop extension **1504**A and second signal loop extension **1504**B as well as in first idler loop extension **1506**A and second idler loop extension **1506**B without further nonlinear optical generation of signal photons or idler photons. Pump light **1512**, from which the signal light **1514** and idler light **1516** are generated, is absent from those waveguides.
(365) In this illustrative example, the phases of the pump light **1512**, signal light **1514** and idler light **1516** in the two halves of optical waveguide structure **1500** can be adjusted to achieve a constructive interaction between the signal light and idler light generated in the first half of optical waveguide structure **1500** and the signal light and idler light generated in the second half of optical waveguide structure **1500**. This constructive interaction can be achieved even though the nonlinear optical coefficient can have a first sign in first main nonlinear optical waveguide segment **1510**A of the first half and a second sign, opposite to the first sign, in second main nonlinear optical waveguide segment **15103** of the second half.
(366) In this illustrative example, the nonlinear optical coefficient for light propagating in the first main nonlinear optical waveguide segment **1510**A of the upper-right half-structure **1591** of optical waveguide structure **1500** has one sign for the nonlinear optical coefficient **112**. The light propagating in second main nonlinear optical waveguide segment **15103** in lower-left half-structure **1592** of optical waveguide structure **1500** has an opposite sign for the nonlinear optical coefficient.
(367) In other words, the two segments, first main nonlinear optical waveguide segment **1510**A and second main nonlinear optical waveguide segment **15103**, of main nonlinear optical waveguide **1510** can be considered as part of two half-structures, upper-right half-structure **1591** and lower-left half-structure **1592**. As depicted, these two half-structures are separated by reference line **1595** extending from the upper left corner of optical waveguide structure **1500** to the lower right corner of optical waveguide structure **1500**. As shown, reference line **1595** intersects optical waveguide structure **1500** at a location A between second wavelength-selective coupler **1586** for reinserting pump light **1512** in second main nonlinear optical waveguide segment **1510**B of main nonlinear optical waveguide **1510** and the tuning electrode **1560**B in second main nonlinear optical waveguide segment **1510**B and at another location B between fourth wavelength-selective coupler **1582** for reinserting pump light **1512** into first main nonlinear optical waveguide segment **1510**A of main nonlinear optical waveguide **1510** and tuning electrode **1560**A in first main nonlinear optical waveguide segment **1510**A.
(368) For the upper-right half-structure **1591**, the relative phase walk-off for travel from upper left to lower right (i.e., from location A to location B) of upper-right half-structure **1591** should preferably be an odd multiple of π radians. Also, the relative phase walk-off from travel through first main nonlinear optical waveguide segment **1510**A of main nonlinear optical waveguide **1510**, where the nonlinear optical generation occurs, is preferably less than π radians and as close to zero as possible. The cross-sectional structure of first main nonlinear optical waveguide segment **1510**A can be designed to achieve the desired phase match (and minimal relative phase walk-off) for travel through first main nonlinear optical waveguide segment **1510**A. Similarly, for lower-left half-structure **1592**, the relative phase walk-off for travel from lower right to upper left (i.e., from location B to location A) of lower-left half-structure **1592** should be an odd multiple of π radians. Also, the relative phase walk-off from travel through the second main nonlinear optical waveguide segment **1510**B, where the nonlinear optical generation occurs, is less than π radians and as close to zero as possible. The cross-sectional structure of second main nonlinear optical waveguide segment **1510**B can be designed to achieve the desired phase match (and minimal relative phase walk-off) for travel through second main nonlinear optical waveguide segment **1510**B.
(369) Thus, the lengths of the pump loop **1552**, the signal loop **1554**, and idler loop **1556** in each of the upper-right half-structure **1591** and the lower-left half-structure **1592**, as well as the cross-sectional structures of the waveguides in each of those two half-structures can be designed to achieve the

desired relative phase walk-off that is preferably an odd multiple of π radians. Also, the relative phase walk-off from travel through first main nonlinear optical waveguide segment **1510**A for main nonlinear optical waveguide **1510**, where additional nonlinear optical generation occurs, is preferably less than π radians and ideally is zero. Similarly, the relative phase walk-off from travel through second main nonlinear optical waveguide segment **1510**B, where additional nonlinear optical generation again occurs, is preferably less than π radians and ideally is zero. Furthermore, the lengths and the cross-sectional structure of the waveguides traversed in both upper-right half-structure **1591** and the lower-left half-structure **1592** can be selected to also achieve round-trip phase matching for the nonlinear optical generation that occurs in the combination of two halves of optical waveguide structure **1500**. Thus, the round-trip phase for the nonlinear optical interaction of the pump, signal and idler light is preferably a multiple of 360 degrees or 2π radians.

(370) Making the phase walk-off for each half-structure, such as upper-right half-structure **1591** and lower-left half-structure **1592**, have a value that is an odd multiple of 180 degrees or π radians compensates for the reversal in sign of the nonlinear optical coefficient of the nonlinear optical material in the nonlinear optical waveguide segments, such as first main nonlinear optical waveguide segment **1510**A and second main nonlinear optical waveguide segment **15103**, of those two half-structures. First main nonlinear optical waveguide segment **1510**A is in upper-right half-structure **1591** and second main nonlinear optical waveguide segment **15103** is in lower-left half-structure **1592**. The nonlinear optical coefficient **112** in first main nonlinear optical waveguide segment **1510**A has a first sign **107** and the nonlinear optical coefficient **112** in second main nonlinear optical waveguide segment **15103** has a second sign **109** that is opposite from the first sign. The configuration of two half-structures is especially useful for optical waveguide structures **1500** that comprise second-order nonlinear optical material. An example of such material is x-cut lithium niobate. This configuration of two half-structures is especially useful when the nonlinear optical waveguide segments, such as first main nonlinear optical waveguide segment **1510**A and second main nonlinear optical waveguide segment **15103** containing x-cut lithium niobate are oriented parallel to the material Y-axis, with the propagating optical fields of the pump light **1512**, signal light **1514** and idler light **1516** having transverse electric (TE) components that are aligned parallel to the material X-axis.

(371) Besides meeting the phase matching conditions for the two half-structures, upper-right half-structure **1591** and lower-left half-structure **1592** that form optical waveguide structure **1500**, the other optical waveguides in optical waveguide structure **1500** can be designed to enable the pump light **1512**, signal light **1514**, and idler light **1516** to match resonances of their respective resonator loops, pump loop **1552**, signal loop **1554**, and idler loop **1556**.

(372) Turning next to FIG. **19**, an illustration of a flowchart of a process for a non-linear optical process is depicted in accordance with an illustrative embodiment. The process in this flowchart can be implemented in optical waveguide structure **100** in FIG. **1** as well the other optical waveguide structures depicted in other figures.

(373) The process begins by routing a first-wavelength light in a main nonlinear optical waveguide having a first length (operation **1900**). The process optically couples, by a first wavelength-selective coupler, a first main location in the main nonlinear optical waveguide and a first extension location in the extension optical waveguide to each other such that the first-wavelength light is coupled from the main nonlinear optical waveguide at the first main location to the extension optical waveguide at the first extension location (operation **1902**). The process does not optically couple a second-wavelength light from the main nonlinear optical waveguide at the first main location to the extension optical waveguide at the first extension location (operation **1903**). The process does not optically couple a third-wavelength light from the main nonlinear optical waveguide at the first main location to the extension optical waveguide at the first extension location (operation **1904**).

(374) The process optically couples, by a second wavelength-selective coupler, a second main location in the main nonlinear optical waveguide and a second extension location in the extension optical waveguide to each other such that the first wavelength-light is coupled from the extension optical waveguide at the second extension location to the main nonlinear optical waveguide at the second main location (operation **1905**). The process does not optically couple the second-wavelength light from the extension optical waveguide at the second extension location to the main nonlinear optical waveguide at the second main location (operation **1906**). The process does not optically couple the third-wavelength light from the extension optical waveguide at the second extension location to the main nonlinear optical waveguide at the second main location (operation **1908**). The process terminates thereafter.

(375) With reference to FIG. **20**, an illustration of a flowchart of additional operations for a process for a non-linear optical process is depicted in accordance with an illustrative embodiment. The process in this flowchart depicts additional operations that can be performed in addition to the operations in FIG. **19**.

(376) The process optically couples, by the first wavelength-selective coupler the first main location in the main nonlinear optical waveguide and a first secondary location in the secondary optical waveguide to each other such that the second-wavelength light is coupled from the main nonlinear optical waveguide at the first main location to the secondary optical waveguide at the first secondary location (operation **2000**). The process optical couples, by a third wavelength-selective coupler, a third secondary location in the secondary optical waveguide and a primary second extension location in the second extension optical waveguide to each other such that the second-wavelength light is coupled from the secondary optical waveguide at the third secondary location to the second extension optical waveguide at the primary second extension location (operation **2001**). The process does not optically couple a third-wavelength light from the secondary optical waveguide at the third secondary location to the second extension optical waveguide at the primary second extension location (operation **2003**). The process optically couples, by a fourth wavelength-selective coupler, a fourth secondary location in the secondary optical waveguide and a secondary second extension location in the second extension optical waveguide to each other such that the second-wavelength light is coupled from the second extension optical waveguide at the secondary second extension location to the secondary optical waveguide at the fourth secondary location (operation **2004**). The process does not optically couple the third-wavelength light from the second extension optical waveguide at the secondary second extension location to the secondary optical waveguide at the fourth secondary location (operation **2006**). The process optically couples, by the second wavelength-selective coupler, a second secondary location in the secondary optical waveguide and the second main location in the main nonlinear optical waveguide to each other such that the second-wavelength light is coupled from the secondary optical waveguide at the second secondary location to the main nonlinear optical waveguide at the second main location (operation **2008**). The process terminates thereafter.

(377) Turning to FIG. **21**, an illustration of a flowchart of additional operations for a process for a non-linear optical process is depicted in accordance with an illustrative embodiment. The process in this flowchart depicts additional operations that can be performed in addition to the operations in FIG. **19**.

(378) The process optically couples, by the first wavelength-selective coupler, the first main location in the main nonlinear optical waveguide and a first secondary location in the secondary optical waveguide to each other such that the third-wavelength light is coupled from the main nonlinear optical waveguide at the first main location to the secondary optical waveguide at the first secondary location (operation **2100**). Also, the process optical couples, by the third wavelength-selective coupler, a third secondary location in the secondary optical waveguide and a primary third extension location in the third extension optical waveguide to each other such that the third-wavelength light is coupled from the secondary optical waveguide at the third secondary location to the third extension optical waveguide at the primary third extension location (operation **2101**). The process does not optically couple the second-wavelength light from the secondary optical waveguide at the third secondary location to the third extension optical waveguide at the primary third extension location (operation **2102**). The process optically couples, by the fourth wavelength-selective coupler, a fourth secondary location in the secondary optical waveguide and a secondary third extension location in the third extension optical waveguide to each other such that the third-wavelength light is coupled from the third extension optical waveguide at the secondary third extension location to the secondary optical waveguide at the fourth secondary location (operation **2103**). The process does not optically couple the second-wavelength light from the third extension optical waveguide at the secondary third extension location to the secondary optical waveguide at

the fourth secondary location (operation **2104**). The process optically couples, by the second wavelength-selective coupler, the second secondary location in the secondary optical waveguide and the second main location in the main nonlinear optical waveguide to each other such that the third-wavelength light is coupled from the secondary optical waveguide at the second secondary location to the main nonlinear optical waveguide at the second main location (operation **2106**). The process terminates thereafter.
(379) Turning to FIG. **22**, an illustration of a flowchart of an additional operation for a process for a non-linear optical process is depicted in accordance with an illustrative embodiment. The process in this flowchart depicts additional operations that can be performed in addition to the operations in FIGS. **19**-**21**.
(380) The process applies an activation to a portion of the main nonlinear optical waveguide such that a phase shifts in the first-wavelength light to achieve a resonance condition for the first-wavelength light (operation **2200**). The process terminates thereafter.
(381) With reference next to FIG. **23**, an illustration of a flowchart of an additional operation for a process for a non-linear optical process is depicted in accordance with an illustrative embodiment. The process in this flowchart depicts additional operations that can be performed in addition to the operations in FIG. **21** and FIG. **22**.
(382) The process applies an activation to a portion of the second extension waveguide such that a phase shifts in the second-wavelength light to achieve a resonance condition for the second-wavelength light (operation **2300**). The process terminates thereafter.
(383) Turning now to FIG. **24**, an illustration of a flowchart of an additional operation for a process for a non-linear optical process is depicted in accordance with an illustrative embodiment. The process in this flowchart depicts additional operations that can be performed in addition to the operations in FIG. **21** and FIG. **23**.
(384) The process applies an activation to a portion of the third extension optical waveguide such that a phase shifts in the third-wavelength light to achieve a resonance condition for the third-wavelength light (operation **2400**). The process terminates thereafter.
(385) Turning now to FIG. **25**, an illustration of a flowchart of an additional operation for a process for a non-linear optical process is depicted in accordance with an illustrative embodiment. The process in this flowchart depicts additional operations that can be performed in addition to the operations in FIGS. **22**-**24**.
(386) The process applies at least one of an activation to a portion of the main nonlinear optical waveguide such that a phase shifts in the first-wavelength light, an activation to a portion of the second extension waveguide such that a phase shifts in the second-wavelength light, and an activation to a portion of the third extension optical waveguide such that a phase shifts in the third-wavelength light to achieve a round-trip phase matching condition for the nonlinear optical process involving the first-wavelength light, the second-wavelength light, and the third-wavelength light (operation **2500**). The process terminates thereafter.
(387) To achieve phase matching, the activation does not necessarily need to be applied to all three of the main nonlinear optical waveguide, the second extension waveguide, and the third extension waveguide. The activation can be applied to one of some combination of the three waveguides or waveguide portions.
(388) Turning now to FIG. **26**, an illustration of a flowchart of an additional operation for a process for a non-linear optical process is depicted in accordance with an illustrative embodiment. The process in this flowchart depicts additional operations that can be performed in addition to the operations in FIGS. **22**-**25**.
(389) The process applies an activation to a portion of the first extension optical waveguide such that a phase shifts in the first-wavelength light to achieve a resonance condition for the first-wavelength light and to achieve a round-trip phase matching condition for the nonlinear optical process involving the first-wavelength light, the second-wavelength light, and the third-wavelength light (operation **2600**). The process terminates thereafter. In operation **2600**, this activation can be accomplished by tuning electrode **1362** in FIG. **17**.
(390) The flowcharts and block diagrams in the different depicted embodiments illustrate the architecture, functionality, and operation of some possible implementations of apparatuses and methods in an illustrative embodiment. In this regard, each block in the flowcharts or block diagrams can represent at least one of a module, a segment, a function, or a portion of an operation or step. For example, one or more of the blocks can be implemented as program code, hardware, or a combination of the program code and hardware. When implemented in hardware, the hardware can, for example, take the form of integrated circuits that are manufactured or configured to perform one or more operations in the flowcharts or block diagrams. When implemented as a combination of program code and hardware, the implementation may take the form of firmware. Each block in the flowcharts or the block diagrams can be implemented using special purpose hardware systems that perform the different operations or combinations of special purpose hardware and program code run by the special purpose hardware.
(391) In some alternative implementations of an illustrative embodiment, the function or functions noted in the blocks may occur out of the order noted in the figures. For example, in some cases, two blocks shown in succession may be performed substantially concurrently, or the blocks may sometimes be performed in the reverse order, depending upon the functionality involved. Also, other blocks may be added in addition to the illustrated blocks in a flowchart or block diagram.
(392) Turning now to FIG. **27**, an illustration of a block diagram of a product management system is depicted in accordance with an illustrative embodiment. Product management system **2700** is a physical hardware system. In this illustrative example, product management system **2700** includes at least one of manufacturing system **2702** or maintenance system **2704**.
(393) Manufacturing system **2702** is configured to manufacture products. As depicted, manufacturing system **2702** includes manufacturing equipment **2706**. Manufacturing equipment **2706** includes at least one of fabrication equipment **2708** or assembly equipment **2710**.
(394) Fabrication equipment **2708** is equipment that used to fabricate the nonlinear optical waveguide structure. Multiple copies or multiple versions of nonlinear optical waveguide structures can be fabricated on a substrate wafer.
(395) The substrate wafer can comprise a material such as silicon, lithium niobate, quartz, sapphire, silicon carbide, or some other suitable substrate. Fabrication equipment **2708** can be used to fabricate at least one of optical waveguide structures, nonlinear optical waveguides, optical couplers, optical waveguide segments, laser transmitters, ultraviolet transmission systems, point-to-point communication devices, laser infrared countermeasure sources, through water optical communication devices, or other suitable devices, antennas, or other suitable types of parts. For example, fabrication equipment **2708** can include machines and tools.
(396) With respect to fabricating semiconductor components and optical waveguide components, fabrication equipment **2708** can comprise at least one of an epitaxial reactor, an oxidation system, a diffusion system, an etching system, a cleaning system, a bonding machine, a dicing machine, a wafer saw, an ion implantation system, a physical vapor deposition system, a chemical vapor deposition system, a photolithography system, an electron-beam lithography system, a plasma etcher, a die attachment machine, a wire bonder, a die overcoat system, molding equipment, a hermetic sealer, an electrical tester, a burn-in oven, a retention bake oven, a UV erase system, or other suitable types of equipment that can be used to manufacture semiconductor structures.
(397) Assembly equipment **2710** is equipment used to assemble parts to form a product such as a chip, an integrated circuit, a multi-chip module, a computer, a signal processor, an aircraft, or some other product. Assembly equipment **2710** also can include machines and tools. These machines and tools may be at least one of a robotic arm, a spinner system, a sprayer system, and elevator system, a rail-based system, or a robot.
(398) In this illustrative example, maintenance system **2704** includes maintenance equipment **2712**. Maintenance equipment **2712** can include any equipment needed to perform maintenance on and evaluation of a product. Maintenance equipment **2712** may include tools for performing different operations on parts on a product. These operations can include at least one of disassembling parts, refurbishing parts, inspecting parts, reworking parts, manufacturing replacement parts, or other operations for performing maintenance on the product. These operations can be for routine maintenance, inspections, upgrades, refurbishment, or other types of maintenance operations.

(399) In the illustrative example, maintenance equipment **2712** may include optical inspection devices, electron-beam imaging systems, x-ray imaging systems, surface-profile measurement systems, drills, vacuum leak checkers, and other suitable devices. In some cases, maintenance equipment **2712** can include fabrication equipment **2708**, assembly equipment **2710**, or both to produce and assemble parts that needed for maintenance.
(400) Product management system **2700** also includes control system **2714**. Control system **2714** is a hardware system and may also include software or other types of components. Control system **2714** is configured to control the operation of at least one of manufacturing system **2702** or maintenance system **2704**. In particular, control system **2714** can control the operation of at least one of fabrication equipment **2708**, assembly equipment **2710**, or maintenance equipment **2712**.
(401) The hardware in control system **2714** can be implemented using hardware that may include computers, circuits, networks, and other types of equipment. The control may take the form of direct control of manufacturing equipment **2706**. For example, robots, computer-controlled machines, and other equipment can be controlled by control system **2714**. In other illustrative examples, control system **2714** can manage operations performed by human operators **2716** in manufacturing or performing maintenance on a product. For example, control system **2714** can assign tasks, provide instructions, display models, or perform other operations to manage operations performed by human operators **2716**. In these illustrative examples, the different processes for fabricating semiconductor structures, optical structures, nonlinear optical waveguides, laser transmitters, photon generators, photon transmitters, photon detectors, ultraviolet transmission systems, point-to-point communication devices, laser infrared countermeasure sources, through water optical communication devices, or other suitable devices can be manufactured using processes implemented in control system **2714**.
(402) In the different illustrative examples, human operators **2716** can operate or interact with at least one of manufacturing equipment **2706**, maintenance equipment **2712**, or control system **2714**.
(403) This interaction can occur to manufacture semiconductor structures and other components for products such as semiconductor devices or components for use in products such as aircraft, spacecraft, communications systems, computation systems, and sensor systems.
(404) Further, control system **2714** can be used to adjust manufacturing of nonlinear optical waveguides, optical waveguides, optical couplers, phase shifters, and other components dynamically in or by the waveguides during the manufacturing process. For example, many points in the process of fabricating the optical waveguide structure including the nonlinear optical waveguide as well as other components are present at which adjustments can be made to control characteristics of components in an optical waveguide structure.
(405) Some features of the illustrative examples are described in the following clauses. These clauses are examples of features not intended to limit other illustrative examples.
Clause 1
(406) An optical waveguide structure comprising: a main nonlinear optical waveguide, wherein a first-wavelength light and a second-wavelength light travel in the main nonlinear optical waveguide; a first extension optical waveguide; a secondary optical waveguide; a first wavelength-selective coupler that optically couples the main nonlinear optical waveguide and the first extension optical waveguide to each other such that the first-wavelength light is coupled from the main nonlinear optical waveguide to the first extension optical waveguide,
(407) and that optically couples the main nonlinear optical waveguide and the secondary optical waveguide to each other such that the second-wavelength light is coupled from the main nonlinear optical waveguide to the secondary optical waveguide;
(408) and a second wavelength-selective coupler that optically couples the main nonlinear optical waveguide and the first extension optical waveguide to each other such that the first-wavelength light is coupled from the first extension optical waveguide to the main nonlinear optical waveguide,
(409) and that optically couples the main nonlinear optical waveguide and the secondary optical waveguide to each other such that the second-wavelength light is coupled from the secondary optical waveguide to the main nonlinear optical waveguide.
Clause 2
(410) The optical waveguide structure according to clause 1 further comprising: a second extension optical waveguide; a third wavelength-selective coupler that optically couples the secondary optical waveguide and the second extension optical waveguide to each other such that the second-wavelength light is coupled from the secondary optical waveguide to the second extension optical waveguide; and a fourth wavelength-selective coupler that optically couples the secondary optical waveguide and the second extension optical waveguide to each other such that the second-wavelength light is coupled from the second extension optical waveguide to the secondary optical waveguide.
Clause 3
(411) The optical waveguide structure according to clause 2 further comprising: a third extension optical waveguide; wherein the third wavelength-selective coupler optically couples the secondary optical waveguide and the third extension optical waveguide to each other such that a third-wavelength light is coupled from the secondary optical waveguide to the third extension optical waveguide and the second-wavelength light is not coupled into the third extension optical waveguide; and wherein the fourth wavelength-selective coupler optically couples the secondary optical waveguide and the third extension optical waveguide to each other such that the third-wavelength light is coupled from the third extension optical waveguide to the secondary optical waveguide.
Clause 4
(412) The optical waveguide structure according to any of clauses 2-4, wherein the first-wavelength light travels in a first loop through a main segment between a first main location and a second main location within the main nonlinear optical waveguide, through the first extension optical waveguide, and through the first wavelength-selective coupler and the second wavelength-selective coupler, in which the first loop has a first length, and wherein the second-wavelength light travels in a second loop through the main segment between the first main location and the second main location within the main nonlinear optical waveguide, through a secondary segment in the secondary optical waveguide, through the second extension optical waveguide, and through the first wavelength-selective coupler and the second wavelength-selective coupler, in which the second loop has a second length for the second-wavelength light.
Clause 5
(413) The optical waveguide structure according to clause 3, wherein the first-wavelength light travels in a first loop through a main segment within the main nonlinear optical waveguide, through and a first extension segment, through the first wavelength-selective coupler and the second wavelength-selective coupler, in which the first loop has a first length; wherein the second-wavelength light travels in a second loop through a secondary segment in the secondary optical waveguide, through the second extension optical waveguide, through the first wavelength-selective coupler and the second wavelength-selective coupler, through the third wavelength-selective coupler and the fourth wavelength-selective coupler, and through the main segment in the nonlinear optical waveguide, in which the second loop has a second length for the second-wavelength light; and wherein the third-wavelength light travels in a third loop through the secondary segment in the secondary optical waveguide, through the third extension optical waveguide, through the first wavelength-selective coupler and the second wavelength-selective coupler, through the third wavelength-selective coupler and the fourth wavelength-selective coupler, and through the main segment in the nonlinear optical waveguide, in which the third loop has a third length for the third-wavelength light.
Clause 6
(414) The optical waveguide structure according to any of clauses 2-6, wherein the first-wavelength light is a pump light and the second-wavelength light is one of a signal light and an idler light, and wherein an intensity of the first-wavelength light is greater than an intensity of the second-wavelength light.

Clause 7

(415) The optical waveguide structure according to any of clauses 3 or 5 wherein the first-wavelength light is a pump light, the second-wavelength light is a signal light, and the third-wavelength light is an idler light; and wherein an intensity of the first-wavelength t light is greater than an intensity of the second-wavelength light and is greater than an intensity of the third-wavelength light.

Clause 8

(416) The optical waveguide structure according to any of clauses 1-7, wherein the main nonlinear optical waveguide is comprised of an electro-optic material.

Clause 9

(417) The optical waveguide structure according to any of clauses 2-8, wherein the second extension optical waveguide is comprised of at least one of an electro-optic material, a nonlinear optical material or a non-nonlinear optical material

Clause 10

(418) The optical waveguide structure according to any of clauses 3, 5, or 7, wherein the third extension optical waveguide is comprised of at least one of an electro-optic material, a nonlinear optical material or a non-nonlinear optical material

Clause 11

(419) The optical waveguide structure according to any of clauses 1-10, wherein the main nonlinear optical waveguide is comprised of a nonlinear optical material.

Clause 12

(420) The optical waveguide structure according to any of clauses 2-11, wherein the second extension optical waveguide is comprised of an electro-optic material.

Clause 13

(421) The optical waveguide structure according to any of clauses 3, 5, 7, or 10, wherein the third extension optical waveguide is comprised of an electro-optic material.

Clause 14

(422) The optical waveguide structure according to any of clauses 2-13, wherein the first wavelength-selective coupler, the second wavelength-selective coupler, the third wavelength-selective coupler, and the fourth wavelength-selective coupler are selected from at least one of a two-waveguide coupler, a multi-mode interference coupler, a pulley coupler, a Mach-Zehnder interferometer, or a 4-port micro-optical waveguide resonator coupler.

Clause 15

(423) The optical waveguide structure according to any of clauses 3, 5, 7, 10, or 13 further comprising: a set of output optical waveguides that outputs output light out of at least one of the first extension optical waveguide, the second extension optical waveguide, or the third extension optical waveguide.

Clause 16

(424) The optical waveguide structure according to any of clauses 3, 5, 7, 10, 13, or 15 further comprising: a set of input optical waveguides that inputs input light into at least one of the first extension optical waveguide, the second extension optical waveguide, or the third extension optical waveguide.

Clause 17

(425) The optical waveguide structure according to clause 4 further comprising: a phase shifter located adjacent to a portion of the main nonlinear optical waveguide, wherein the phase shifter applies an activation such that a phase shifts in the first-wavelength light to achieve a resonance condition for the first-wavelength light.

Clause 18

(426) The optical waveguide structure according to any of clauses 4 or 17 further comprising: a phase shifter located adjacent to a portion of the second extension optical waveguide, wherein the phase shifter applies an activation such that a phase shifts in the second-wavelength light to achieve a resonance condition for the second-wavelength light.

Clause 19

(427) The optical waveguide structure according to clause 5 further comprising: a phase shifter located adjacent to a portion of the third extension optical waveguide, wherein the phase shifter applies an activation such that a phase shifts in the third-wavelength light to achieve the resonance condition for the third-wavelength light.

Clause 20

(428) The optical waveguide structure according to any of clauses 1-19 further comprising: a phase shifter located adjacent to a portion of the main nonlinear optical waveguide, wherein the phase shifter applies an activation such that a phase shifts in the first-wavelength light to achieve a round-trip phase matching condition for a nonlinear optical process involving the first-wavelength light.

Clause 21

(429) The optical waveguide structure according to any of clauses 2-20 further comprising: a phase shifter located adjacent to a portion of the second extension optical waveguide, wherein the phase shifter applies an activation such that a phase shifts in the second-wavelength light to achieve a round-trip phase matching condition for a nonlinear optical process involving the second-wavelength light.

Clause 22

(430) The optical waveguide structure according to any of clauses 3, 5, 7, 10, 13, 15, or 16 further comprising: a phase shifter located adjacent to a portion of the third extension optical waveguide, wherein the phase shifter applies an activation such that a phase shifts in the third-wavelength light to achieve a round-trip phase matching condition for a nonlinear optical process involving the third-wavelength light.

Clause 23

(431) The optical waveguide structure according to any of clauses 1-24 further comprising: a phase shifter located adjacent to a portion of the main nonlinear optical waveguide, wherein the phase shifter applies an activation such that a phase shifts in the first-wavelength light to achieve a phase walk-off that is an odd multiple of 180 degrees.

Clause 24

(432) The optical waveguide structure according to any of clauses 2-23 further comprising: a phase shifter located adjacent to a portion of the second extension optical waveguide, wherein the phase shifter applies an activation such that a phase shifts in the second-wavelength light to achieve a phase walk-off that is an odd multiple of 180 degrees.

Clause 25

(433) The optical waveguide structure according to any of clauses 35, 7, 10, 13, 15, 16, or 22 further comprising:

(434) a phase shifter located adjacent to a portion of the third extension optical waveguide, wherein the phase shifter applies an activation such that a phase shifts in the third-wavelength light to achieve a phase walk-off that is an odd multiple of 180 degrees.

Clause 26

(435) A method for facilitating a non-linear optical process comprising: routing a first-wavelength light and a second-wavelength light in a main nonlinear optical waveguide; optically coupling, by a first wavelength-selective coupler, the main nonlinear optical waveguide and an extension optical waveguide to each other such that the first-wavelength light is coupled from the main nonlinear optical waveguide to the extension optical

waveguide and the second-wavelength light is not coupled from the main nonlinear optical waveguide to the extension optical waveguide but rather is coupled to a secondary optical waveguide; and optically coupling, by a second wavelength-selective coupler, the main nonlinear optical waveguide and the extension optical waveguide to each other such that the first-wavelength light is coupled from the extension optical waveguide to the main nonlinear optical waveguide.

Clause 27

(436) The method of according to clause 26 further comprising: optically coupling, by a third wavelength-selective coupler, the secondary optical waveguide and a second extension optical waveguide to each other such that the second-wavelength light is coupled from the secondary optical waveguide to the second extension optical waveguide, and such that a third-wavelength light is not coupled from the secondary optical waveguide to the second extension optical waveguide; and optically coupling, by a fourth wavelength-selective coupler, the secondary optical waveguide and the second extension optical waveguide to each other such that the second-wavelength light is coupled from the second extension optical waveguide to the secondary optical waveguide.

Clause 28

(437) The method of according to clause 27 comprising: routing the third-wavelength light in the main nonlinear optical waveguide;

(438) optically coupling, by the third wavelength-selective coupler, the secondary optical waveguide and a third extension optical waveguide to each other such that the third-wavelength light is coupled from the secondary optical waveguide to the third extension optical waveguide and the second-wavelength light is not coupled from the secondary optical waveguide to the third extension optical waveguide; and optically coupling, by the fourth wavelength-selective coupler, the secondary optical waveguide and the third extension optical waveguide to each other such that the third-wavelength light is coupled from the third extension optical waveguide to the secondary optical waveguide.

Clause 29

(439) The method according to clause 27, wherein the first-wavelength light travels in a first loop through a main segment between a first main location and a second main location within the main nonlinear optical waveguide and through a first extension segment, in which the first loop has a first length selected to achieve a resonance condition for the first-wavelength light; and wherein the second-wavelength light travels in a second loop through a secondary segment in the secondary optical waveguide, through the second extension optical waveguide, and through the main segment in the main nonlinear optical waveguide, in which the second loop has a second length for the second-wavelength light selected to achieve the resonance condition for the second-wavelength light.

Clause 30

(440) The method according to clause 27, wherein the first-wavelength light travels in a first loop through a main segment between a first main location and a second main location within the main nonlinear optical waveguide and through a first extension optical waveguide, in which the first loop has a first length selected to achieve a resonance condition for the first-wavelength light; wherein the second-wavelength light travels in a second loop through a segment in the secondary optical waveguide, through the second extension optical waveguide, and through the main segment in the nonlinear optical waveguide, in which the second loop has a second length for the second-wavelength light selected to achieve the resonance condition for the second-wavelength light; and wherein the third-wavelength light travels in a third loop through the segment in the secondary optical waveguide, through the third extension optical waveguide, and through the main segment in the nonlinear optical waveguide, in which the third loop as a third length selected to achieve a resonance condition for the third-wavelength light.

Clause 31

(441) The method according to any of clauses 27-30, wherein the first-wavelength light is a pump light, the second-wavelength light is one of a signal light and an idler light.

Clause 32

(442) The method according to any of clauses 27-30, wherein the first-wavelength light is one of a signal light and an idler light and the second-wavelength light is a pump light.

Clause 33

(443) The method according to any of clauses 27-30, wherein the first-wavelength light is a pump light, the second-wavelength light is a signal light, and the third-wavelength light is an idler light.

Clause 34

(444) The method according to any of clauses 26-33 further comprising: applying an activation to a portion of the main nonlinear optical waveguide such that a phase shifts in the first-wavelength light to achieve a resonance condition for the first-wavelength light.

Clause 35

(445) The method according to any of clauses 27-34 further comprising: applying an activation such to a portion of the second extension optical waveguide such that a phase shifts in the second-wavelength light to achieve a resonance condition for the second-wavelength light.

Clause 36

(446) The method according to clause 30 further comprising: applying an activation to a portion of the third extension optical waveguide such that such that a phase shifts in the third-wavelength light to achieve a resonance condition for the third-wavelength light.

Clause 37

(447) The method according to any of clauses 27-36 further comprising: applying an activation to a portion of the second extension optical waveguide such that a phase shifts in the second-wavelength light.

Clause 38

(448) The method according to any of clauses 27-37 further comprising: applying an activation to a portion of the main nonlinear optical waveguide such that a phase shifts in the first-wavelength light to achieve a round trip phase matching condition for a nonlinear optical process involving the first-wavelength light, the second-wavelength light, and the third-wavelength light.

(449) Thus, the illustrative examples include the wavelength-selective couplers that enable selective coupling of light in a manner that establishes loops in which light of different wavelengths can travel. Additionally, optical waveguides in the illustrative examples are designed to manage a reversal in the sign of the nonlinear optical coefficient that occurs for the two halves of an optical waveguide structure for which the light travels in opposite directions in portions of those two halves. The optical waveguide structures in this optical waveguide structure can avoid undesired effects of the sign reversal in the nonlinear optical coefficient by removing the pump light or by having an absence of a non-linear optical material in part of the structure.

(450) In another illustrative embodiment, loops formed from optical waveguides is unnecessary. For example, the nonlinear optical waveguide structure in the different illustrative examples described above in FIGS. **1**-**27** can comprise triple partially overlapping loops for entanglement (TriPOLE). In this illustrative example, these partially overlapping loops for entanglement are unnecessary to obtain a desired level of performance.

(451) The illustrative embodiments recognize and take into account a number of different considerations. Some of these considerations are recognized and taken into account as described below.

(452) For example, the illustrative embodiments recognize and take into account that energy is conserved for a nonlinear optical process to occur. Furthermore, the illustrative embodiments recognize and take into account that the efficiency with which a nonlinear optical process generates light of a second wavelength from light of a first wavelength can be increased by achieving and maintaining phase matching for the nonlinear optical interaction to remain constructive and thereby generate more and more light of the second wavelength for longer and longer distances in which the nonlinear optical interaction occurs.

(453) The illustrative embodiments also recognize and take into account that a problem is not how substantial the nonlinear optical conversion is, but rather whether the nonlinear optical interaction can continue to be constructive and to generate more light of the second wavelength from light of the first wavelength as the interaction distance is increased. For a closed-loop route, the interaction distance can be increased by having the light make many round trips through the closed-loop route.
(454) The illustrative embodiments recognize and take into account that perfect phase-matching, i.e., when the phase mismatch of the optical fields participating in the nonlinear optical interaction is exactly 0, can be achieved in certain bulk crystals which exhibit birefringence. Phase-matching is achieved through angle tuning or temperature tuning and requires that at least one optical field has polarization orthogonal to another. However, if the dispersion in the linear refractive index is too big or the birefringence is too small, phase-matching may not be possible. Furthermore, for angles between the optic axis and propagation direction that are not exactly 0 or 90°, the optical fields experience significant spatial walk-off that reduces the spatial overlap of the optical fields participating in the nonlinear optical interaction and thus limits the interaction distance over which there continues to be generation of light at the second wavelength from light at the first wavelength. This spatial walk-off, and corresponding limitation on the interaction distance over which spatial overlap of the optical fields is maintained, limits the efficiency of the nonlinear optical process. In some applications, the temperatures required for phase-matching may not be practical. In addition, because one of the optical fields has different polarization, the largest nonlinear optical process coefficient cannot be utilized for all of the optical fields. As a result the efficiency of the nonlinear optical process is limited. In general, bulk crystals are fragile and large, making their use impractical in some applications.
(455) The illustrative embodiments recognize and take into account that an alternative approach to true phase-matching in bulk crystals is quasi phase-matching. For a certain crystal, the desired wavelengths of the optical fields for some nonlinear optical process will have a nonzero phase-match, i.e., the fields will have some finite phase walk-off. When this phase walk-off exceeds π radians or 180°, the nonlinear optical process begins to occur in reverse. Thus, instead of generating more light of the second wavelength from light of the first wavelength, the nonlinear process starts to generate light of the first wavelength from light of the second wavelength. This change in the nonlinear optical process can effectively cancel out the nonlinear optical generation of light at the second wavelength that had occurred when the phase walk-off was between 0 and π radians. Quasi phase matching as implemented in bulk crystals utilizes a periodic reversal of the crystal axes so that when the phase walk-off is between 0 and π radians the optical fields experience the positive value of the χ.sup.(2) nonlinear optical susceptibility coefficient, and when the phase walk-off is between n and 2π radians the optical fields experience the negative value of the χ.sup.(2) nonlinear optical susceptibility coefficient.
(456) Thus, the illustrative embodiments recognize and take into account that the nonlinear optical process continues to be enhanced over many cycles of the periodic modulation of the χ.sup.(2) nonlinear optical susceptibility coefficient. This technique can be advantageous in place of using regular bulk crystals because the optical fields can all have identical polarization. This technique can make use of the material's largest nonlinear optical coefficient. This technique can also reduce or eliminate spatial walk-off. However, for efficient enhancement of the nonlinear optical process the duty cycle of the poling period should be 50:50. Furthermore, the poling period typically required for quasi phase-matching ranges from 2-10 microns.
(457) The illustrative embodiments also recognize and take into account that even with modern fabrication techniques, making periodically poled crystals with the correct duty cycle and poling period is very challenging, limiting the nonlinear optical enhancement of this strategy and its practicality. Temperature tuning can be used to compensate for imperfection in the poling period. Temperature tuning can be most effective when the poling period has a constant offset. For example, if some periods are too small and others too large, temperature tuning has reduced effectiveness or is ineffective. As with phase matching accomplished in bulk crystals, periodically poled bulk crystals for accomplishing quasi phase matching are large and fragile and may not be suitable for some applications.
(458) The illustrative embodiments also recognize and take into account that the nonlinear optical process can be further enhanced by confining the optical fields in waveguides of the periodically poled crystal. This technique can increase the optical field amplitude, which in turn increases the efficiency of the nonlinear optical process. However, this technique still suffers from many of the issues encountered with bulk periodically poled crystals. In addition, applying the periodic poling across an entire wafer-scale substrate for mass production is currently impractical.
(459) The illustrative embodiments recognize and take into account that instead of a periodic modulation of the crystal orientation, a periodic modulation of waveguide width or height can be used to compensate for the phase walk-off of the nonlinear optical process. However, such modulations also can induce significant reflection or scattering of the optical fields. This optical loss consequently lowers the efficiency of the nonlinear optical process by reducing the interaction distance over which a high optical-field amplitude can be sustained. In addition, the modulation typically employs sub-micron size spatial features which may require multi-step etch processes. As a result, this technique can require complex fabrication processes with very tight tolerances, but still incur significant optical losses which reduce the interaction distance over which a high optical-field amplitude can be sustained.
(460) The illustrative embodiment provides an apparatus, system, and method that does not require periodic poling of the crystal substrate, which is costly, prone to fabrication errors, and not amenable to wafer-scale mass production. The illustrative examples use waveguide structures and components that are relatively straight-forward to fabricate and amenable to wafer-scale mass production. For example, in the illustrative examples, optical structures can be fabricated in a single etch step. This simple fabrication is not feasible with optical waveguides that use a periodic modulation of waveguide height to enhance the nonlinear optical process. The illustrative examples also do not require components which are inherently prone to significant optical losses, such as periodic modulations of the waveguide height, width, or both.
(461) In the illustrative examples, phase-matching can also be achieved in some nonlinear optical waveguides through a process called modal phase-matching. In this method of modal phase-matching, a combination of waveguide geometry optimization and higher-order modes of the light traveling and guided in a waveguide are utilized so that the phase-matching condition is satisfied, i.e., the wave-vector mismatch is equal to zero. Modal phase matching involves using a combination of higher-order-mode optical fields for some frequencies or wavelengths of the light and fundamental-mode optical fields for other frequencies or wavelengths of the light involved in the nonlinear optical process.
(462) Some illustrative examples have a combination of higher-order-mode optical fields for some frequencies or wavelengths of the light and fundamental-mode optical fields for other frequencies or wavelengths of the light involved in the nonlinear optical process. This combination can be selected to achieve a value for the wave-vector mismatch that achieves a desired value for the phase walk-off after a specific length or distance of nonlinear optical interaction. By using separate paths of different lengths of travel for light of different frequencies or wavelengths, the phase match can be reestablished on a periodic basis, even though there is wave-vector mismatch. This result can occur because the phase of an optical field is due to the product of the wave vector and the distance traveled by the optical field and because the phase is cyclic with a modulus of 2π radians.
(463) In an illustrative example, open-ended optical waveguide structures can operate with the enhancement of χ.sup.(2) and/or χ.sup.(3) non-linear optical (NLO) processes, such as spontaneous parametric down conversion (SPDC), second harmonic generation (SHG), and spontaneous four-wave mixing (SFWM). In particular, the structures described in this illustrative example spatially separate the optical fields involved in the nonlinear optical process to enable precise phase-matching of the relevant optical fields to be reestablished at multiple locations along the route for the light traveling in a nonlinear optical waveguide structure. An illustrative example can enhance targeted nonlinear optical processes by providing portions of the waveguide structure in which both the nonlinear optical process occurs, and the phases of the propagating optical fields change and providing other portions of the waveguide structure in which the nonlinear optical process does not occur but the phases of the propagating optical field change.
(464) In this example, wavelength-selective components are used. These wavelength selective components take the form of wavelength selective couplers that separate the optical fields involved in the nonlinear optical process into these different portions of the waveguide structure. With consideration of the phase shifts for the optical fields propagating in the different paths, this type of repeated re-establishment of phase matching can enhance the interaction distance over which the nonlinear optical process will continue to generate light of a second wavelength or frequency from

light of a first wavelength or frequency, thereby increasing the efficiency of the nonlinear optical generation.
(465) The nonlinear optical structure in these illustrative examples can be used multiple times in a single device, enabling even greater cumulative enhancement of the nonlinear optical process. In order to make the waveguide dimensions more practical or to increase the possible frequencies the optical fields can have, a higher-order wave-guided mode for one or more of the optical fields involved in the nonlinear optical interaction can be used. The optical waveguide structure also can provide an optional ability to actively tune the phase of the separated optical fields to achieve a phase-matched condition. Such tuning can be used to compensate for at least one of an error in fabrication of the optical waveguide structure, a departure of a frequency of the light from a design value, and a change in an environmental condition such as the temperature. The illustrative examples recognize and take into account that current techniques either do not spatially separate the optical fields to travel in different optical waveguides based on different wavelengths of the light or require the separated optical fields to propagate in one or more closed-loop resonators.
(466) In the illustrative examples, an optical waveguide structure comprises a nonlinear optical waveguide that is comprised of a set of segments. The optical waveguide structure also comprises a set of extension optical waveguides and a set of wavelength selective couplers. The set of wavelength selective couplers couples light between the nonlinear optical waveguide and the set of extension optical waveguides based on a wavelength of light.
(467) In one example, the nonlinear optical waveguide has three segments, a first segment, a second segment, and a third segment. In the first segment, all of the light are present and contribute to the positive enhancement of the nonlinear optical process. For example, light traveling in the first segment comprises a first wavelength light, a second wavelength light, and a third wavelength light. The second wavelength light, and the third wavelength light are produced by a nonlinear optical interaction of the first wavelength light in the first segment. The nonlinear optical waveguide also produces a second wavelength light and a third wavelength light by the nonlinear optical interaction of the first wavelength light in the second segment. The nonlinear optical waveguide also produces a second wavelength light and a third wavelength light by the nonlinear optical interaction of the first wavelength light in the third segment.
(468) A first wavelength selective coupler in the set of wavelength selective couplers couples the first wavelength light from a first ending point for the first segment to a second starting point for the second segment and couples the second wavelength light and the third wavelength light from the first ending point for the first segment to an extension starting point for a first extension optical waveguide in the set of extension optical waveguides. A second wavelength selective coupler in the set of wavelength selective couplers couples the second wavelength light and the third wavelength light from an extension ending point for the first extension optical waveguide to a third starting point for the third segment in the nonlinear optical waveguide.
(469) In the illustrative example, the first segment has a first length from a first starting point to the first ending point produces a first phase walk-off that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer of π radians for the nonlinear optical interaction in the first segment. The third segment has a third length from the third starting point to a third ending point that produces a third phase walk off that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer of π radians for the nonlinear optical interaction in the third segment.
(470) In this example, relative phase walk-off is the phase walk-off for all the components of light involved in the nonlinear optical process. Different components of light can have different wavelengths in these examples. The phase walk-off is defined with relation to the nonlinear optical process that occurs at two different locations or points in the nonlinear optical waveguide.
(471) The optical fields generated from the nonlinear optical process occurring in the third segment can build upon, and be enhanced by, the optical fields generated from the nonlinear optical process occurring in the first segment. The nonlinear optical interaction in one portion of a nonlinear optical waveguide can build upon the nonlinear optical interaction that occurs in all preceding portions of the nonlinear optical waveguide. Whether “building upon or enhancement” or a constructive contribution occurs, versus a “tearing down” or “destructive” contribution from the light generated in the preceding portions of the nonlinear optical waveguide occurs depends on the values for the phase walk-off obtained for the nonlinear optical interaction occurring in those different portions of the nonlinear optical waveguide.
(472) In this example, any optical fields generated from nonlinear optical processes occurring in the second segment can be removed to avoid reducing the enhancement. In this example, second wavelength light is removed when the phase walk-off obtained at the end of the second segment for the nonlinear optical interaction that occurs between the start point and end point of the second segment has a value of π radians (or an odd multiple of π radians).
(473) The nonlinear optical enhancement can continue to increase as these sets of two segments of the nonlinear optical waveguide, an extension optical waveguide and one or more wavelength selective couplers are repeated in an optical waveguide structure. For example, the first segment and the second segment of the nonlinear optical waveguide, the first extension optical waveguide, and the associated wavelength-selective couplers can form a set of optical structures that can be repeated. Similarly, the third segment, a fourth segment, a third extension optical waveguide in the set of extension optical waveguides, and associated wavelength-selective couplers can also form a set of optical structures that can be repeated. The third segment and fourth segment are essentially a repeat of the first segment and second segment when multiple sets of sub-structures are cascaded together to form the entire optical waveguide structure.
(474) In the illustrative examples, the first, second and third waveguides and associated wavelength-selective couplers can comprise a set of structures that can be repeated. Similarly, second, third and fourth waveguides and associated wavelength-selective couplers can also comprise a set of structure that can be repeated. In these examples, the first and fourth waveguides are essentially the same components when multiple sets of these structure are connected together to form a repeating pattern of structures.
(475) This illustrative embodiment can be an optical waveguide structure that uses at least one material that has a sufficiently large χ.sup.(2) and/or χ.sup.(3) nonlinear optical (NLO) susceptibility. The material selected can be processed into suitable waveguides in an optical waveguide structure with cross-sectional structures having geometries on the order of several microns or less. These geometries can be, for example, width and height.
(476) Light in these types of optical waveguides is able to undergo various nonlinear optical processes. Examples of χ.sup.(2) nonlinear optical processes include spontaneous parametric down conversion (SPDC), second harmonic generation (SHG), sum frequency generation, and difference frequency generation. Examples of χ.sup.(3) nonlinear optical processes include spontaneous four wave mixing (SFWM) and third harmonic generation (THG).
(477) In the illustrative examples, optical waveguide structures are used that enhance χ.sup.(2) nonlinear optical processes. Specifically, spontaneous parametric down conversion is used in an illustrative example, but these examples are not meant to exclude the principles of these examples from being applied to other χ.sup.(2) and χ.sup.(3) nonlinear optical processes.
(478) In an illustrative example, light can be described as comprising optical fields that travel or propagate in the optical waveguide structure. The optical fields are also referred to as wavelength light of different types. A pump optical field can be referred to as a pump light; a signal optical field can be referred to as a signal light; and an idler signal optical field can be referred to as an idler light.
(479) In nonlinear optical processes of spontaneous parametric down conversion, an input optical field, i.e., the pump, spontaneously decays or is converted into and thereby generates two other optical fields, i.e., the signal and idler. In such a process, energy is conserved, and momentum is conserved:
(480) $h\ _p = h\ _s + h\ _i$; (1) $\frac{{}_p n_p(\ _p)}{c} = \frac{{}_s n_s(\ _s)}{c} + \frac{{}_i n_i(\ _i)}{c}$
(481) In Equation 1 ω.sub.p, ω.sub.s, and ω.sub.i are the angular frequencies of the pump, signal, and idler optical fields, respectively. For a significant nonlinear optical generation of signal and idler light from pump light to occur, the phase walk-off of the nonlinear optical process involving the pump, signal and idler optical fields is also considered. Phase walk-off in a nonlinear optical process results from wave-vector

mismatch.

(482) For convenience, we will describe this phenomenon in terms of wave vectors. The wave vector, k, of an optical field is given by:

(483) $k = \frac{n(\ )}{c} = \frac{2\ n(\ )}{}$ (2)

where n(ω) is the refractive index of the material at the relevant angular frequency, or in the case of guided optical modes the effective index of that mode, c is the speed of light, and λ is the vacuum wavelength of the optical field. Thus, the wave-vector mismatch, Δk for nonlinear optical spontaneous parametric down conversion involving three optical fields—pump (p), signal (s) and idler (i)—can be described by:

(484) $k = \frac{{}_p n_p(\ {}_p)}{c} - \frac{{}_s n_s(\ {}_s)}{c} - \frac{{}_i n_i(\ {}_i)}{c}$ (3)

(485) The parameter Δk describes the relation between the optical fields at some instantaneous point in space and time. However, it is also useful to describe how the phases of the previously generated signal and idler optical fields relative to the phase of the pump field (and thus the phases of newly generated signal and idler optical fields) change as the optical fields propagate over some distance, L. The phase relation between the optical fields as those optical fields propagate can be described by a cumulative phase walk-off, Φ, which is given by:

$\Phi(l)=L\Delta k$ (4)

(486) The change in amplitude of the idler and signal optical fields at a particular location in an optical waveguide structure, in this example of spontaneous parametric down conversion, is given by:

(487) $\frac{dM_{i,s}}{dl} = \frac{2id_{eff}\ {}_{i,s}}{n_{i,s}c} M_p M_{s,i} \exp(i\ \ (l))$ (5)

(488) Where M.sub.i,s,p are the amplitudes of the idler, signal, and pump optical fields, respectively, and d.sub.eff is the effective nonlinear optical coefficient for particular polarizations of the optical fields traveling in a particular direction in a nonlinear optical material.

(489) From equation 5, the amplitude of signal and idler optical fields as the pump, signal and idler fields propagate from a point y.sub.1 to another point y.sub.2 is determined by:

(490) $M_{i,s}(y_2) = M_{i,s}(y_1) + \frac{2id_{33}\ {}_{i,s}}{n_{i,s}c} M_p M_{s,i} \int_{y_1}^{y_2} \exp(i\ \ ky)dy = M_{i,s}(y_1) + \frac{2id_{33}\ {}_{i,s}}{n_{i,s}c} M_p M_{s,i} L_{1,2}\left[\frac{-i\exp(i\ \ ky_2)}{kL_{1,2}} - \frac{-i\exp(i\ \ ky_1)}{kL_{1,2}}\right]$ (6)

(491) Where we make the slowly varying amplitude approximation. This approximation assumes that the conversion efficiency of the NLO process is relatively small, so that the terms M.sub.p and M.sub.s,i can be taken as constants. The parameter L.sub.1,2 the length of the route or routes traveled by the pump, signal, and idler light from point y.sub.1 to point y.sub.2. The pump light, signal light and idler light can propagate through different paths or routes between point y.sub.1 and point y.sub.2. In this example, the pump light signal and idler light can propagate through different paths or routes between point y.sub.1 and point y.sub.2.

(492) Thus, the idler and signal optical fields increase or decrease in amplitude according to the magnitude of the cumulative phase walk-off. For a given, non-zero phase mismatch the coherent interaction length of the nonlinear optical process, L.sub.coh, is defined as the distance for which the phase walk-off becomes equal to π:

(493) $L_{coh} = \frac{}{k}$ (7)

(494) If the spontaneous parametric down conversion process is assumed to begin at some point of origin and that the nonlinear optical coefficient in the direction of propagation is positive, then the amplitudes of the generated signal and idler optical fields increase as the value for the length or distance L.sub.1,2 increases and reach a maximum at a length L.sub.1,2=L.sub.coh, as pump light is converted to signal and idler light. Thus, the nonlinear optical interaction is considered constructive for generation of signal light and idler light from pump light.

(495) Beyond this length, and up to a distance of 2×L.sub.coh, the amplitudes of the signal and idler optical fields decrease, as the signal and idler light is converted back to pump light, and eventually reach 0 at a propagation distance of exactly 2×L.sub.coh. This conversion of light is a destructive nonlinear optical interaction in terms of generating signal light and idler light from pump light.

(496) Then, from a distance of 2×L.sub.coh up to 3×L.sub.coh the amplitudes of the signal and idler optical fields increase again. Thus, the nonlinear optical interaction is again constructive for generation of signal and idler light from pump light. As the amplitudes of the signal and idler optical fields decrease, the amplitude of the pump optical field increases, and vice versa.

(497) This process continues in a periodic fashion for as long as the optical fields remain in the nonlinear optical material. Without any phase-matching engineering, the amplitudes of the signal and idler optical fields can only reach a maximum value consistent with one coherent interaction length.

(498) In order to further enhance the amplitudes of the signal and idler optical fields resulting from the nonlinear optical interaction beyond the amplitudes obtained for a single L.sub.coh, the subsequent decrease in amplitude (after the optical fields travel one L.sub.coh) should be avoided entirely or at least minimized. However, if some of the signal and idler optical fields are present again at the beginning of the next cycle of increasing amplitude for idler and signal optical fields, then the cumulative amplitude of the signal and idler optical fields will continue to increase and a substantial nonlinear optical process will occur, beyond the maximum expected for a single L.sub.coh. In fact, the efficiency of the nonlinear optical process for converting pump light to signal and idler light increases as the amplitude of the signal and idler optical fields increase (assuming the decrease in the amplitude of the pump optical field relative to the value of the amplitude of the pump optical field is negligible). Typically, the signal amplitude for signal light or idler amplitude for idler light is much smaller than the pump amplitude. In this example, much smaller is at least one or two orders of magnitude smaller. For example, doubling the signal amplitude for signal light may result in only a 5 percent decrease in the pump amplitude pump light.

(499) Thus, it is desirable to have the nonlinear optical process occur over a distance that is many coherent interaction lengths. The key to our invention which enables this phenomenon is to use a strategy of wavelength selective separation of optical fields to propagate in different waveguides followed by subsequent wavelength selective combination of the optical field in order to (i) control the relative amplitude of each optical field in every successive nonlinear optical waveguide segment of length L.sub.coh and (ii) control the magnitude of the cumulative phase walk-off for the nonlinear optical process that occurs in each successive nonlinear optical waveguide segment.

(500) With reference now to the figures describing this illustrative example and in particular with reference to FIG. **28**, an illustration of a block diagram of an optical waveguide structure is depicted in accordance with an illustrative embodiment. In this illustrative example, optical waveguide structure **2800** comprises nonlinear optical waveguide **2809** which comprises multiple segments **2804** and in which at least two segments **2804** of nonlinear optical waveguide **2809** is comprised of nonlinear optical material **2897**. In this example, optical waveguide structure **2800** further comprises first extension optical waveguide **2841** of extension optical waveguides **2840**.

(501) As depicted in this example, nonlinear optical waveguide **2809** comprises first segment **2801**, second segment **2802**, and third segment **2803**. As further depicted in this example, extension optical waveguides **2840** comprises first extension optical waveguide **2841**. In this illustrative example, first segment **2801** and third segment **2803** are comprised of nonlinear optical material **2897**. First extension optical waveguide **2841** and second segment **2802** can also be comprised of nonlinear optical material **2897** but also can be comprised of a non-nonlinear optical material.

(502) In this illustrative example, first segment **2801** has first starting point **2871** and first ending point **2872**. Second optical waveguide has second starting point **2873** and second ending point **2874**. Third segment **2803** has third starting point **2875** and third ending point **2876**. First extension optical waveguide **2841** has extension starting point **2877** and extension ending point **2878**.

(503) Additionally, optical waveguide structure **2800** also includes wavelength selective couplers **2820** such as first wavelength selective coupler **2821** and second wavelength selective coupler **2822**. First wavelength selective coupler **2821** couples first ending point **2872** for first segment **2801**

to extension starting point **2877** for first extension optical waveguide **2841**. Second wavelength selective coupler **2822** couples extension ending point **2878** for first extension optical waveguide **2841** to third starting point **2875** for third segment **2803**.

(504) During operation of optical waveguide structure **2800**, light **2810** traveling in first segment **2801** comprises first wavelength light **2811**, second wavelength light **2813**, and third wavelength light **2815**. In this example, second wavelength light **2813** and third wavelength light **2815** are produced by nonlinear optical interaction **2898** of first wavelength light **2811** traveling within first segment **2801**.

(505) In one illustrative example, first wavelength light **2811** can be pump light **2812**. In this example, second wavelength light **2813** can be signal light **2814**, and third wavelength light **2815** can be idler light **2816**.

(506) As depicted, first wavelength selective coupler **2821** couples first wavelength light **2811** from first ending point **2872** for first segment **2801** to second starting point **2873** for second segment **2802**. First wavelength selective coupler **2821** also couples second wavelength light **2813** and third wavelength light **2815** from first ending point **2872** for first segment **2801** to extension starting point **2877** for first extension optical waveguide **2841**.

(507) Further, second wavelength selective coupler **2822** couples second wavelength light **2813** and third wavelength light **2815** from extension ending point **2878** for first extension optical waveguide **2841** to third starting point **2875** for third segment **2803**. Second wavelength selective coupler **2822** also couples first wavelength light **2811** from second ending point **2874** for second segment **2802** to third starting point **2875** for third segment **2803**.

(508) In this example, second segment **2802** comprises a nonlinear optical material, second wavelength light **2813** and third wavelength light **2815** can be generated in second segment **2802**. In this example, second wavelength light **2813** and third wavelength light **2815** are produced by nonlinear optical interaction **2898** of first wavelength light **2811** traveling within second segment **2802**. In this example, second wavelength light **2813** can be signal light **2814**, and third wavelength light **2815** can be idler light **2816**. In such cases, second wavelength selective coupler **2822** also couples second wavelength light **2813** and third wavelength light **2815** from second ending point **2874** for second segment **2802** away from third segment **2803**. Second wavelength light **2813** and third wavelength light **2815** generated in the second segment **2802** are not coupled by second wavelength selective coupler **2822** into the third segment **2803**. Second wavelength selective coupler **2822** also couples second wavelength light **2813** and third wavelength light **2815** from second ending point **2874** for second segment **2802** to exit port **2879**.

(509) In this example, optical waveguide structure **2800** can also comprise phase shifter **2860** located along extension optical waveguide **2841**. In this example, phase shifter **2860** applies activation **2895** to light **2810** in first extension optical waveguide **2841** that produces an extension phase walk-off that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer for nonlinear optical interaction **2898** that occurs from first starting point **2871** for first segment **2801** through first extension optical waveguide **2841** and through second segment **2802** to third starting point **2875** for third segment **2803**.

(510) In this example, the phase walk-off is evaluated at the start of the third segment. The signal light and idler light generated in the first segment travels through the first extension optical waveguide. The pump light from the first segment travels through the second segment. Pump, signal, and idler light all contribute to the phase walk-off in these examples.

(511) In yet another example, extension optical waveguides **2840** includes optical wavelength selective filter **2852**. Further, first extension optical waveguide **2841** in extension optical waveguides **2840** can take the form of a set of micro-rings **2854**.

(512) Turning now to FIG. **29**, an illustration of block diagram of geometries for optical waveguides is depicted in accordance with an illustrative embodiment. In this illustrative example, parts in nonlinear optical waveguide **2909** have geometries **2900**. Geometries **2900** comprises cross-sectional structures **2980** for segments **2804** in nonlinear optical waveguide **2909** and lengths **2930** between start points and end points defining the beginning and ending of segments **2804** in nonlinear optical waveguide **2809**.

(513) For example, first segment **2901** has first cross-sectional structure **2981** and first length **2931**, and second segment **2902** has second cross-sectional structure **2982** and second length **2932**. In this example, third segment **2903** has third cross-sectional structure **2983** and third length **2933**. First extension optical waveguide **2941** has extension cross-sectional structure **2984** and extension length **2934**.

(514) These geometries for nonlinear optical waveguide **2909** can be selected such that phase walk-offs **2990** for light **2910** traveling through nonlinear optical waveguide **2909** have values that provide a desired level for nonlinear optical interaction **2998**. These geometries can also be selected such that light generation **2919** occurs through nonlinear optical interaction **2998** that is constructive. Light **2910** can be, for example, first wavelength light **2911**, pump light **2912**, second wavelength light **2913**, signal light **2914**, third wavelength light **2915**, and idler light **2916**.

(515) For example, first segment **2901** has first length **2931** from first starting point **2871** to first ending point **2872** produces a first phase walk-off **2991** that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer of π radians for nonlinear optical interaction **2998** in first segment **2901** from first starting point **2871** to first ending point **2872**. In this example, the value for first phase walk-off **2991** is from 0 to π, 2π to 3π, 4π to 5π, and so on. Further, first segment **2901** has first cross-sectional structure **2981** from first starting point **2871** to first ending point **2872** produces a first phase walk-off **2991** that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer of π radians for nonlinear optical interaction **2998** in first segment **2901** from first starting point **2871** to first ending point **2872**. The length of each segment is selected to obtain the desired phase walk-off.

(516) In this example, first cross-sectional structure **2981** and first length **2931** from first starting point **2871** to first ending point **2872** produces first phase walk-off **2991** that results in light generation **2919** through nonlinear optical interaction **2998** that is constructive in first segment **2901**.

(517) As another example, second segment **2902** has second cross-sectional structure **2982** and second length **2932** from second starting point **2873** to second ending point **2874** that produces second phase walk-off **2992**. Second phase walk-off **2992** can be at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer of π radians for nonlinear optical interaction **2998** in first segment **2901** and second segment **2902** from first starting point **2871** to second ending point **2874**. This second phase walk-off results in light generation **2919** through nonlinear optical interaction **2998** that is constructive at the start of third segment **2903**. In this example, the geometry of second segment **2902** affects nonlinear optical interaction **2998** in second segment **2902** and in third segment **2903**.

(518) In another example, third segment **2903** has third cross-sectional structure **2983** and third length **2933** from third starting point **2875** to third ending point **2876** that produces third phase walk-off **2993** that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer of π radians for nonlinear optical interaction **2998** in third segment **2903** from third starting point **2875** to third ending point **2876**. The length of the third segment is selected to obtain the desired third phase walk-off. This third phase walk-off can result in light generation **2919** through nonlinear optical interaction **2998** that is constructive in third segment **2903**.

(519) In yet another example, first extension optical waveguide **2941** has extension cross-sectional structure **2984** with extension length **2934** from extension starting point **2877** to extension ending point **2878** that produces extension phase walk-off **2994** that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer of π radians for nonlinear optical interaction **2998** in first segment **2901** and third segment **2903**. Extension phase walk-off **2994** can result in light generation **2919** through nonlinear optical interaction **2998** that is constructive in third segment **2903**. The geometry of first extension optical waveguide **2941** affects nonlinear optical interaction **2998** in third segment **2903**. The length of the extension optical waveguide is selected to accomplish a desired nonlinear optical generation in segments in the nonlinear optical waveguide, which are separate from that extension optical waveguide.

(520) In yet another example, first extension optical waveguide **2941** has extension cross-sectional structure **2984** with extension length **2934** from extension starting point **2877** to extension ending point **2878** that produces extension phase walk-off **2994** that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer for nonlinear optical interaction **2998** that occurs from first starting point **2871** for first segment **2901** to third ending point **2876** for third segment **2903**. As another example, first extension optical waveguide

2841 has extension cross-sectional structure **2984** with extension length **2934** from extension starting point **2877** to extension ending point **2878** of first extension optical waveguide **2941** that produces extension phase walk-off **2994** that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer for nonlinear optical interaction **2998** that occurs from first starting point **2871** to first ending point **2872** for first segment **2901** and from third starting point **2875** to third ending point **2876** for third segment **2903**.
(521) Values for the length of the extension optical waveguide depends on the nonlinear optical interaction that occurs through both the entire first segment and the entire third segment. However, the value for the length of the extension optical waveguide can be selected to provide a selected phase walk-off for the nonlinear optical interaction that occurs through the length of the first segment and that resumes again at the start of the third segment but does not include the length of the third segment.
(522) As another example, first extension optical waveguide **2941** has extension cross-sectional structure **2984** with extension length **2934** from extension starting point **2877** to extension ending point **2878** of first extension optical waveguide **2941** that produces extension phase walk-off **2994** that is at least one of 0 radians or an even-numbered integer of π radians for nonlinear optical interaction **2998** that occurs from first starting point **2871** to first ending point **2872** for first segment **2901** involving pump, signal and idler light, propagation of pump light through first segment **2901**, and propagation of signal light and idler light through first extension optical waveguide **2941**. In another example, phase shifter **2860** is located in first extension optical waveguide **2941**. Phase shifter **2860** can apply activation **2895** to light **2910** propagating in first extension optical waveguide **2941** such that extension phase walk-off **2994** is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer for nonlinear optical interaction **2998** that occurs from first starting point **2871** for first segment **2901** to third ending point **2876** for third segment **2903**
(523) The optical waveguide structure depicted in FIGS. **28** and **29** can include nonlinear optical processes used in applications that require frequency conversion of an input optical field or optical fields, such that part or all of the output contains one or more optical field(s) whose frequency is different from the frequency of the input optical field(s). For example, nonlinear optical processes can be used to generate at least one of high purity single photons or entangled photon pairs. However, the efficiencies of current nonlinear optical processes are typically quite low, making enhancing nonlinear optical processes highly desirable.
(524) In one illustrative example, complicated, error-prone fabrication processes such as periodic poling or multi-etch steps (e.g., periodically grooved phase matching waveguides) are unnecessary to fabricate the optical waveguide structure. The illustrative example can use optical waveguides and components that are relatively straight-forward to fabricate and amenable to wafer-scale mass production. The illustrative examples do not need components which are inherently prone to significant optical losses, such as periodic modulations of at least one of the waveguide height or width.
(525) In another example, optional phase tuning elements, such as phase shifters, can be included in the optical waveguide structure to provide an ability to compensate for fabrication tolerances and errors. For example, at least one of fabrication tolerances or errors can limit the coherent interaction distance to less than 1 mm. Phase shifters can be used in various locations in the optical waveguide structure to compensate for at least one of these tolerances or errors. As a result, the distance for a cumulative coherent interaction can extend far beyond 1 mm.
(526) In some illustrative examples, the optical waveguide structure can operate at temperatures near room temperature all the way down to cryogenic temperatures. Phase shifters in some optical waveguide structures can provide activations in the form of heat, which might not be practical in certain applications, such as at cryogenic temperatures or when heat-sensitive components are nearby. In some optical waveguide structures that are intended to operate at cryogenic temperatures, phase shifters can provide activations in the form of an electric field or a stress that changes the effective index of a guided optical mode in an extension optical waveguide or a segment of a nonlinear optical waveguide.
(527) In another illustrative example, nonlinear optical enhancement does not occur in a resonator. For example, in a micro-ring resonator designed for spontaneous four wave mixing, the frequency of signal and idler must not only meet requirements for energy conservation but must also match a resonant mode of the micro-ring. Thus, engineering a resonator for specific, targeted nonlinear optical frequencies can be difficult with current techniques.
(528) In an illustrative example, a narrow bandwidth of output optical fields is enabled because over the many iterations or repeats of segments of nonlinear optical waveguide, extension optical waveguide and associated wavelength selective couplers, optical fields that are not at the target wavelength will develop an increasingly large phase walk-off and therefore the nonlinear optical process for frequencies outside the narrow bandwidth will not be enhanced.
(529) Also, the illustrative example, does not rely on any changes in the sign of the nonlinear optical coefficients in order to enhance the nonlinear optical process. For isotropic media, such as silicon, quasi-phase-matching approaches based on changing the sign of the nonlinear optical coefficient is not possible because the χ.sup.(3) nonlinear optical coefficients are equivalent in all directions. As a result, an additional feature in the illustrative example is compatibility with both χ.sup.(2) and χ.sup.(3) nonlinear optical processes. Thus, the illustrative example in FIGS. **28** and **29** provides a robust, efficient solution for the enhancement of nonlinear optical processes on a chip-scale platform.
(530) With reference next to FIG. **30**, an illustration of an optical waveguide structure using optical waveguides is depicted in accordance with an illustrative example. In this illustrative example, optical waveguide structure **3000** comprises nonlinear optical waveguide **3009**, first extension optical waveguide C.sub.1 **3041**, second extension optical waveguide C.sub.2 **3042**, first wavelength selective coupler B.sub.1 **3021**, second wavelength selective coupler E.sub.1 **3022**, third wavelength selective coupler B.sub.2 **3023**, and fourth wavelength selective coupler E.sub.2 **3024**.
(531) Nonlinear optical waveguide **3009** is comprised of segments. As depicted, nonlinear optical waveguide **3009** comprises first segment A.sub.1 **3001**, second segment D.sub.1 **3002**, third segment A.sub.2 **3003**, fourth segment D.sub.2 **3004**, and fifth segment A.sub.3 **3005**.
(532) In this illustrative example, optical waveguide structure **3000** and other components in optical waveguide structure **3000** are formed on a yz plane defined by z-axis **3093** and y-axis **3092** in which an x-axis **3091** is perpendicular to the plane. In an illustrative example, the nonlinear optical waveguides can be fabricated from a nonlinear optical material such as x-cut lithium niobate. In other examples, the nonlinear optical waveguides could be fabricated from other nonlinear optical materials such as z-cut lithium niobate, c-axis SiC, and aluminum nitride.
(533) With x-cut lithium niobate, these axes shown in FIG. **30** are crystal axes for x-cut lithium niobate that can be used to describe the propagation direction and polarization orientation of light in the optical waveguide structure **3000**. In the example of an optical waveguide structure fabricated in x-cut lithium niobate, x-axis **3091** of the structure corresponds to the x-axis of the lithium niobate crystal. The nonlinear optical waveguide segments, extension optical waveguides and wavelength selective couplers in optical waveguide structure **3000** are oriented along a yz plane of the lithium niobate crystal. For an input light, such as pump light **3012** with transverse electric (TE) polarization, propagation in the y direction enables the nonlinear optical process to utilize the nonlinear optical coefficient of lithium niobate in optical waveguide structure **3000** that has the greatest magnitude, namely, d.sub.33. Thus, an incremental change in the amplitudes of signal light **3014** and/or idler light **3016** that result from a second-order nonlinear optical interaction such as parametric down conversion (PDC), difference frequency generation (DFG) or sum frequency generation (SFG) occurring at a given point in the nonlinear optical waveguide can be described by:
(534) $\frac{\mathrm{dM}_s}{\mathrm{dy}} = \frac{2\mathrm{id}_{33}\ {}_s}{n_s c} M_p M_i \exp(i\ \ \mathrm{ky})$ (9) andby$\frac{\mathrm{dM}_i}{\mathrm{dy}} = \frac{2\mathrm{id}_{33}\ {}_i}{n_i c} M_p M_s \exp(i\ \ \mathrm{ky})$; orequivalently, $\frac{\mathrm{dM}_{i,s}}{\mathrm{dy}} = \frac{2\mathrm{id}_{33}\ {}_{i,s}}{n_{i,s} c} M_p M_{s,i} \exp(i\ \ \mathrm{ky})$
(535) These expressions illustrate that both the pump light and the idler light contribute to the generation of signal light by their nonlinear optical interaction with the nonlinear optical waveguide. Likewise, both the pump light and the signal light contribute to the generation of idler light by their nonlinear optical interaction with the nonlinear optical waveguide. As described in equations 9, the incremental change in the signal light resulting from the nonlinear optical interaction, and/or the incremental change in the idler light resulting from the nonlinear optical interaction, also depends on the match, Δky, between the phase of the previously generated light that has propagated to the given point in the nonlinear optical waveguide and

the phases of the contributing light at that point, which determine, as a result of momentum conservation, the phase of the light newly generated at that given point. The amplitude M.sub.s of signal light **3014** and/or the amplitude M.sub.i of idler light **3016** at point y.sub.2 that results from the nonlinear optical process that occurs in the optical waveguide structure from a point y.sub.1 to the point y.sub.2 can be described by:

(536) $M_s(y_2) = M_s(y_1) + \frac{2i\ \ _s}{c}\int_{y_1}^{y_2} \frac{d_{33}}{n_s} M_p M_i \exp(i\ \ ky)dy$, and $M_i(y_2) = M_i(y_1) + \frac{2i\ \ _i}{c}\int_{y_1}^{y_2} \frac{d_{33}}{n_i} M_p M_s \exp(i\ \ ky)dy$; or, equivalently,

$$M_{i,s}(y_2) = M_{i,s}(y_1) + \frac{2i\ \ _{i,s}}{c}\int_{y_1}^{y_2} \frac{d_{33}}{n_{i,s}} M_p M_{s,i} \exp(i\ \ ky)dy$$

(10)

(537) Where the slowly varying amplitude approximation is made. This approximation assumes that the conversion efficiency of the nonlinear optical process is relatively small, so that the terms M.sub.p and M.sub.s,i within the integral can be taken as constants for a given portion of the optical waveguide structure between points y.sub.1 and y.sub.2. Equation 10 illustrates that the amplitude of the generated signal light at point y.sub.2 depends on the amplitude of the signal light at point y.sub.1 and on the nonlinear optical interaction occurring between points y.sub.1 and y.sub.2. Likewise, the amplitude of the generated idler light at point y.sub.2 depends on the amplitude of the idler light at point y.sub.1 and on the nonlinear optical interaction occurring between points y.sub.1 and y.sub.2. For the special case of spontaneous parametric down conversion (SPDC), only pump light is supplied initially into the optical waveguide structure. Thus, the terms M.sub.s,i in the integral often can be described by expressions that include the photon energy of the signal or idler photon and a spectral bandwidth over which the spontaneously generated idler or signal photons are evaluated. The center frequency of the spectral bandwidth typically corresponds to a frequency at which phase matching (or momentum conservation) of the nonlinear optical process is achieved. In most cases of spontaneous parametric down conversion, once the amplitude of the electromagnetic wave of the generated light exceeds the amplitude associated with the spontaneous generation, additional generation of signal or idler light can be described by equation 10.

(538) As described in equation 10, for each portion of the optical waveguide structure in which nonlinear optical generation of idler and/or signal light is being considered, both nonlinear optical material must be present (i.e., d.sub.33 is non-zero) and pump light must be present (M.sub.p is non-zero) in order for nonlinear optical generation of idler light and/or signal light to occur. Furthermore, the phase walk-off affects the nonlinear optical generation, as described by the expression ∫.sub.y.sub.1.sup.y.sup.2exp(iΔky)dy.

(539) In one example, optical waveguide structure **3000** can be designed so that after each segment ‘A.sub.i’ in nonlinear optical waveguide **3009**, the amplitude of the optical fields of signal light and idler light reach a maximum value allowed by the phase walk-off. For a given nonlinear optical waveguide segment ‘A.sub.i’, the nonlinear optical generation process can be described by the expression

(540) 0 $M_{i,s}(y_2) = M_{i,s}(y_1) + \frac{2id_{33}\ \ _{i,s}}{n_{i,s}c} M_p M_{s,i} L_{A_i} [\frac{-i\exp(i\ \ ky_2)}{kL_{A_i}} - \frac{-i\exp(i\ \ ky_1)}{kL_{A_i}}]$ (11)

(541) Expression 11 is obtained by integrating expression 10 over the route taken by the light through segment ‘A.sub.i’. For this expression, point y.sub.1 is the starting point of segment ‘A.sub.i’ and point y.sub.2 is the ending point of segment. To achieve maximum generation of signal idler and/or idler light, the length L.sub.Ai of segments ‘A.sub.i’ satisfies the following equation:

L.sub.Ai*Δk*=*m*.sub.Aπ (12)

where m.sub.A is an odd, positive integer.

(542) For the example of optical waveguide structure **3000**, a wavelength-selective coupler separates at least one of the signal light and idler light from the others at the end of each of these segments ‘A.sub.i’ and routes the separated parts of the light into different waveguides of the optical waveguide structure **3000**. In the example illustrated in FIG. **30**, signal light **3014** and idler light **3016** are separated from the pump light **3012** by a wavelength-selective coupler ‘B.sub.i’ and are routed into extension waveguides ‘C.sub.i’. Also, the pump optical field is routed by wavelength-selective coupler ‘B.sub.i’ to continue into the subsequent nonlinear optical waveguide segment ‘D.sub.i’. Another wavelength-selective coupler ‘E.sub.i’ is used to recombine all of the optical fields, for pump, signal, and idler, back into another segment ‘A.sub.i+1’ of the nonlinear optical waveguide. In this example, a wavelength-selective coupler ‘E.sub.i’ is used to couple signal light **3014** and idler light **3016** from extension optical waveguide ‘C.sub.i’ into the starting point of segment ‘A.sub.i+1’, and also is used to couple the pump light **3012** from the ending point of segment ‘D.sub.i’ into the starting point of segment ‘A.sub.i+1’.

(543) To make the amplitude of the generated signal light **3014** and/or idler light **3016** continue to increase as efficiently as possible in both segments ‘A.sub.i’ and ‘A.sub.i+1’, the cumulative phase walk-off for the nonlinear optical interaction involving pump light **3012**, signal light **3014**, and idler light **3016** a point at the start of segment ‘A.sub.i’ to a point at the start of segment ‘A.sub.i+1’ should be an even multiple of π, or should be a multiple of 2π. Now, if the length of segment ‘A.sub.i’ is chosen such that the phase walk-off from the starting point of segment ‘A.sub.i’ to the ending point of the same segment ‘A.sub.i’ is and odd multiple of π, this constraint means the cumulative phase walk-off for pump light **3012**, signal light **3014** and idler light **3016** traversing the optical waveguide structure from the ending point of segment ‘A.sub.i’ to the starting point of segment ‘A.sub.i+1’ should be an odd multiple of π. The extension waveguides ‘C.sub.i’ are used to control the relative phase walk-off for the pump light **3012** that travels through segment ‘A.sub.i’, wavelength selective coupler ‘B.sub.i’, segment ‘D.sub.i’ and wavelength selective coupler ‘E.sub.i’ to the starting point of segment ‘A.sub.i+1’, and for the signal light **3014** and idler light **3016** that travel through the segment ‘A.sub.i’, wavelength selective coupler ‘B.sub.i’, extension optical waveguide ‘C.sub.i’ and wavelength selective coupler ‘E.sub.i’ to the starting point of segment ‘A.sub.i+1’. The extension optical waveguides ‘C.sub.i’ in optical waveguide structure **3000** are designed to achieve a value for this cumulative phase walk-off from the starting point of segment ‘A.sub.i’ to the starting point of segment ‘A.sub.i+1’ that is a multiple of 2π. Thus, the nonlinear optical process that occurs in successive segments ‘A.sub.i’ is always constructive. For example, being constructive can be when the amplitude of signal and idler optical fields continually increases. The design parameters for these extension optical waveguides are the length and the cross-sectional structure, which can be selected to achieve a desired value for the phase walk-off.

(544) Referring again to FIG. **30**, the amplitudes Ms of signal light **3014** and M.sub.i of idler light **3016** can be described for different points in optical waveguide structure **3000**. In nonlinear optical waveguide first segment A.sub.1 **3001** of optical waveguide structure **3000**, the amplitude of generated signal light **3014** and/or idler light **3016**, obtained by integrating Equation 10 over the distance travelled through first segment A.sub.1, is given by:

(545) $M_{i,s}(A_1) = \frac{2id_{33}\ \ _{i,s}}{n_{i,s}c} M_p M_{s,i} \int_0^{L_{A1}} \exp(i\ \ ky)dy = \frac{2id_{33}\ \ _{i,s}}{n_{i,s}c} M_p M_{s,i} L_{A1} [\frac{\exp(i\ \ kL_{A1}) - 1}{kL_{A_i}}]$ (13)

(546) For nonlinear optical waveguide first segment A.sub.1 **3001**, pump light **3012** as well as signal light **3014** and/or idler light **3016** are present through the entire length of segment A.sub.1. Nonlinear optical material as described by nonlinear optical coefficient d.sub.33 also is present through the entire length of segment A.sub.1. The length L.sub.A1 is the distance along first segment A.sub.1 between its starting point and its ending point. The intensity P.sub.s of the generated signal light **3014** and/or the intensity P.sub.i of the generated idler light at the end of segment A.sub.1 can be described by:

(547)

$P_{i,s}(A_1) = 2n_{i,s}\ \ _0 c$ .Math. $\frac{2id_{33}\ \ _{i,s}}{n_{i,s}c}$ .Math. ^{2} .Math. M_p .Math. ^{2} .Math. $M_{s,i}$ .Math. $^2 L_{A1}{}^2$ .Math. $(\frac{\exp(i\ \ kL_{A1}) - 1}{i\ \ kL_{A1}})$ .Math. ^{2} $= 4n_{i,s}\ \ _0 c$ .Math. $\frac{2id_{33}\ \ _{i,s}}{n_{i,s}c}$ .M

(548) In this expression, the intensity of the signal or idler wave is given by the magnitude of its time averaged Poynting vector. The phase walk-off ΔkL.sub.A1 of the nonlinear optical interaction between the starting point of segment A.sub.1 and the ending point of segment A.sub.1 affects this generation of the signal light and/or idler light in segment A.sub.1. The wave-vector mismatch Δk for the light in an optical waveguide can be

described for the case of parametric down conversion or difference frequency generation from pump light to signal light and/or idler light by:

(549) $k = \frac{1}{c}(\ _{p}n_{p} - \ _{s}n_{s} - \ _{i}n_{i})$ (15)

(550) The parameters n.sub.p, n.sub.s and n.sub.i are the effective refractive indices for the pump light, signal light and idler light, respectively, traveling in that optical waveguide. The cross-sectional structure of the optical waveguide can be designed to achieve specific values for the effective refractive indices. Examples of design parameters associated with the cross-sectional structure of an optical waveguide include the width and height of the core region, the refractive index of the material comprising the core region, the refractive index of the material comprising the cladding region, the relative placement of the core region and the cladding region, and the height of the cladding region. In this case, the optical waveguide is first segment A.sub.1.

(551) In one example, first segment A.sub.1 **3001** of nonlinear optical waveguide **3009** is designed to have a length, L.sub.A1, and a cross-sectional structure, which affect Δk, that results in a cumulative phase walk-off that is an odd multiple of π. In other words,

L.sub.A1*Δk*=*m*.sub.Aπ (16)

with m.sub.A being any odd, positive integer. When this condition is met, the intensity of the generated signal light and/or idler light is the maximum value consistent with the non-zero wave-vector mismatch Δk. In another example, first segment A.sub.1 **3001** of nonlinear optical waveguide **3009** is designed to have a length, L.sub.A1, and a cross-sectional structure, which affect Δk, that results in a cumulative phase walk-off that does not exceed π. In other words,

0≤*L*.sub.A1*Δk*≤*π* (17)

(552) When this condition is met, the nonlinear optical interaction in the first segment A.sub.1 remains constructive for the generation of signal light and/or idler light.

(553) Turning next to FIG. **31**, an illustration of a graph of the amplitude of the idler light in an optical waveguide structure is depicted in accordance with an illustrative embodiment. As depicted, graph **3100** has x-axis **3112** for distance propagated as the repeated unit of the structure. Graph **3100** also has y-axis **3114** that indicates the relative intensity of idler light. Such idler light could be generated, for example, by second order nonlinear optical processes such as parametric down conversion or difference frequency generation and by spontaneous parametric down conversion. In this illustrative example, graph **3100** comprises lines that indicate the intensity of idler light in the different portions of an optical waveguide structure. In this depicted example, the optical waveguide structure has a configuration with a nonlinear optical waveguide that includes segment A.sub.1, segment D.sub.1, segment A.sub.2, segment D.sub.2, segment A.sub.3, segment D.sub.3, segment A.sub.4, segment D.sub.4, and segment A.sub.5. The optical waveguide structure also has four extension optical waveguides C.sub.1, C.sub.2, C.sub.3 and C.sub.4.

(554) In the optical waveguide structure represented by graph **3100**, the generation of idler light is significant only in segments ‘A.sub.i’ and ‘D.sub.i’ since pump light is present only in those segments of nonlinear optical waveguide and is not present in the extension optical waveguides. In this example, the distance is normalized to the length of one repeat unit of optical waveguide structure **3000**, such as L.sub.Ai+L.sub.Di. As depicted, line **3121** represents light in first segment A.sub.1; line **3122** to represents light in second segment D.sub.1, line **3123** represents light in third segment A.sub.2; line **3124** represents light in fourth segment D.sub.2; line **3125** represents light in fifth segment A.sub.3; line **3126** represents light in sixth segment D.sub.3; line **3127** represents light in seventh segment A.sub.4; line **3128** represents light in eighth segment D.sub.4; and line **3129** represents light in ninth segment A.sub.5. As depicted, line **3141** represents idler light in first extension optical waveguide C.sub.1; line **3142** to represents idler light in second extension optical waveguide C.sub.2; line **3143** represents idler light in third extension optical waveguide C.sub.3; line **3144** represents idler light in fourth extension optical waveguide C.sub.4. Line **3120**, which includes line **3121**, line **3141**, line **3123**, line **3142**, line **3125**, line **3143**, line **3127**, line **3144**, and line **3129**, represents the intensity of idler light that receives an enhanced nonlinear optical generation when the wavelength selective couplers couple the light generated in segments ‘A.sub.i’ to and from the extension optical waveguides ‘C.sub.i’ and when the condition for phase walk-off is met to achieve a constructive interaction of the idler light generation in the multiple segments ‘A.sub.i’. Line **3130** represents the intensity of idler light that would be present in the segments of nonlinear optical waveguide if the wavelength selective couplers did not couple any of the idler light and signal light between the segments of nonlinear optical waveguide and the extension optical waveguides and all of the idler light and signal light remained in the segments of nonlinear optical waveguide.

(555) In graph **3100**, the intensity values of the idler light were calculated using expressions for the nonlinear optical process described herein and a model of the optical waveguide structure **3000** in FIG. **30**. Some of the parameters and values for this model are speed of light=299792458 m/s, d.sub.33=31.5 pm/V, pump light wavelength=655 nm, n.sub.p=2.0, signal light wavelength=1130 nm, n.sub.s=1.8, idler light wavelength=1558 nm, n.sub.i=1.6, M.sub.p=1, M.sub.i=1, M.sub.s=1, η.sub.p=η.sub.s=η.sub.i=0.99, m.sub.A=1, m.sub.C=1, and m.sub.D=1.

(556) The nonlinear optical generation of idler light from pump light and signal light through a process such as parametric down conversion or difference frequency generation would result in an intensity of the generated idler optical field that increases as the square of the length of the distance propagated in a nonlinear optical waveguide if the wave-vectors are always matched to the momentum conservation condition, which means Δk=0. This is the condition commonly referred to as that of perfect phase matching. However, when perfect phase matching is not achieved, and Δk≠0, the intensity of the idler optical field will vary in an oscillatory manner with increasing distance propagated and the idler intensity does not exceed a maximum value, as illustrated by line **3130** and as described by equations 11 and 14. When the intensity of the idler field increases, the nonlinear optical interaction is considered to be constructive for the generation of idler light from pump light. When the intensity of the idler field decreases, the nonlinear optical interaction is considered to be destructive for the generation of idler light from pump light. For the example of optical waveguide structure **3000**, the length of first segment A.sub.1 can be selected such that distance propagated is sufficiently short to ensure the nonlinear optical interaction remains constructive for the generation of idler light, as illustrated by line **3121**.

(557) At the end of first segment A.sub.1, a wavelength selective coupler B.sub.1 removes the idler light that was generated in segment A.sub.1 and couples that idler light as well as signal light, but not pump light, into extension optical waveguide C.sub.1. This wavelength selective coupler B.sub.1 also couples the pump light, but not idler light or signal light, from first segment A.sub.1 into second segment D.sub.1. Since no pump light is coupled into extension optical waveguide C.sub.1, there is no generation of idler light in that extension optical waveguide. With respect to signal light **3014** and idler light **3016** that is coupled into extension optical waveguide C.sub.1, there is no additional increase in the intensity of that signal light and idler light while they propagate in extension optical waveguide C.sub.1, as illustrated by line **3141**, since essentially no pump light is present. There could be some generation of idler light in second segment D.sub.1 of nonlinear optical waveguide since pump light is present in that segment. However, since the previously generated idler light is removed before the starting point of second segment D.sub.1, the intensity of the idler light must again grow from a value of zero, as illustrated by line **3122**.

(558) Thus, in second segment D.sub.1, the amplitude of signal light **3014** and idler light **3016** can be described by:

(559)

$$M_{i,s}(D_1) = (1 - \ _{i,s})M_{i,s}(A_1) + \frac{2id_{33}\ _{i,s}}{n_{i,s}c}\ _{p}M_p(1 - \ _{i,s})M_{s,i}\int_{B_1}^{E_1}\exp(i(\ _{A1} + \ ky))dy = (1 - \ _{i,s})M_{i,s}(A_1) + \frac{2id_{33}\ _{i,s}}{n_{i,s}c}\ _{p}M_p(1 - \ _{i,s})M_{s,i}(\frac{-i\times\exp(i\ k(L_{A1}$$

where the integral is taken only over segment ‘D.sub.1’ which starts at its junction with wavelength selective coupler B.sub.1 and ends at its junction with wavelength selective coupler E.sub.1. Because it is unlikely under actual operating and fabrication conditions that the wavelength-selective couplers are able to completely remove signal light **3014** and idler light **3016**, the factors η.sub.p,s,i are included. The factors η.sub.s,i account for the percent of the signal optical field or idler optical field that is coupled into extension optical waveguide ‘C.sub.i’ by wavelength selective coupler ‘B.sub.i’, which we also take to be the percent of signal optical field or idler optical field that is coupled from extension optical waveguide ‘C.sub.i’ into another segment of nonlinear optical waveguide by wavelength selective coupler ‘E.sub.i’. The factor η.sub.p accounts for the percent of the

pump optical field that is coupled from a segment such as segment 'A.sub.i' into a subsequent segment such as segment 'D.sub.i'.
(560) In the illustrative example, signal light **3014** and/or idler light **3016** generated in second segment D.sub.1 and in other segments 'D.sub.i' are coupled by a wavelength selective coupler E.sub.1 and other couplers 'E.sub.i' away from the subsequent segments 'A.sub.i+1'. Thus, signal light **3014** and/or idler light **3016** generated in segments 'D.sub.i' do not impact the signal and idler fields generated in segments 'A.sub.i+1'. Instead, the generation of signal light and/or idler light in a segment 'A.sub.i+1' is affected only by the signal light and/or idler light generated in the preceding segments 'A.sub.i', 'A.sub.i−1', 'A.sub.i−2', ...
(561) Turning again to FIG. **30**, consider an example of difference frequency generation in which idler light is generated in optical waveguide structure **3000** from pump light and signal light that is supplied to optical waveguide structure **3000** at a starting point in first segment A.sub.1 **3001** of the nonlinear optical waveguide **3009**. Specifically, signal light **3014**, supplied to segment A.sub.1 and idler light **3016** generated in segment A.sub.1 will traverse through first segment A.sub.1 **3001** then be coupled by first wavelength selective coupler B.sub.1 **3021** into first extension optical waveguide C.sub.1 **3041**, and travel through extension waveguide C.sub.1 **3041** and then be coupled by second wavelength selective coupler E.sub.1 **3022** into a starting point of third segment A.sub.2 **3002**. Meanwhile, the pump light **3012** supplied to segment A.sub.1 **3001** will traverse through segment A.sub.1 **3001** and be coupled by wavelength selective coupler B.sub.1 **3021** into second segment D.sub.1 **3002**; travel through second segment D.sub.1 and be coupled by wavelength selective coupler E.sub.1 **3022** in the starting point of third segment A.sub.2 **3002**. Signal light **3014** and idler light **3016** are recombined with pump light **3012** at the starting point of third segment A.sub.2. Segment A.sub.1, coupler B.sub.1, segment D.sub.1 and extension waveguide C.sub.1, and coupler E.sub.1 to the starting point of subsequent segment A.sub.2 can together be considered as comprising a basic cell of optical waveguide structure **3000**. This basic cell can be repeated multiple times to construct the overall optical waveguide structure.
(562) For the amplitude of signal light **3014** and idler light **3016** to continue to increase in second segment A.sub.2 **3003**, the cumulative phase walk-off for nonlinear optical interaction of pump light **3012**, signal light **3014** and idler light **3016** from the starting point of segment A.sub.1 to the starting point of segment A.sub.2 should be an even multiple of π. This condition on the cumulative phase walk-off ensures that the relative phase difference between the signal light and/or idler light generated at the start of third segment A.sub.2 and the signal light and/or idler light generated at the start of first segment A.sub.1 is zero, since phase has a modulus of 2π. Thus, the nonlinear optical generation that occurs in third segment A.sub.2 **3003** can be constructive and build upon the nonlinear optical generation that occurs in first segment A.sub.1 **3001**. The pump light **3012** traverses a different route to the starting point of segment A.sub.2 than the route traversed by the signal light **3014** and idler light **3016**. The cumulative phase walk-off between the pump light **3012**, signal light **3014** and idler light **3016** from the starting point of first segment A.sub.1 to the starting point of third segment A.sub.2 is thus given by:
Φ.sub.A2,start=(*k*.sub.p−*k*.sub.i−*k*.sub.s)*L*.sub.A1+*k*.sub.p*L*.sub.D1−*k*.sub.i,C*L*.sub.C1−*k*.sub.s,C*L*.sub.C1 (19)
(563) The pump light **3012**, signal light **3014** and idler light **3016** all travel through first segment 'A.sub.1' from its starting point to its ending point. Pump light **3012** then travels through second segment 'D.sub.1' whereas signal light **3014** and idler light **3016** travel through extension optical waveguide 'C.sub.1'. The wave vectors k.sub.i,C and k.sub.s,C are used to reflect the fact that the effective index of signal light **3014** and idler light **3016** in an extension optical waveguide 'C.sub.i' may not be the same as their effective index in segments 'A.sub.i' and 'D.sub.i' of the nonlinear optical waveguide **3009**. For simplicity, and without loss of generality, the model assumes that the effective indices for pump light **3012**, signal light **3014** and idler light **3016** in different segments 'A.sub.i' and 'D.sub.i' of nonlinear optical waveguide **3009** are identical so that the wave-vectors in the segments 'A.sub.i' and 'D.sub.i' can be described by k.sub.p, k.sub.s and k.sub.i.
(564) The nonlinear optical process can generate more signal light and/or idler light in third segment A2 if a proper phase walk-off is achieved. The amplitude of signal light **3014** and idler light **3016** in segment A.sub.2 **3003** can be described by:
(565)

$$M_{i,s}(A_2) = M_{i,s}(A_{2,\text{start}}) + \frac{2\mathrm{id}_{33}\ {}_{i,s}}{n_{i,s}c}\ {}_p\ {}_p M_p\ {}_{s,i}\ {}_{s,i} M_{s,i} \int_{E_1}^{B_2} \exp(i(\ {}_{A2,\text{start}} +\ ky))dy = M_{i,s}(A_{2,\text{start}}) + \frac{2\mathrm{id}_{33}\ {}_{i,s}}{n_{i,s}c}\ {}_p\ {}_p M_p\ {}_{s,i}\ {}_{s,i} M_{s,i}(\frac{-i \times \exp(i\ {}_{A2,\text{start}} +}{}$$

$${}_{A2,\text{start}} = (k_p - k_i - k_s)L_{A1} + k_p L_{D1} - k_{i,C}L_{C1} - k_{s,C}L_{C1} = m_C 2 \qquad (21)$$

It is desirable for the phase walk-off at the starting point of segment A.sub.2 to be reset to zero (modulo 2π) as discussed above. Thus,
Φ.sub.A2,start=(*k*.sub.p−*k*.sub.i−*k*.sub.s)*L*.sub.A1+*k*.sub.p*L*.sub.D1−*k*.sub.i,C*L*.sub.C1−*k*.sub.s,C*L*.sub.C1=*m*.sub.C2π (21)
(566) where m.sub.C is any positive integer. The length of extension optical waveguide C.sub.1 is therefore given by the following equation:
(567) $L_{C1} = \frac{(k_p - k_i - k_s)L_{A1} + k_p L_{D1} - m_C 2}{k_{i,C} + k_{s,C}}$ (22)
(568) From here similar equations can be produced to describe the increase in amplitude of signal light **3014** and idler light **3016** for many iterations of the basic cell in optical waveguide structure **3000**.
(569) Turning again to FIG. **31**, graph **3100** illustrates the greater intensity of generated idler light that can be achieved when the condition described in equation 21 is met for the phase walk-off obtained in the segment A.sub.2 **3002** in the nonlinear optical waveguide. Equation 21 describes constraints on the phase walk-off at the starting point of third segment A.sub.2 **3002**, which can be set by adjusting the length L.sub.C1 of the extension optical waveguide C.sub.1 and/or the length L.sub.D1 of the second segment D.sub.1, and by adjusting the cross-sections of those portions of optical waveguide structure **3000** in order to obtain desired values for the wave-vectors for the pump, signal and idler light traveling in those portions. When the condition for phase walk-off is met, the nonlinear optical generation of idler light in segment A.sub.2 is constructive with the nonlinear optical generation of idler light in segment A.sub.1. Thus, the intensity of the idler light in segment A.sub.2 can continue to increase, as illustrated by line **3123** in FIG. **31**. If the constraint of equation 21 also is met for additional iterations of the basic cell, such as by properly selecting the lengths and cross-sectional structures of the segments 'D.sub.i' and the lengths and cross-sectional structures of the extension optical waveguides 'C.sub.i', even more idler light can be generated and the intensity of the idler can be greater and greater for successive iterations of the basic cell, as illustrated by line **3125**, line **3127**, and line **3129** in FIG. **31**.
(570) In optical waveguide structure **3000** in FIG. **30**, the wavelength selective couplers 'B.sub.i' and 'E.sub.i' can be implemented using at least one of a directional coupler, a Mach-Zehnder interferometer, a multi-mode interference coupler, a micro-ring add coupler, a micro-ring drop coupler, or some other suitable optical coupler that can couple one set of wavelengths of light from a first waveguide to a second waveguide while coupling another set of wavelength of light from the first waveguide to a third waveguide instead of to the second waveguide.
(571) In optical waveguide structure **3000**, a type of coupler such as the types listed above can be selected to implement a wavelength selective coupler 'E.sub.i' that can transfers pump light **3012** from segment 'D.sub.i' to segment 'A.sub.i+1' and signal light **3014** and idler light **3016** from extension optical waveguide 'C.sub.i' to segment 'A.sub.i+1'. Further, the same type of coupler or a different type of coupler can be selected to implement a wavelength selective coupler 'B.sub.i' that can transfer pump light **3012** from segment 'A.sub.i' to segment 'D.sub.i' and signal light **3014** and idler light **3016** from segment 'A.sub.i' to extension optical waveguide 'C.sub.i'. The coupling will occur over some distance and may induce a phase shift of its own. These effects can be included in the model without loss of generality but were omitted for simplicity.
(572) In another illustrative example, the effective refractive indices of the pump light, signal light and idler light, which determine the wave-vector mismatch, such as Δk=k.sub.p−k.sub.s-k.sub.i relevant for parametric down conversion and difference frequency generation, can be modified by changing the cross-sectional geometry of the nonlinear optical waveguide. The wave-vector mismatch also can be modified by changing the shape and arrangement of the cladding material that surrounds the core region of the main nonlinear optical waveguide, which are segment 'A.sub.i' and segment 'D.sub.i' in nonlinear optical waveguide **3009**. For example, when viewed at a cross-section through nonlinear optical waveguide **3009**, the

core region comprises a material that has an appreciable second or third order nonlinear optical coefficient. However, the cladding that surrounds the core region comprises a material that has a lower refractive index than the refractive index of the material comprising the core region. For the waveguides of this invention, the material of the cladding does not have an appreciable second or third order nonlinear optical coefficient. In another example, the cross-sectional geometry of the nonlinear optical waveguide can be selected to involve a higher-order transverse mode of the pump light in the nonlinear optical waveguide involved in the nonlinear optical process. Use of a higher-order transverse mode for the pump light could be beneficial when the wavelength of the pump light is very different from the wavelengths of the signal light and the idler light.
(573) In some illustrative examples, the cladding can comprise multiple regions of two different materials having different refractive index. By adjusting the dimensions and locations of these multiple regions of the cladding, the dispersion of the waveguide can be configured to decrease the wave-vector mismatch when such a cladding induces a greater change in effective index for the optical fields of some frequencies of light (such as for the idler light) than for the optical fields of other frequencies of light (such as for the pump light or signal light). In some illustrative examples, the higher index cladding portion covers the two sides of the core region but does not cover the top or bottom of the core region. In other illustrative examples, the higher index cladding portion covers only the bottom and top of the core region but not the two sides. In yet other examples, the higher index cladding portion is displaced from the core region, with a lower index cladding portion immediately adjacent to the core region.
(574) In some illustrative examples, an optical waveguide structure has an outline whose shape or aspect ratio is more like a square than like a long rectangle. In this type of implementation, two or more nonlinear optical waveguides can be connected by an optical waveguide.
(575) With reference to FIG. **32**, an illustration of an optical waveguide structure having two sets of nonlinear optical waveguides and extension optical waveguides connected by an optical waveguide is depicted in accordance with an illustrative embodiment.
(576) As depicted, optical waveguide structure **3200** comprises nonlinear optical waveguide **3280** with first portion **3281** and second portion **3282**, first extension optical waveguide C.sub.1 **3241**, second extension optical waveguide C.sub.2 **3242**, first wavelength selective coupler **3221**, second wavelength selective coupler **3222**, third wavelength selective coupler **3223**, fourth wavelength selective coupler **3224**. Optical waveguide structure also comprises third extension optical waveguide C.sub.3 **3243**, fourth extension optical waveguide C.sub.4 **3244**, fifth wavelength selective coupler **3225**, sixth wavelength selective coupler **3226**, seventh wavelength selective coupler **3227**, and eight wavelength selective coupler **3228**.
(577) In this illustrative example, first portion **3281** of nonlinear optical waveguide **3280** comprises first segment A.sub.1 **3201**, second segment D.sub.1 **3202**, third segment A.sub.2 **3203**, and fourth segment D.sub.2 **3204**. Idler light **3216** is generated by the nonlinear optical process in first segment A.sub.1. First wavelength selective coupler B.sub.1 **3221** couples generated idler light **3216** and signal light **3214** from first segment A.sub.1 into extension optical waveguide **3241** and couples pump light **3212** from first segment A.sub.1 into second segment D.sub.1 **3202**. Second wavelength selective coupler E.sub.1 **3222** couples idler light **3216** and signal light **3214** from extension optical waveguide **3241** into third segment A.sub.2 **3203** and also couples pump light **3212** from second segment D.sub.1 into third segment A.sub.2 **3203**. The coupling of pump light **3212**, signal light **3214**, and idler light **3216** continues through optical waveguide structure **3200** using wavelength selective couplers and extension optical waveguides from third segment A.sub.2 **3203** to ninth segment A.sub.5 **3219** as depicted in FIG. **32**.
(578) Some practical implementations of first wavelength selective coupler B.sub.1 **3221** may allow some pump light **3212** to also couple into extension optical waveguide **3241**. Extension optical waveguide **3241** has an optical filter that removes pump light **3212** and allows only idler light **3216** and signal light **3214** to reach wavelength selective coupler E.sub.1 **3222** and be coupled by coupler E.sub.1 into third segment A.sub.2 **3203**.
(579) Second portion **3282** of nonlinear optical waveguide **3280** comprises fifth segment A.sub.3 **3205**, sixth segment D.sub.3 **3206**, seventh segment A.sub.4 **3207**, and eight segment D.sub.4 **3208**, and ninth segment A.sub.5 **3219**.
(580) As depicted, optical waveguide **3260** connects fourth segment D.sub.2 **3204** in first portion **3281** to fifth segment A.sub.3 **3205** in second portion **3282**. In this illustrative example, optical waveguide **3260** is configured with a material and dimensions such that the nonlinear optical process does not occur. The configuration of optical waveguide **3260** is such that light is propagated with high fidelity. For example, light is propagated without undesired optical losses.
(581) In this illustrative example, optical waveguide structure **3200** and other components in optical waveguide structure **3200** are formed on a yz plane defined by z-axis **3293** and y-axis **3292** in which an x-axis **3291** is perpendicular to the plane. In this illustrative example, first portion **3281** and second portion **3282** begin at some −y position on y-axis **3292** of the substrate, end at some position in the +y direction on y-axis **3292**, and are offset from each other by some distance relative to z-axis **3293**
(582) In this illustrative example, the length of a connecting optical waveguide **3260** can be selected to reset the phase walk-off such that the nonlinear optical process is efficiently enhanced in the subsequent ‘A.sub.i’ segments in second portion **3282**.
(583) When optical waveguide structure **3200** is fabricated in nonlinear optical material such as z-cut lithium niobate, the light with transverse magnetic (TM) polarization experiences the largest nonlinear optical coefficient, such as, d.sub.33. Because the nonlinear optical coefficient does not change with waveguide orientation, direction, both orientation and direction, segments ‘A.sub.i’ and segments ‘D.sub.i’ do not have to be aligned with a particular crystallographic direction or even to maintain that direction over multiple iterations of the waveguide sections to achieve the maximum nonlinear optical enhancement. This selection of materials for optical waveguide structure **3200** provides increased flexibility in the design of waveguides and can be used to reduce the overall device footprint of optical waveguide structure **3200**.
(584) In some illustrative examples, the aspect ratio for the optical waveguide structure can be shaped more like a square than like a long rectangle. Additionally, in some illustrative examples, multiple segments such as ‘A.sub.i’ and ‘A.sub.i+1’ could be displaced or offset laterally from each other.
(585) With reference now to FIG. **33**, an illustration of an optical waveguide structure with square-shaped aspect ratio obtained by having extension optical waveguides and segments displaced or offset laterally is depicted in accordance with an illustrative embodiment.
(586) As depicted, optical waveguide structure **3300** comprises nonlinear optical waveguide **3309**, first extension optical waveguide C.sub.1 **3341**, second extension optical waveguide C.sub.2 **3342**, third extension optical waveguide C.sub.3 **3343**, first wavelength selective coupler **3321**, second wavelength selective coupler **3322**, third wavelength selective coupler **3323**, fourth wavelength selective coupler **3324**, fifth wavelength selective coupler **3325**, six wavelength selective coupler **3326**, seventh wavelength selective coupler **3327**, input coupler **3332**, input waveguide **3372**, output waveguide **3374**, first pump removing filter **3361**, second pump removing filter **3362**, signal/idler removing filter **3368**, third pump removing filter **3363**, and fourth pump removing filter **3364**.
(587) In this illustrative example, nonlinear optical waveguide **3309** comprises segments. As depicted, the segments are first segment A.sub.1 **3301**, second segment D.sub.1 **3302**, third segment A.sub.2 **3303**, fourth segment D.sub.2 **3304**, fifth segment A.sub.3 **3305**, sixth segment D.sub.3 **3306**, seventh segment A.sub.4 **3307**, and eighth segment D.sub.4 **3308**. In this example, first wavelength selective coupler **3321**, second wavelength selective coupler **3322**, third wavelength selective coupler **3323**, fourth wavelength selective coupler **3324**, fifth wavelength selective coupler **3325** and sixth wavelength selective coupler **3326** couple idler light **3316** between segments of the nonlinear optical waveguide **3309** and extension optical waveguide **3341**, extension optical waveguide **3342**, and extension optical waveguide **3343**. The same wavelength selective couplers couple pump light **3312** and signal between a segment of the nonlinear optical waveguide and a succeeding segment of the nonlinear optical waveguide, such as between first segment **3301** and second segment **3302** and between second segment **3302** and third segment **3303**.
(588) In this illustrative example, optical waveguide structure **3300** and other components in optical waveguide structure **3300** are formed on a yz plane defined by z-axis **3393** and y-axis **3392** in which an x-axis **3391** is perpendicular to the plane.
(589) In this depicted example, third segment A.sub.2 **3303** and fifth segment A.sub.3 **3305** are not co-linear. Instead, these two segments are offset laterally from each other. Further, second extension optical waveguide C.sub.2 **3342** and fourth segment D.sub.2 **3304** have bends and a “switchback” configuration that provide connection between third segment A.sub.2 **3303** and fifth segment A.sub.3 **3305** through third wavelength

selective coupler B.sub.2 **3323** and through fourth wavelength selective coupler E.sub.2 **3324**. In this example, third wavelength selective coupler B.sub.2 couples idler light **3316** from third segment A.sub.2 **3303** into second extension optical waveguide C.sub.2 **3342** and also couples pump light **3312** and signal light **3314** from third segment A.sub.2 **3303** into fourth segment D.sub.2 **3304**. Fourth wavelength selective coupler E.sub.2 then couples idler light **3316** from second extension optical waveguide C.sub.2 **3342** into fifth segment A.sub.3 **3305** and also couples pump light **3312** and signal light **3314** from fourth segment D.sub.2 **3304** into fifth segment A.sub.3 **3305**. The length of second extension optical waveguide C.sub.2 **3342** and the length of fourth segment D.sub.2 **3304** can be selected such that the phase walk-off for the nonlinear optical interaction from the starting point of first segment A.sub.1 **3301** to the starting point of fifth segment A.sub.3 **3305** is an even multiple of π.
(590) In another example, third wavelength selective coupler B.sub.2 **3323** does not couple idler light **3316** from third segment A.sub.2 **3303** into fourth segment D.sub.2 **3304**. Thus, any idler light traveling in fourth segment D.sub.2 **3304** is generated in fourth segment D.sub.2 by the nonlinear optical process occurring in that fourth segment D.sub.2. Fourth wavelength selective coupler E.sub.2 **3324** does not couple the idler light generated in fourth segment D.sub.2 **3304** into fifth segment A.sub.3 **3305** but, instead, couples that idler light, generated in fourth segment D.sub.2 into an output port F.sub.2 **3385**. Thus, idler light generated in fourth segment D.sub.2 **3304** is prevented from affecting the nonlinear optical process that occurs in fifth segment A.sub.3 **3305**.
(591) In another illustrative example, segments ‘D.sub.i’ of the nonlinear optical waveguide **3309** can be comprised of a different material or cross-sectional structure from segments ‘A.sub.i’ of the nonlinear optical waveguide **3309** This selection of material or cross-sectional structure for segments ‘D.sub.i’ can be made such that an effective coefficient for the nonlinear optical interaction in segments ‘D.sub.i’, which depends on the overlap of the optical fields in segments ‘D.sub.i’ with the nonlinear optical material in segments ‘D.sub.i’ is smaller by at least a factor of 3 compared to an effective coefficient for the nonlinear optical interaction in segments ‘A.sub.i’. Alternatively, the loss for the generated idler light **3316** in segments ‘D.sub.i’ can be much higher as compared to the loss for idler light in segments ‘A.sub.i’. In some examples, selective loss for the idler signal light traveling in a segment ‘D.sub.i’ can be achieved by an optional filter such as signal/idler removing filter **3368** shown in segment D.sub.2 **3304** of the nonlinear optical waveguide **3309**. Thus, the amplitude of idler light **3316** in the segments ‘D.sub.i’ remains sufficiently small to not impact the nonlinear optical process occurring in a subsequent segment ‘A.sub.i+1’ even if the wavelength selective coupler ‘E.sub.i’ allows some idler light from segment ‘D.sub.i’ to be coupled in the subsequent segment ‘A.sub.i+1’ of the nonlinear optical waveguide.
(592) In this depicted example, extension optical waveguides ‘C.sub.i’ can have first pump removing filter **3361**, second pump removing filter **3362**, third pump removing filter **3363** and fourth pump removing filter **3364** to remove the pump light **3312**. As depicted, first pump removing filter **3361** is connected to first extension optical waveguide C.sub.1 **3341**; second pump removing filter **3362** is connected to second extension optical waveguide C.sub.2 **3342**; third pump removing filter **3363** is connected to third extension optical waveguide C.sub.3 **3343**; and a fourth pump removing filter **3364** can be connected to output waveguide **3374**. In this example, seventh wavelength selective coupler **3327** couples idler light **3316** from seventh segment A.sub.4 **3307** into an output waveguide **3374**. Seventh wavelength selective coupler **3327** also couples pump light **3312** and signal light **3314** into eighth segment D.sub.5 **3308**.
(593) In other illustrative examples different segments ‘A.sub.i’ can have different lengths or cross-sectional structures. Similarly, different segments ‘D.sub.i’ or different extension optical waveguides ‘C.sub.i’ can have different lengths or cross-sectional structures. As long as the condition to achieve the appropriate phase walk-off is met, such as described in Expression 12 or Expression 21, a net enhancement of the nonlinear optical generation process can still occur.
(594) With reference now to FIG. **34**, an illustration of an optical waveguide structure is depicted that implements a filter in an extension optical waveguide is depicted in accordance with an illustrative embodiment.
(595) In this example, optical waveguide structure **3400** has a nonlinear optical waveguide **3409** comprising first segment A.sub.1 **3401**, second segment D.sub.1 **3402** and third segment A.sub.2 **3403**. Idler light **3416** is generated by the nonlinear optical process in first segment A.sub.1. First wavelength selective coupler B.sub.1 **3421** couples generated idler light **3416** and signal light **3414** from first segment A.sub.1 into extension optical waveguide **3440** and couples pump light **3412** from first segment A.sub.1 into second segment D.sub.1 **3402**. Second wavelength selective coupler E.sub.1 **3422** couples idler light **3416** and signal light **3414** from extension optical waveguide **3440** into third segment A.sub.2 **3403** and also couples pump light **3412** from second segment D.sub.1 into third segment A.sub.2. Some practical implementations of first wavelength selective coupler B.sub.1 **3421** may allow some pump light **3412** to also couple into extension optical waveguide **3440**. Extension optical waveguide **3440** has an optical filter that removes pump light **3412** and allows only idler light **3416** and signal light **3414** to reach wavelength selective coupler E.sub.1 **3422** and be coupled by coupler E.sub.1 into third segment A.sub.2 **3403**.
(596) As depicted in FIG. **34**, extension optical waveguide **3440** comprises first waveguide portion **3441**, first coupler G.sub.1 **3444**, ring resonator **3442**, second coupler G.sub.2 **3446** and second waveguide portion **3443**. In one example of extension optical waveguide **3440**, first coupler G.sub.i **3444**, ring resonator **3442** and second coupler G.sub.2 **3446** comprise a ring resonator **3448**. Ring resonator is designed such that both the wavelength of idler light **3416** and the wavelength of signal light **3414** are equal to resonant wavelengths of ring resonator **3448** and such that the wavelength of pump light **3412** is not equal to any resonant wavelength of ring resonator **3448**. Thus, idler light **3416** and signal light **3414** are coupled through first coupler G.sub.1 **3444**, ring resonator **3442** and second coupler G.sub.2 **3446** from first waveguide portion **3441** of extension optical waveguide **3440** into second waveguide portion **3443** of extension optical waveguide **3440**. However, any pump light **3412** that is coupled into first waveguide portion **3441** is coupled into a pump dump port F.sub.5 **3475** rather than into second waveguide portion **3443**. The combination of first coupler G.sub.1**3444**, ring resonator **3442** and second coupler G.sub.2 **3446** can function as a pump removing filter such as first pump removing filter **3361**, second pump removing filter **3362**, third pump removing filter **3363**, and fourth pump removing filter **3364** in optical waveguide structure **3300**. For extension optical waveguide **3440**, the lengths of first waveguide portion **3441** and of second waveguide portion **3443** can be selected to achieve a desired phase walk-off for the nonlinear optical process at the starting point of third segment A.sub.2 **3403**.
(597) For a nonlinear optical generation process such as parametric down conversion or difference frequency generation that involves generation of, for example, idler light from both pump light and signal light that are supplied to the optical waveguide structure, the specific wavelength (or the optical frequency) of the generated idler light is constrained by the specific wavelengths of the supplied pump light and the supplied signal light, because of the condition for conservation of energy. However, for a nonlinear optical process such as spontaneous parametric down conversion (SPDC), only the pump light is supplied and both signal light and idler light are generated from the supplied pump light. For SPDC, the condition of conservation of energy constrains the relative wavelengths of the generated signal light and idler light. However, the specific wavelength of the generated signal light, and of the generated idler light, can have values within a broad spectral span, which is constrained by the condition for momentum conservation or phase-matching. An optical filter, such as the ring resonator **3448**, can impose a constraint on the wavelengths of signal light and idler light that has a narrow spectral span, since only the span of wavelength matching the resonance condition of the ring resonator will be coupled into the next segment of the nonlinear optical waveguide with appropriate phase walk-off and thereby experience the enhancement of the nonlinear optical generation process.
(598) In another illustrative example, one or more of the extension optical waveguides can be comprised of n+1 micro-rings where n is some even, positive integer.
(599) With reference now to FIG. **35**, an illustration of an optical waveguide structure with three coupled micro-rings for an extension optical waveguide is depicted in accordance with an illustrative embodiment. In this illustrative example, optical waveguide structure **3500** comprises nonlinear optical waveguide **3509**, extension optical waveguide **3540**, first wavelength selective coupler B.sub.1 **3521**, and second wavelength selective coupler E.sub.1 **3522**.
(600) In this illustrative example, nonlinear optical waveguide **3509** is comprised of segments. As depicted, the segments are first segment A.sub.1

3501, second segment D.sub.1 **3502**, and third segment A.sub.2 **3503**. Extension optical waveguide **3540** is comprised of micro-rings that are coupled to each other. In this example, three micro-rings are present in extension optical waveguide **3540**: first micro-ring C.sub.11 **3541**, second micro-ring C.sub.12 **3542**, and third micro-ring C.sub.13 **3543**. First micro-ring C.sub.11 and second micro-ring C.sub.12 are coupled together via first coupler G.sub.1 **3544**. Second micro-ring C.sub.12 and third micro-ring C.sub.13 are coupled together via second coupler G.sub.2 **3546**. The circumference of first micro-ring C.sub.1 **3541**, second micro-ring C.sub.2 **3542**, and third micro-ring C.sub.3 **3543** can be selected in a similar manner to selecting lengths for extension optical waveguides comprised of a single optical waveguide, with the object being to achieve a desired condition for the phase walk-off at the starting point of the next segment of the nonlinear optical waveguide, such as third segment A.sub.2 **3503** for this example. The length of second segment D.sub.1 **3502** likewise can be selected to achieve the desired condition for the phase walk-off at the starting point of third segment A.sub.2 **3503** of the nonlinear optical waveguide. In this illustrative example, optical waveguide structure **3500** and other components in optical waveguide structure **3500** are formed on a yz plane defined by z-axis **3593** and y-axis **3592** in which an x-axis **3591** is perpendicular to the plane.

Φ.sub.A2,start=(*k*.sub.p−*k*.sub.i−*k*.sub.s)*L*.sub.A1+*k*.sub.p*L*.sub.D1−Φ.sub.C1,i−Φ.sub.C1s=*m*.sub.C2π (23)

In the example of optical waveguide structure **3500**, the first wavelength selective coupler B.sub.1 **3521** is designed to couple signal light **3514** and idler light **3516** from first segment A.sub.1 **3501** into first micro-ring C.sub.11 **3541** and to couple pump light **3512** into second segment D.sub.1 **3502**. The second wavelength selective coupler E.sub.1 **3522** is designed to couple signal light **3514** and idler light **3516** from third micro-ring C.sub.13 **3543** into third segment A.sub.2 **3503** and to couple pump light from second segment D.sub.1 **3502** into third segment A.sub.2 **3503**. Signal light **3514** and idler light **3516** with wavelengths over a fairly broad spectral range could be coupled by first wavelength selective coupler B.sub.1 and by second wavelength selective coupler E.sub.1 to/from the extension optical waveguide **3540**. However, the combination of coupled ring resonators C.sub.11, C.sub.12 and C.sub.13 can impose a narrower spectral range for the specific wavelengths of the signal light **3514** and idler light **3516** that are transmitted through the resonator structure comprising those coupled micro-rings. Wavelengths that are not resonant with the coupled micro-ring resonator structure comprising extension optical waveguide **3540** are not coupled through that resonator structure to third segment A.sub.3 **3503**. Instead, those non-resonant wavelengths are coupled into second segment D.sub.1 **3502** and then from second segment D.sub.1 **3502** into third segment A.sub.2 **3503**. The length and cross-sectional structure of second segment D.sub.1 **3502** can be selected such that the phase walk-off at the starting point of segment A.sub.2 is reset to zero (modulo 2π) as discussed above. Thus,

Φ.sub.A2,start=(*k*.sub.p−*k*.sub.i−*k*.sub.s)*L*.sub.A1+*k*.sub.p*L*.sub.D1−Φ.sub.C1,i−Φ.sub.C1s=*m*.sub.C2π (23)

where m.sub.C is any positive integer.

(601) In some example, the condition for phase walk-off at the starting point of segment A.sub.2 **3503** is met for those wavelengths of signal light **3514** and idler light **3516** that are transmitted through the coupled micro-rings in extension optical waveguide **3540** so that there is enhancement of the nonlinear optical generation occurring for those wavelength of signal light **3514** and idler light **3516**. However, for light of other wavelengths that might be generated in first segment A.sub.1 **3501**, through a process such as spontaneous parametric down conversion, and that is not coupled through extension optical waveguide **3540** into third segment A.sub.2 **3503**, but rather that must traverse through second segment D.sub.1 **3502**, the condition for phase walk-off described in Expression 23 is not met. As a result, nonlinear optical generation in third segment A.sub.2 **3503** is not enhanced for the light of those other wavelengths.

(602) The illustration of the different examples in FIGS. **30** thru **35** are provided as examples of some of the dictations for optical waveguide structures to provide light generation. These examples are not meant to limit the manner in which other illustrative examples can be implemented. For example, in the optical waveguide structure depicted in FIG. **30**, both the signal light and the idler light are coupled to/from the extension optical waveguides. However, in a different example of this optical waveguide structure, only the idler light would be coupled to/from the extension optical waveguide and both the signal light and the pump light would not. For another example, in the optical waveguide structure depicted in FIG. **33**, the idler light is coupled to/from the extension optical waveguides. However, in a different example of this optical waveguide structure, both the idler light and the signal light would be coupled to/from the extension optical waveguide and only the pump light would not. For example, although the examples of optical waveguide structures have been described with respect to second order, χ.sup.(2), nonlinear optical processes such as difference frequency generation (DFG), spontaneous parametric down conversion (SPDC), sum frequency generation (SFG) and second harmonic generation (SHG), other illustrative examples can be applied to other nonlinear optical processes such as third order, χ.sup.(3), nonlinear optical processes such as spontaneous four wave mixing (SFWM) and third harmonic generation (THG). With third order nonlinear optical process, the design of optical waveguide structures can apply taking into account the desired modifications or values for nonlinear optical coefficients and phase-matching conditions.

(603) The illustrative embodiments described herein by FIGS. **30** thru **35** and associated descriptions are of an optical waveguide structure comprising a nonlinear optical waveguide and extension waveguides. The nonlinear optical waveguide comprises multiple segments. As discussed above, the generation of generated light from source light through a nonlinear optical process occurring in at least some of those multiple segments is made constructive by suitably selecting the cross-sectional structure and length of the segments as well as the cross-sectional structure and length of one or more extension waveguides. As a result, the effective length of the constructive nonlinear optical generation accomplished by the nonlinear optical waveguide structure can be much longer than the length of a single nonlinear optical waveguide segment. In general, the length of each nonlinear optical waveguide segment is kept no larger than the coherent interaction distance or coherent interaction length L.sub.coh. A benefit of the nonlinear optical waveguide structure described herein is that the length of nonlinear optical waveguide for which a constructive nonlinear optical generation occurs can be much greater than the coherent interaction length. As a result, the efficiency of the nonlinear optical generation can be increased, and the intensity of the generated light can be increased.

(604) In the examples discussed above, the source light includes pump light, and the generated light includes one or both of signal light and idler light. One way to increase the coherent interaction length L.sub.coh, especially when the wavelengths of the pump light, signal light and idler light are very different from each other and when there is substantial dispersion in the spectral characteristics of the nonlinear optical waveguide, is to use modal phase matching. In one example of modal phase matching, the pump light is guided in a higher-order mode of the nonlinear optical waveguide segments for the wavelength of the pump light, and the signal light and idler light are guided in the fundamental mode of the nonlinear optical waveguide for those wavelength of the signal light and idler light. FIGS. **36** thru **38** show examples of the cross-sectional structure of a nonlinear optical waveguide segment and the cross-sectional structure of an extension optical waveguide.

(605) Turning to FIG. **36**, an illustration of a cross-section of an optical waveguide or of an extension optical waveguide is depicted in accordance with an illustrative embodiment. Optical waveguide structure **3600** can be used in at least one of a nonlinear optical waveguide or of an extension optical waveguide.

(606) As depicted, optical waveguide structure **3600** comprises core region **3602** and cladding region **3604** formed on substrate **3610**. The refractive index of core region **3602** is higher than the refractive index of cladding region **3604**.

(607) In this example, core region **3602** comprises first core portion **3606** and second core portion **3608**.

(608) First core portion **3606** comprises a nonlinear optical material. Second core portion **3608** comprises a non-nonlinear optical material. For example, with a second-order nonlinear optical process such as parametric down conversion, the nonlinear optical material can be lithium niobate and the non-nonlinear optical material can be silicon nitride, or the nonlinear optical material can be silicon carbide and the non-nonlinear optical material can be aluminum nitride, gallium nitride or gallium aluminum nitride.

(609) An example of the material comprising cladding region **3604** is silicon dioxide. First core portion **3606** can be located between second core portion **3608** and substrate **3610**, as depicted in FIG. **36**, or vice versa.

(610) As depicted, first core portion has width **3622** and height **3626**. Second core region has width **3624** and height **3628**. Cladding region has thickness **3630**. These dimensions of the nonlinear optical waveguide or of the extension optical waveguide can be adjusted to achieve a desired value for the phase walk-off in the nonlinear optical process that occurs between two specified points along the nonlinear optical waveguide, as discussed above.
(611) In one illustrative example, the width and height of the first core portion and the width and height of the second core portion are selected such that the nonlinear optical waveguide can support both the fundamental mode and a first higher-order mode for the pump light, assumed to have a wavelength that is shorter than the wavelengths of the signal light and the idler light. Also, that nonlinear optical waveguide can support only the fundamental mode for the signal light and can support only the fundamental mode for the idler light.
(612) The first higher-order mode for the pump light has an optical-field profile with two peaks that corresponds to regions of maximum optical-field intensity or maximum optical-field magnitude and a null (or zero-crossing). The two peaks of the optical field profile are aligned such that one peak overlaps with the first core portion and the other peak overlaps with the second core portion, and the null is located near the interface between the first core portion and the second core portion. This selection of core-region widths and heights can achieve nonlinear optical generation of signal light and/or idler light from pump light with greater efficiency.
(613) With reference to FIG. **37**, an illustration of a cross-section of an optical waveguide is depicted in accordance with an illustrative embodiment. Optical waveguide structure **3700** can be used in at least one of a nonlinear optical waveguide or of an extension optical waveguide.
(614) As depicted, optical waveguide structure **3700** comprises core region **3702** and cladding region **3704** formed on substrate **3710**. The refractive index of core region **3702** is higher than the refractive index of cladding region **3704**. Core region **3702** comprises first core portion **3706** and second core portion **3708**. Cladding region **3704** comprises lower cladding portion **3712** and upper cladding portion **3714**.
(615) At least one of first core portion **3706** or second core portion **3708** comprises a nonlinear optical material whose nonlinear optical parameter, such as χ.sup.(2), is much larger than the nonlinear optical parameter of the material comprising the other core portion, which is considered a non-nonlinear optical material. To be considered much larger, the value for the nonlinear optical parameter would be at least three times larger and preferably at least ten times larger.
(616) Optical waveguide structure **3700** further comprises top electrode **3732**, and at least one of side electrode **3734** and side electrode **3736**. Top electrode **3732** is aligned above core region **3702**. In the cross-section view of optical waveguide structure **3700**, side electrode **3734** and side electrode **3736** are recessed into lower cladding portion **3712** and are aligned below the level of the portion of core region **3702** that comprises nonlinear optical material. In some examples, top electrode **3732** and side electrodes **3734** and **3736** are separated from core region **3702** by a portion of cladding region **3704**. Optical waveguide structure **3700** is especially suitable for a phase shifter, which can be located along an extension optical waveguide or along a segment of the nonlinear optical waveguide. The combination of a top electrode and one or more recessed side electrodes is especially suitable for applying an electro-optic activation when first core portion **3706** or second core portion **3708** has an electro-optic coefficient that is larger for light whose polarization is aligned perpendicular to the interface between substrate **3710** and cladding region **3704**. In a variation (not shown) of optical waveguide structure **3700**, only top electrode **3732** is present and side electrode **3734** and side electrode **3736** are not present. Such a variation, comprising only top electrode **3732**, is especially suitable for applying a thermo-optic activation or a stress or elasto-optic activation.
(617) Turning to FIG. **38**, an illustration of a cross-section of an optical waveguide is depicted in accordance with an illustrative embodiment. Optical waveguide structure **3800** can be used in at least one of a nonlinear optical waveguide or an extension optical waveguide.
(618) As depicted, optical waveguide structure **3800** comprises core region **3802** and cladding region **3804** that are formed on substrate **3810**. The refractive index of core region **3802** is higher than the refractive index of cladding region **3804**. Core region **3802** comprises first core portion **3806** and second core portion **3808**. Cladding region **3804** comprises lower cladding portion **3812** and upper cladding portion **3814**.
(619) At least one of first core portion **3806** or second core portion **3808** comprises a nonlinear optical material whose nonlinear optical parameter, such as χ.sup.(2), is much larger than the nonlinear optical parameter of the material comprising the other core portion, which is considered a non-nonlinear optical material.
(620) Optical waveguide structure **3800** further comprises side electrode **3834** and side electrode **3836**. In the cross-section view of optical waveguide structure **3800**, side electrode **3834** and side electrode **3836** are aligned approximately level with the portion of core region **3802** that comprises nonlinear optical material. In some examples, side electrodes **3834** and **3836** are separated from core region **3802** by a portion of cladding region **3804**. Optical waveguide structure **3800** is especially suitable for a phase shifter, which can be located along an extension optical waveguide or along a segment of the nonlinear optical waveguide. A small portion of the side electrode **3834** and side electrode **3836** can be recessed slightly into lower cladding portion **3812**. This structure with two side electrodes is especially suitable for applying an electro-optic activation when first core portion **3806** or second core portion **3808** has an electro-optic coefficient that is larger for light whose polarization is aligned parallel to the interface between substrate **3810** and cladding region **3804**.
(621) Some features of the illustrative examples are described in the following clauses. These clauses are examples of features and are not intended to limit other illustrative examples.
Clause 1
(622) An optical waveguide structure comprising: a nonlinear optical waveguide comprising a set of segments; a set of extension optical waveguides; and a set of wavelength selective couplers couples light between the set of segments in the nonlinear optical waveguide and the set of extension optical waveguides based on a wavelength of light.
Clause 2
(623) The optical waveguide structure according to clause 1, further comprising: a first segment in the set of segments in the nonlinear optical waveguide, wherein the light traveling in the first segment comprises a first wavelength light, a second wavelength light, and a third wavelength light and wherein the second wavelength light, and the third wavelength light are produced by a nonlinear optical interaction of the first wavelength light in the first segment; a second segment in the set of segments in the nonlinear optical waveguide, wherein the second wavelength light and the third wavelength light are produced by the nonlinear optical interaction of the first wavelength light in the second segment; a third segment in the set of segments in the nonlinear optical waveguide, wherein the second wavelength light and the third wavelength light are produced by the nonlinear optical interaction of the first wavelength light in the third segment; a first wavelength selective coupler in the set of wavelength selective couplers couples the first wavelength light from a first ending point for the first segment to a second starting point for the segment and couples the second wavelength light and the third wavelength light from the first ending point for the first segment to an extension starting point for an extension optical waveguide in the set of extension optical waveguides; and a second wavelength selective coupler in the set of wavelength selective couplers couples the second wavelength light and the third wavelength light from an extension ending point for the extension optical waveguide to a third starting point for the third segment in the nonlinear optical waveguide.
Clause 3
(624) The optical waveguide structure according to clause 2, wherein the first segment has a first length from a first starting point to the first ending point selected to produce a first phase walk-off that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer of π radians for the nonlinear optical interaction in the first segment.
Clause 4
(625) The optical waveguide structure according to one of clauses 2 or 3, wherein the third segment has a third length from the third starting point to a third ending point selected to produce a third phase walk-off that is at least one of from 0 to π radians or from an even-numbered integer of π

radians to a next larger odd-numbered integer of π radians for the nonlinear optical interaction in the third segment.

Clause 5

(626) The optical waveguide structure according to one of clauses 2, 3, or 4, wherein the first segment has a first cross-sectional structure and a first length from a first starting point to the first ending point produces a first phase walk-off that results in a light generation through the nonlinear optical interaction that is constructive in the first segment.

Clause 6

(627) The optical waveguide structure according to clause 5, wherein the third segment has a third cross-sectional structure and a third length from the third starting point to a third ending point selected to produce a third phase walk-off that results in the light generation through the nonlinear optical interaction that is constructive in the third segment.

Clause 7

(628) The optical waveguide structure according to one of clauses 5 or 6, wherein the second segment has a second cross-sectional structure and a second length from the second starting point to a second ending point that are selected to produce a second phase walk-off that results in the light generation through the nonlinear optical interaction that is constructive in the third segment.

Clause 8

(629) The optical waveguide structure according to one of clauses 5, 6, or 7, wherein the extension optical waveguide has an extension cross-sectional structure and an extension length from the extension starting point to the extension ending point that are selected to produce an extension phase walk-off that results in the light generation through the nonlinear optical interaction that is constructive in the third segment.

Clause 9

(630) The optical waveguide structure according to one of clauses 5, 6, 7, or 8, wherein the extension optical waveguide has an extension cross-sectional structure with an extension length from the extension starting point to the extension ending point that are selected to produce an extension phase walk-off that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer for the nonlinear optical interaction that occurs from the first starting point for the first segment to the third starting point for the third segment.

Clause 10

(631) The optical waveguide structure according to one of clauses 2, 3, 4, 5, 6, 7, 8, or 9, wherein the second segment has a second cross-sectional structure with a second length from the second starting point to a second ending point of the nonlinear optical waveguide that are selected to produce a second phase walk-off that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer for the nonlinear optical interaction that occurs from a first starting point for the first segment to the third starting point for the third segment.

Clause 11

(632) The optical waveguide structure according to one of clauses 2, 3, 4, 5, 6, 7, 8, 9, or 10, wherein the first wavelength light is a pump light, the second wavelength light is a signal light, and the third wavelength light is an idler light.

Clause 12

(633) The optical waveguide structure according to one of clauses 2, 3, 4, 5, 6, 7, 8, 9, 10, or 11, wherein the first segment has a first cross-sectional structure from a first starting point to the first ending point that is selected to produce a first phase walk-off for the light that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer of π radians for the nonlinear optical interaction in the first segment.

Clause 13

(634) The optical waveguide structure according to one of clauses 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, or 12, wherein the second wavelength selective coupler couples the second wavelength light and the third wavelength light from a second ending point for the second segment away from the third segment.

Clause 14

(635) The optical waveguide structure according to one of clauses 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, or 13, wherein the extension optical waveguide includes an optical wavelength-selective filter.

Clause 15

(636) The optical waveguide structure according to one of clauses 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, or 14, wherein the extension optical waveguide comprises a set of micro-rings.

Clause 16

(637) The optical waveguide structure according to one of clauses 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 14, or 15, wherein the nonlinear optical waveguide comprises a core region and a cladding region and wherein the core region comprises a first core portion and a second core portion,

(638) wherein the first core portion comprises a nonlinear optical material and the second core portion comprises a non-nonlinear optical material.

Clause 17

(639) The optical waveguide structure according to clause 16, further comprising a top electrode.

Clause 18

(640) The optical waveguide structure according to clause 17, further comprising a side electrode.

Clause 19

(641) The optical waveguide structure according to one of clauses 16, 17, or 18, further comprising a side electrode.

Clause 20

(642) An optical waveguide structure comprising: a nonlinear optical waveguide comprising a first segment having a first starting point and a first ending point, wherein a nonlinear optical interaction results in a generation of a second wavelength light from a first wavelength light traveling through the first segment; a second segment having a second starting point and a second ending point; a third segment having a third starting point and a third ending point; an extension optical waveguide; a first wavelength selective coupler that couples the second wavelength light from the first segment at the first ending point into the extension optical waveguide; and a second wavelength selective coupler that couples the second wavelength light from the extension optical waveguide into the third segment at the third starting point, wherein the first wavelength light travels from the first ending point to the third starting point through the second segment; the second wavelength light travels from the first ending point to the third starting point through the extension optical waveguide; both the first wavelength light and the second wavelength light travel from the third starting point of the third segment to the third ending point.

Clause 21

(643) The optical waveguide structure according to clause 20, wherein the first wavelength light is a pump light and the second wavelength light is at least one of a signal light or an idler light.

Clause 22

(644) The optical waveguide structure according to one of clauses 20 or 21, wherein the nonlinear optical interaction results in the generation of a third wavelength light from the first wavelength light traveling through the first segment.

Clause 23

(645) The optical waveguide structure according to one of clauses 20, 21, or 22, wherein the first wavelength selective coupler couples the second wavelength light and the third wavelength light from the nonlinear optical waveguide at the first ending point into the extension optical waveguide, wherein the second wavelength selective coupler couples the second wavelength light and the third wavelength light into the third segment at the third starting point.

Clause 24
(646) The optical waveguide structure according to one of clauses 20, 21, 22, or 23, wherein the first wavelength light is a pump light, the second wavelength light is a signal light, and a third wavelength light is an idler light.
Clause 25
(647) A method for facilitating a non-linear optical process comprising: routing a first wavelength light traveling through a first segment in a nonlinear optical waveguide having a first starting point and a first ending point; generating a second wavelength light and a third wavelength light by a nonlinear optical interaction of the first wavelength light between the first starting point and the first ending point in the first segment; coupling, by a first wavelength selective coupler, the first wavelength light from the first ending point to a second starting point for a second segment in the nonlinear optical waveguide; coupling, by the first wavelength selective coupler, the second wavelength light and the third wavelength light from the first ending point to an extension starting point for an extension optical waveguide; coupling, by a second wavelength selective coupler, the second wavelength light and the third wavelength light from an extension ending point for the extension optical waveguide to a third starting point for a third segment in the nonlinear optical waveguide; and coupling, by the second wavelength selective coupler, the first wavelength light from the second segment in the nonlinear optical waveguide to the third starting point for the third segment in the nonlinear optical waveguide.
Clause 26
(648) The method according to clause 25, wherein the first segment has a first cross-sectional structure and a first length from the first starting point to the first ending point produces a first phase walk-off that results in a light generation through the nonlinear optical interaction that is constructive in the first segment.
Clause 27
(649) The method according to clause 26, wherein the second segment has a second cross-sectional structure and a second length from the second starting point to a second ending point produces a second phase walk-off that results in the light generation through the nonlinear optical interaction that is constructive in the third segment.
Clause 28
(650) The method according to clause 27, wherein the extension optical waveguide has an extension cross-sectional structure and an extension length from the extension starting point to the extension ending point that produces an extension phase walk-off that results in the light generation through the nonlinear optical interaction that is constructive in the third segment.
(651) The description of the different illustrative embodiments has been presented for purposes of illustration and description and is not intended to be exhaustive or limited to the embodiments in the form disclosed. The different illustrative examples describe components that perform actions or operations. In an illustrative embodiment, a component can be configured to perform the action or operation described. For example, the component can have a configuration or design for a structure that provides the component an ability to perform the action or operation that is described in the illustrative examples as being performed by the component. Further, To the extent that terms “includes”, “including”, “has”, “contains”, and variants thereof are used herein, such terms are intended to be inclusive in a manner similar to the term “comprises” as an open transition word without precluding any additional or other elements.
(652) Many modifications and variations will be apparent to those of ordinary skill in the art. Further, different illustrative embodiments may provide different features as compared to other desirable embodiments. The embodiment or embodiments selected are chosen and described in order to best explain the principles of the embodiments, the practical application, and to enable others of ordinary skill in the art to understand the disclosure for various embodiments with various modifications as are suited to the particular use contemplated.

Claims

1. An optical waveguide structure comprising: a nonlinear optical waveguide comprising a set of segments; a set of extension optical waveguides; and a set of wavelength selective couplers that couples light between the set of segments in the nonlinear optical waveguide and the set of extension optical waveguides based on a wavelength of light, wherein the set of segments comprise: a first segment in the set of segments in the nonlinear optical waveguide, wherein the light traveling in the first segment comprises a first wavelength light, a second wavelength light, and a third wavelength light and wherein the second wavelength light, and the third wavelength light are produced by a nonlinear optical interaction of the first wavelength light in the first segment; a second segment in the set of segments in the nonlinear optical waveguide, wherein the second wavelength light and the third wavelength light are produced by the nonlinear optical interaction of the first wavelength light in the second segment; a third segment in the set of segments in the nonlinear optical waveguide, wherein the second wavelength light and the third wavelength light are produced by the nonlinear optical interaction of the first wavelength light in the third segment; wherein the set of wavelength selective couplers comprise: a first wavelength selective coupler in the set of wavelength selective couplers couples the first wavelength light from a first ending point for the first segment to a second starting point for the first segment and couples the second wavelength light and the third wavelength light from the first ending point for the first segment to an extension starting point for an extension optical waveguide in the set of extension optical waveguides; and a second wavelength selective coupler in the set of wavelength selective couplers couples the second wavelength light and the third wavelength light from an extension ending point for the extension optical waveguide in the set of extension optical waveguides to a third starting point for the third segment in the nonlinear optical waveguide.
2. The optical waveguide structure of claim 1, wherein the first segment has a first length from a first starting point to the first ending point selected to produce a first phase walk-off that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer of π radians for the nonlinear optical interaction in the first segment.
3. The optical waveguide structure of claim 1, wherein the third segment has a third length from the third starting point to a third ending point selected to produce a third phase walk-off that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer of π radians for the nonlinear optical interaction in the third segment.
4. The optical waveguide structure of claim 1, wherein the first segment has a first cross-sectional structure and a first length from a first starting point to the first ending point produces a first phase walk-off that results in a light generation through the nonlinear optical interaction that is constructive in the first segment.
5. The optical waveguide structure of claim 4, wherein the third segment has a third cross-sectional structure and a third length from the third starting point to a third ending point selected to produce a third phase walk-off that results in the light generation through the nonlinear optical interaction that is constructive in the third segment.
6. The optical waveguide structure of claim 4, wherein the extension optical waveguide in the set of extension optical waveguides has an extension cross-sectional structure and an extension length from the extension starting point to the extension ending point that are selected to produce an extension phase walk-off that results in the light generation through the nonlinear optical interaction that is constructive in the third segment.
7. The optical waveguide structure of claim 4, wherein the extension optical waveguide in the set of extension optical waveguides has an extension cross-sectional structure with an extension length from the extension starting point to the extension ending point that are selected to produce an extension phase walk-off that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer for the nonlinear optical interaction that occurs from the first starting point for the first segment to the third starting point for the third segment.
8. The optical waveguide structure of claim 1, wherein the second segment has a second cross-sectional structure and a second length from the

second starting point to a second ending point that are selected to produce a second phase walk-off that results in the light generation through the nonlinear optical interaction that is constructive in the third segment.

9. The optical waveguide structure of claim 1, wherein the second segment has a second cross-sectional structure with a second length from the second starting point to a second ending point of the nonlinear optical waveguide that are selected to produce a second phase walk-off that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer for the nonlinear optical interaction that occurs from a first starting point for the first segment to the third starting point for the third segment.

10. The optical waveguide structure of claim 1, wherein the first wavelength light is a pump light, the second wavelength light is a signal light, and the third wavelength light is an idler light.

11. The optical waveguide structure of claim 1, wherein the first segment has a first cross-sectional structure from a first starting point to the first ending point that is selected to produce a first phase walk-off for the light that is at least one of from 0 to π radians or from an even-numbered integer of π radians to a next larger odd-numbered integer of π radians for the nonlinear optical interaction in the first segment.

12. The optical waveguide structure of claim 1, wherein the second wavelength selective coupler couples the second wavelength light and the third wavelength light from a second ending point for the second segment away from the third segment.

13. The optical waveguide structure of claim 1, wherein the extension optical waveguide in the set of extension optical waveguides includes an optical wavelength-selective filter.

14. The optical waveguide structure of claim 1, wherein the extension optical waveguide in the set of extension optical waveguides comprises a set of micro-rings.