United States Patent	12395263
Kind Code	B2
Date of Patent	August 19, 2025
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Wavelength division multiplexing architecture based on integrated bragg and adiabatic TE0 mode add/drop filter

Abstract

A method and apparatus are provided. The method includes receiving, at a TE.sub.0 mode add/drop filter, a TE.sub.0 mode optical signal having a first wavelength and a second wavelength, and transmitting, from the TE.sub.0 mode add/drop filter, the TE.sub.0 mode optical signal having the first wavelength and the second wavelength towards a Bragg grating, without converting the TE.sub.0 mode optical signal having the first wavelength and the second wavelength to another mode. The method further includes receiving, at the TE.sub.0 mode add/drop filter, a reflected TE.sub.1 mode optical signal having the first wavelength from the Bragg grating, and transmitting, from the TE.sub.0 mode add/drop filter, the reflected TE.sub.1 mode optical signal having the first wavelength towards a photodetector, without converting the reflected TE.sub.1 mode optical signal having the first wavelength to another mode.

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Appl. No.: **18/096128**

Filed: **January 12, 2023**

Prior Publication Data

Document Identifier	Publication Date
US 20240243832 A1	Jul. 18, 2024

Publication Classification

Int. Cl.: **H04J14/02** (20060101); **H04B10/294** (20130101); H04B10/25 (20130101); H04B10/2581 (20130101); H04J14/04 (20060101)

U.S. Cl.:

CPC **H04J14/0201** (20130101); **H04B10/294** (20130101); H04B10/25 (20130101); H04B10/2581 (20130101); H04J14/02 (20130101); H04J14/0307 (20230801); H04J14/04 (20130101)

Field of Classification Search

CPC: H04J (14/0201); H04J (14/0307); H04J (14/02); H04J (14/04); H04B (10/294); H04B (10/25); H04B (10/2581); G02B (2006/1215); G02B (6/12007); G02B (6/124); G02B (6/14)

USPC: 398/43-103; 398/140-172

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Background/Summary

TECHNICAL FIELD
(1) Embodiments described herein are directed to a photonic device, and specifically to a wavelength division multiplexing architecture including an integrated Bragg grating, an adiabatic TE.sub.0 mode add/drop filter, and a TE.sub.1.fwdarw.TE.sub.0 mode converter.
BACKGROUND
(2) A photonic device is designed to have components with minimal loss, footprint and, if possible, complexity. Propagation loss, back-reflection, high power handling, extinction ratio and yield all, ultimately, have an impact on the optical link performance of the device.
(3) One component of interest is a mode multiplexer (often referred to as a “modemux”). A modemux is a general purpose photonic component, which can be used, for example, with a

polarization rotator to form a polarization splitter rotator (PSR), or in a receiver's integrated wavelength division multiplexing (WDM) filter used in, e.g., the O-band. Such a filter preferably meet desired specifications including accurate channel center and width, as well as steep channel edge roll off and extinction ratio. Some platforms use a set of integrated Bragg gratings for the core filtering process. In some implementations, these gratings may be combined with supporting adiabatic components including adiabatic bends and adiabatic interlayer transitions.
(4) A photonic filter is also characterized by insertion loss (IL) and return loss (RL). Link budget, which is related directly to IL, is a premium on the receive path (compared to the transmit path). The RL of a given receiver is impacted not only by filter design, but also by fiber couplers, photodetectors (e.g., a GePD), variable optical attenuators (VOAs), Si routing, and potentially a PSR.
(5) One integrated Bragg WDM filter architecture uses back-reflection to form a spectral reject or “drop” band, and forward transmission as a spectral “pass” band. Using back-reflection to form a drop band, while producing excellent filtering performance, is clearly at odds with RL. In this architecture, receiver RL is equal to approximately four times the cross-talk of an individual adiabatic modemux. For example, a −30 dB cross-talk modemux (which is already considered very good for a modemux) used in such an integrated WDM filter result in −24 dB of RL, which may fall short of a desired still lower RL. Estimates of the cross-talk to comfortably meet the return loss specification on a receiver place the required cross-talk of the adiabatic modemux at approximately less than −36 dB.
(6) A typical modemux converts TE.sub.1 to TE.sub.0 of an isolated waveguide. However, converting TE.sub.1 to TE.sub.0 to avoid cross-talk can be challenging.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** shows a plan view of a modemux, according to an example embodiment.
(2) FIGS. **2**A, **2**B, and **2**C show, respectively, cross-sectional views at A-A, B-B, and C-C of the modemux shown in FIG. **1**, according to an example embodiment.
(3) FIGS. **3**A, **3**B, and **3**C show simulated power along a bus waveguide, a lower waveguide, and an upper waveguide of the modemux, according to an example embodiment.
(4) FIG. **4**A is a graph showing TE.sub.1 transmission of the modemux, according to an example embodiment.
(5) FIG. **4**B is a graph showing TE.sub.0-TE.sub.1 cross-talk of the modemux, according to an example embodiment.
(6) FIGS. **5**A and **5**B show, respectively, cross-sectional views at A-A and C-C of a variation of the modemux shown in FIG. **1**, according to another example embodiment.
(7) FIGS. **6**A and **6**B are functional block diagrams of a modemux, according to an example embodiment.
(8) FIG. **7** is a flowchart showing a series of operations for processing light with a modemux, according to an example embodiment.
(9) FIG. **8** is a block diagram of a use case device including a TE.sub.0 mode add/drop filter (modemux), a (backward-reflecting) Bragg grating, and a TE.sub.1.fwdarw.TE.sub.0 mode converter to provide a Bragg-based demultiplexer, according to an example embodiment.
(10) FIGS. **9**A, **9**B, and **9**C are block diagrams of different implementations for the TE.sub.1.fwdarw.TE.sub.0 mode converter of FIG. **8**, according to an example embodiment.
(11) FIG. **10** is a block diagram of a full Bragg-based WDM architecture including three Braggs/Bragg-based demultiplexers of FIG. **8** for separating different wavelengths, respectively, according to an example embodiment.

(12) FIG. **11** is a block diagram of another use case device including a TE.sub.0 mode add/drop filter (modemux), a forward Bragg, and a TE.sub.1.fwdarw.TE.sub.0 mode converter to provide a Bragg-based demultiplexer, according to an example embodiment.
(13) FIGS. **12**A-**12**C illustrate a flowchart showing a series of operations for processing light with a Bragg-based demultiplexer of FIG. **8**, according to an example embodiment.
DETAILED DESCRIPTION
(14) Overview
(15) Presented herein is a method that includes receiving, at a TE.sub.0 mode add/drop filter, a TE.sub.0 mode optical signal having a first wavelength (λ.sub.1) and a second wavelength (λ.sub.2) on a lower waveguide, and transmitting, from the TE.sub.0 mode add/drop filter, the TE.sub.0 mode optical signal having the first wavelength and the second wavelength (λ.sub.1, λ.sub.2) towards a Bragg grating on a bus waveguide disposed above the lower waveguide, without converting the TE.sub.0 mode optical signal having the first wavelength and the second wavelength (λ.sub.1, λ.sub.2) to another mode (e.g., TE.sub.1). The method further includes receiving, at the TE.sub.0 mode add/drop filter, a reflected (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1) from the Bragg grating on the bus waveguide, and transmitting, from the TE.sub.0 mode add/drop filter, the reflected (drop-band) TE.sub.1 mode optical signal (λ.sub.1) towards a photodetector on the bus waveguide, without converting the reflected (drop-band) TE.sub.1 mode optical signal (λ.sub.1) to another mode (e.g., TE.sub.0).
(16) According to an aspect, the method further includes mode multiplexing, by the TE.sub.0 mode add/drop filter, the TE.sub.0 mode optical signal having the first wavelength and the second wavelength (λ.sub.1, λ.sub.2) with the reflected (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1). According to an aspect, the method includes receiving, by a TE.sub.1.fwdarw.TE.sub.0 mode converter, the (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1) from the TE.sub.0 add/drop filter on the bus waveguide, converting, by the TE.sub.1.fwdarw.TE.sub.0 mode converter, the (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1) to a (drop-band) TE.sub.0 mode optical signal having the first wavelength (λ.sub.1), and transmitting, from the TE.sub.1.fwdarw.TE.sub.0 mode converter, the converted (drop-band) TE.sub.0 mode optical signal at the first wavelength (λ.sub.1) to the photodetector. According to an aspect, the method further includes transmitting, from the Bragg grating, a non-reflected (pass-band) TE.sub.0 mode optical signal having the second wavelength (λ.sub.2) towards a second TE.sub.0 mode add/drop filter.
(17) According to another aspect, another method is provided. The method includes passing an optical signal through a plurality of TE.sub.0 mode add/drop filters, reflecting respective wavelengths of the optical signal using respective Bragg gratings, and detecting powers of the respective wavelengths using respective photodetectors. According to an aspect, each TE.sub.0 mode add/drop filter in the plurality of TE.sub.0 mode add/drop filters passes the optical signal without converting the optical signal to a different mode. According to an aspect, at least one TE.sub.0 mode add/drop filter in the plurality of TE.sub.0 mode add/drop filters is an adiabatic TE.sub.0 mode add/drop filter.
(18) According to yet another aspect, presented herein is an apparatus including a TE.sub.0 mode add/drop filter, and a Bragg grating connected with the TE.sub.0 mode add/drop filter. The TE.sub.0 mode add/drop filter is configured to receive a TE.sub.0 mode optical signal having a first wavelength (λ.sub.1) and a second wavelength (λ.sub.2) on a lower waveguide, and transmit the TE.sub.0 mode optical signal having the first wavelength and the second wavelength (λ.sub.1, λ.sub.2) towards the Bragg grating on a bus waveguide disposed above the lower waveguide, without converting the TE.sub.0 mode optical signal having the first wavelength and the second wavelength (λ.sub.1, λ.sub.2) to another mode (TE.sub.1). The TE.sub.0 mode add/drop filter is further configured to receive a reflected (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1) from the Bragg grating on the bus waveguide, and transmit the reflected

(drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1) towards the photodetector on the bus waveguide, without converting the reflected (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1) to another mode (TE.sub.0).

(19) According to an aspect, the TE.sub.0 mode add/drop filter of the apparatus is an adiabatic TE.sub.0 mode add/drop filter. According to an aspect, the lower waveguide is a single-mode waveguide comprised of silicon (Si) and the bus waveguide is a multimode waveguide comprised of silicon nitride (SiN). According to an aspect, the TE.sub.0 mode add/drop filter further establishes a pseudo-symmetry about a longitudinal axis of the bus waveguide (SiN) to prevent TE.sub.1-TM.sub.0 mode hybridization of optical signals that traverse the bus waveguide (SiN). According to an aspect, the TE.sub.0 mode add/drop filter is configured to mode multiplex the TE.sub.0 mode optical signal having the first wavelength and the second wavelength (λ.sub.1, λ.sub.2) with the reflected (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1).

(20) According to an aspect, the apparatus further includes further a TE.sub.1.fwdarw.TE.sub.0 mode converter configured to receive the (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1) from the TE.sub.0 mode add/drop filter, convert the (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1) to a (drop-band) TE.sub.0 mode optical signal having the first wavelength (λ.sub.1), and transmit the converted (drop-band) TE.sub.0 mode optical signal having the first wavelength (λ.sub.1) to the photodetector. According to an aspect, the Bragg grating is configured to transmit a non-reflected (pass-band) TE.sub.0 mode optical signal having the second wavelength (λ.sub.2) towards a second TE.sub.0 add/drop filter.

Example Embodiments

(21) Described below is a photonic component or device that operates to strip out or filter TE0 mode light from a multimode waveguide. In one embodiment, a “bus” waveguide comprised of silicon nitride is disposed on a layer of a substrate and remains substantially unchanged along the length of the device. The bus waveguide has a substantially rectangular shape that does not translate (i.e., bend, shift or angle toward or away from a longitudinal axis). The bus waveguide may support at least TE.sub.0, TE.sub.1, and TM.sub.0 guided modes. In one implementation, a lower waveguide comprised of silicon is disposed on a lower layer of the substrate below the bus waveguide, and an upper waveguide comprised of silicon nitride is disposed on an upper layer of the substrate above the bus waveguide. The lower waveguide and the upper layer, in a bend-in region in a first portion of the device, follow substantially the same paths and are translated from non-overlapping positions to overlapping positions with respect to the bus waveguide. The upper and lower waveguides are provided to create a “pseudo-symmetry”, which avoids TE.sub.1-TM.sub.0 mode hybridization. The lower waveguide may taper towards one end of the bend-in region and end. A taper region characterizes a second portion of the device in which the upper waveguide extends toward an end of the device and tapers toward that end.

(22) In a second implementation, the upper waveguide is eliminated and the lower waveguide is disposed further away from the bus waveguide. This increased separation reduces the TM.sub.0 index to avoid mode hybridization.

(23) Those skilled in the art will appreciate that the terms “lower” and “upper” are not meant to suggest strict orientation, and are merely meant to denote a relationship between layers or indicate a relative position, not necessarily that one layer is above or below another layer (e.g., in use, the actual orientation of the device may dictate which layer or waveguide may be referred to as an “upper” or “lower” layer or waveguide, such that the described upper layer or waveguide is actually below the lower layer or waveguide).

(24) More specifically, the present disclosure provides a multimode waveguide with an adiabatic TE.sub.0 mode add/drop filter in the form of a modemux that takes optical power in the TE.sub.0 mode of a high index waveguide, and adiabatically transfers it into the TE.sub.0 mode of a lower index, multimode waveguide. The modemux is designed to have low TE.sub.0-TE.sub.1 cross-talk

by ensuring that when the TE.sub.0 muxing takes place, either: (1) symmetry is used to negate scattering between even and odd modes, or (2) the effective indices of TE.sub.0 (in Si) and TE.sub.1 (in SiN) are substantially different (i.e., result in negligible phase-matching between the two modes).
(25) The overall length of the disclosed device is relatively short. A traditional SiN modemux may be on the order of 200-400 μm long, whereas the modemux described herein is either on the order of ˜100-120 μm long (e.g., first example embodiment of FIGS. **1** and **2**A-**2**C) or on the order of ˜200-250 μm long (e.g., second example embodiment of FIGS. **5**A-**5**B). Thus, the adiabatic modemux of this disclosure has a smaller footprint than many existing modemuxes.
(26) The adiabatic modemux may be used in a WDM filter architecture in the O-band, or in various other applications relating to polarization rotating, multiplexing, TE.sub.1 generation and component characterization. A significant challenge in obtaining a viable modemux using this scheme is overcoming unwanted TE.sub.1-TM.sub.0 mode hybridization. Notably, this challenge can be overcome using the modemux described herein.
(27) As those skilled in the art will come to understand, the photonic component of the present disclosure does not work in the conventional sense, in that the multi-layer modemux transmits TE.sub.1 as TE.sub.1 (instead of converting TE.sub.1 to TE.sub.0 like a standard modemux does), and multiplexes TE.sub.0 onto a TE.sub.1-carrying waveguide.
(28) Reference is now made to the figures, beginning with FIG. **1**, which shows a plan view of a modemux **100**, according to an example embodiment, and to FIGS. **2**A, **2**B and **2**C, which show, respectively, cross-sectional views taken at A-A, B-B, and C-C of modemux **100** shown in FIG. **1**, according to an example embodiment. Modemux **100** comprises two regions: a first region **102** (or “bend in” region) and a second region **106** (or “taper” region). Those skilled in the art will appreciate, however, that these denoted regions are merely meant to help describe the modemux **100**, and are not meant to suggest any clear or specific boundaries between different regions, or that any particular functionality is performed exclusively in any given region.
(29) Modemux **100** is fabricated within/on a substrate **110** (e.g., silicon dioxide) that includes a first edge **112** and a second edge **118**. As shown in FIG. **1**, modemux **100** includes a bus waveguide **120** that is disposed in/on the substrate **110**, and extends between the first edge **112** and the second edge **118** (e.g., along a longitudinal axis **115** in the z-axis direction). The bus waveguide **120** has a first end **122** (at first edge **112** of substrate **110**) and a second end **128** (at second edge **118** of substrate **110**). In an example embodiment, bus waveguide **120** is comprised of silicon nitride (denoted as “SiN 1” in the figures), and has a substantially rectangular cross-section that remains substantially unchanged along its length. The bus waveguide **120** may have a width (in the x-axis direction) of about 1.6 μm, and a thickness (in the y-axis direction) of about 250 nm. The bus waveguide **120** may be bimodal (in TE), thus supporting, at least, both TE.sub.0 and TE.sub.1 modes.
(30) As shown in FIG. **1**, modemux **100** also includes a lower waveguide **130** disposed in/on the substrate **110** below the bus waveguide **120**, and an upper waveguide **140** disposed in/on the substrate **110** above the bus waveguide **120**. Lower waveguide **130** and upper waveguide **140** extend from first edge **112** towards second edge **118**, and at least partially overlie bus waveguide **120**. At the first edge **112** of the substrate **110**, the lower waveguide **130** has an untapered end **132**, and the upper waveguide **140** has a first end **142** that slightly narrows (or tapers) in the x-axis direction (e.g., to better match physical dimensions of prior or follow-on optical components). In an example embodiment, the lower waveguide **130** is comprised of silicon (denoted as “Si” in the figures) and the upper waveguide **140** is comprised of silicon nitride (denoted as “SiN 2” in the figures). The lower waveguide **130** may have a width (in the x-axis direction) that ranges from about 400 nm to 100 nm, and a thickness (in the y-axis direction) of about 110 nm. At the second edge **118** of the substrate **110**, the lower waveguide **130** has a tapered end **138** that narrows (or tapers) in the x-axis direction.
(31) The width of the lower waveguide **130** may remain substantially unchanged in (bend in) first

region **102**, and may gradually narrow or taper in the x-axis direction along the length of (taper) second region **106** (in the z-axis direction, from left to right in FIG. **1**). In an example embodiment, the upper waveguide **140** may have a width (in the x-axis direction) that ranges from about 400 nm to 100 nm, and a thickness (in the y-axis direction) of about 250 nm. The width of the upper waveguide **140** may also narrow or taper in the x-axis direction in (bend in) first region **102** at a second end **144** of the upper waveguide **140**. The first end **142** and the second end **144** of the upper waveguide **140** and the tapered end **138** of the lower waveguide **130** may have a width (in the x-axis direction) of about 100 nm wide at their respective tips.

(32) In (bend in) first region **102**, moving from left to right in FIG. **1**, the lower waveguide **130** (Si) and the upper waveguide **140** (SiN 2) both bend in towards the longitudinal axis **115**. At cross-section A-A, the lower waveguide **130** and the upper waveguide **140** (at untapered end **132** and first end **142**) do not overlap with the bus waveguide **120**. From cross-section A-A to cross-section B-B, the lower waveguide **130** and the upper waveguide **140** both translate in the x-axis direction towards the longitudinal axis **115**, and begin to partially overlap with the bus waveguide **120**. From cross-section B-B to cross-section C-C, the lower waveguide **130** and the upper waveguide **140** both continue translating in the x-axis direction towards the longitudinal axis **115** and both overlap with the bus waveguide **120**. In (taper) second region **106**, continuing from left to right in FIG. **1**, the lower waveguide **130** no longer translates in the x-axis direction. From cross-section C-C to cross section D-D, the lower waveguide **130** overlaps with the bus waveguide **120**.

(33) In an example embodiment, the bus waveguide **120**, the lower waveguide **130**, and the upper waveguide **140** are arranged/patterned/defined on/in a low index (e.g., silicon dioxide) cladding. Also, as shown in FIGS. **2**A, **2**B and **2**C, the lower waveguide **130** and the upper waveguide **140** may be unequally offset from each other with respect to a symmetry axis **125**. That is, in an example embodiment, the lower waveguide **130** may be separated from the bus waveguide **120** (in the y-axis direction) by about 220 nm, while the upper waveguide **140** may be separated from the bus waveguide (in the y-axis direction) by about 100 nm.

(34) In this particular implementation, (bend in) first region **102** (between A-A and C-C) may have a length (in the z-axis direction) of about 75 μm, and (taper) second region **106** (between C-C and D-D) may have a length (in the z-axis direction) of about 25 μm. However, these regions or sections of modemux **100** may have different lengths according to other implementations (e.g., as described below with reference to FIGS. **5**A and **5**B).

(35) FIG. **2**A shows (bend in) first region **102** at cross section A-A of FIG. **1**, where the untapered end **132** of the lower waveguide **130** and the first end **142** of the upper waveguide **140** do not overlap with the first end **122** of the bus waveguide **120**. Bus waveguide **120** (SiN 1) has a width of about 1.6 μm in the x-axis direction, and a thickness of about 250 nm in the y-axis direction. Lower waveguide **130** (Si) has a width of about ˜400 nm in the x-axis direction, and a thickness of about 110 nm in the y-axis direction. There is a gap about 220 nm between the bus waveguide **120** (SiN 1) and the lower waveguide **130** (Si). Upper waveguide **140** (SiN 2) has a length of about ˜400 nm in the x-axis direction, and a width of about 250 nm in the y-axis direction. There is a gap about 100 nm between the bus waveguide **120** (SiN 1) and the upper waveguide **140** (SiN 2). In (bend in) first region **102**, the lower waveguide **130** (Si) and the upper waveguide **140** (SiN 2) both translate (bend inward) in the x-direction (shift from right to left in FIG. **2**A).

(36) FIG. **2**B shows (bend in) first region **102** at cross section B-B of FIG. **1**, where the lower waveguide **130** and the upper waveguide **140** begin to overlap with the bus waveguide **120**. That is, as the lower waveguide **130** (Si) and the upper waveguide **140** (SiN 2) translate (bend in) towards the longitudinal axis **115**, they begin to overlap with the bus waveguide **120** in FIG. **2**B. (Bend in) first region **102** has a length in the z-axis direction of about −75 μm (refer to FIG. **1**). With the disclosed dimensional configuration, there is less than −45 dB of cross-talk (TE.sub.0.fwdarw.TE.sub.1) as shown in FIG. **4**B, and insertion loss (excluding propagation loss) is less than 0.03 dB as shown in FIG. **4**A.

(37) FIG. **2**C shows (taper) second region **106** at cross section C-C of FIG. **1**, where the lower waveguide **130** overlaps with the bus waveguide **120**. In FIG. **2**C, the bus waveguide **120** (SiN 1) maintains the same width of 1.6 μm in the x-axis direction, while the lower waveguide **130** (Si) and the upper waveguide **140** (SiN 2) both narrow (taper) in width in the x-axis direction (e.g., from about ˜400 nm down to about ˜100 nm). (Taper) second region **106** has a length in the z-axis direction of about ˜25 μm (refer to FIG. **1**). Theoretically, no cross-talk occurs in second region **106**. Thus, the modemux **100** has an overall device length on the order of about ˜100 μm and very low cross-talk according to the first example embodiment.
(38) Ideally, the structure shown in FIGS. **2**A-**2**C may not include a second nitride layer (e.g., upper waveguide **140** (SiN 2)). However, when a silicon layer (e.g., lower waveguide **130** (Si)) and a nitride layer (e.g., bus waveguide **120** (SiN 1)) are close to each other, translating the silicon layer (lower waveguide **130**) across the nitride layer (bus waveguide **120**) can result in TE.sub.1-TM.sub.0 mode hybridization. Without a second nitride layer (e.g., upper waveguide **140** (SiN 2)), the structure would be asymmetric in the horizontal axis (the optical axis would have a diagonal component), and would function as a bad polarization rotator (with some of the input light rotated to TM).
(39) In accordance with an embodiment, disposing a nitride component (e.g., upper waveguide **140** (SiN 2)) in the structure shown in FIGS. **2**A, **2**B and **2**C creates a “pseudo-symmetry” (e.g., about symmetry axis **125** shown in FIG. **2**B), such that the structure is symmetric enough in the horizontal axis (with a minimal diagonal component in the optical axis) to prevent this TE.sub.1-TM.sub.0 mode hybridization. Thus, in the first example embodiment, the second nitride layer (e.g., upper waveguide **140** (SiN 2)) shifts together with (and follows the same path as) the silicon layer (e.g., lower waveguide **130** (Si)) to “symmetrize” the design.
(40) FIG. **3**A shows simulated optical power of a TE.sub.0 mode light signal passing through the lower waveguide **130** (Si) and the bus waveguide **120** (SiN 1) of the modemux **100**. The left side of FIG. **3**A shows a cross-section of bus waveguide **120** at first end **122**, lower waveguide **130** at untapered end **132**, and upper waveguide **140** at first end **142** (i.e., at A-A in FIG. **1**). The right side of FIG. **3**A shows a cross-section of bus waveguide **120** at second end **128** and lower waveguide **130** at tapered end **138** (i.e., at D-D in FIG. **1**).
(41) FIG. **3**B shows simulated optical power of a TE.sub.1 mode light signal passing through the bus waveguide **120** (SiN 1) of the modemux **100**. The left side of FIG. **3**B shows a cross-section of bus waveguide **120** at first end **122**, lower waveguide **130** at untapered end **132**, and upper waveguide **140** at first end **142** (i.e., at A-A in FIG. **1**). The right side of FIG. **3**B shows cross-sections of bus waveguide **120** at second end **128** and lower waveguide **130** at tapered end **138** (i.e., at D-D in FIG. **1**).
(42) FIG. **3**C shows simulated optical power of a TE.sub.0 mode light signal passing through the lower waveguide **130** (Si) and the bus waveguide **120** (SiN 1), and simulated optical power of a TE.sub.1 mode light signal passing through the bus waveguide **120** (SiN 1), at relative locations along the length of the modemux **100**. In FIG. **3**C, the lower waveguide **130** (Si) is shown below the bus waveguide **120** (SiN 1), and the upper waveguide **140** (SiN 2) is shown above the bus waveguide **120** (SiN 1). The cross-section designators A-A, B-B, C-C and D-D represent how far along the z-axis direction (refer to FIGS. **1** and **3**A-**3**B) power measurements are detected for purposes of the simulations shown in FIG. **3**C.
(43) As can be seen from FIGS. **3**A, **3**B and **3**C, TE.sub.0 mode light introduced at the untapered end **132** of the lower waveguide **130** passes through the device and exits substantially entirely at the second end **128** of the bus waveguide **120**. TE.sub.1 mode light introduced at the first end **122** of the bus waveguide **120** passes through the device and exits substantially entirely at the second end **128** of the bus waveguide **120**. Notably, the TE.sub.1 mode light is not converted to TE.sub.0 mode light as it passes through the modemux **100** described herein, unlike a standard modemux. Instead, the TE.sub.1 mode light that is input into modemux **100** passes directly through the bus

waveguide **120** with minimal loss. It is also noted that bus waveguide **120** guides both the TE.sub.1 and TE.sub.0 modes.
(44) FIG. **4**A shows simulated TE.sub.1 transmission for (bend in) first region **102** of the modemux **100**, and FIG. **4**B shows simulated TE.sub.0-TE.sub.1 cross-talk for (bend in) first region **102** of the modemux **100**. In a simulation for (bend in) first region **102** of modemux **100**, for a device length of about ˜75-80 μm, there is negligible TE.sub.0 insertion loss and very low TE.sub.1 insertion loss (e.g., about ˜0.025 dB) as shown in FIG. **4**A. There is also low TE.sub.0-TE.sub.1 cross-talk (e.g., less than −45 dB) as shown in FIG. **4**B.
(45) The amount or degree of shifting or translation (bend in) may be linear, or some other slowly varying continuous function, or may be adiabatically calculated, for example. In a simulation for (taper) second region **106** of modemux **100**, for a device length of about ˜25 μm, there is no cross-talk (theoretically), due to symmetry. The lower waveguide **130** (Si) narrows (tapers), but the bus waveguide **120** (SiN 1) does not narrow or taper. The taper shape for the lower waveguide **130** (Si) in (taper) second region **106** of modemux **100** may also be adiabatically calculated, for example.
(46) FIGS. **5**A and **5**B show, respectively, cross-sectional views taken at A-A and C-C of a variation of the modemux **100** shown in FIG. **1**, according to another example embodiment. Instead of using a second nitride layer, such as the upper waveguide **140** (SiN 2) of FIGS. **1** and **2**A-**2**C, FIGS. **5**A-**5**B show a variation of a modemux that ensures the lower waveguide **130** (Si) layer and the bus waveguide **120** (SiN 1) layer are far enough away from each other to avoid the cross-talk. The large separation between these two layers reduces the TM.sub.0 index, avoiding TE.sub.1-TM.sub.0 mode hybridization. As described above, when a silicon layer (e.g., lower waveguide **130**) and a nitride layer (e.g., bus waveguide **120**) are close together, translating the silicon layer across the nitride layer can result in mode hybridization (in the absence of the “pseudo-symmetry” provided by the second nitride waveguide (e.g., upper waveguide **140**) in the first example embodiment above). The second example embodiment of FIGS. **5**A-**5**B does not include the upper waveguide **140** (SiN 2), and instead utilizes a threshold distance between the bus waveguide **120** (SiN 1) and the lower waveguide **130** (Si), to avoid TE.sub.1-TM.sub.0 mode hybridization.
(47) FIG. **5**A shows (bend in) first region **102** at cross section A-A of FIG. **1**. Bus waveguide **120** (SiN 1) has a width (in the x-axis direction) of about 1.6 μm and a thickness (in the y-axis direction) of about 250 nm. Lower waveguide **130** (Si) has a width (in the x-axis direction) of about ˜450 nm and a thickness (in the y-axis direction) of about 110 nm. However, unlike the first example embodiment of FIGS. **1** and **2**A-**2**C, there is not an upper waveguide **140** (SiN 2) in the second example embodiment of FIGS. **5**A-**5**B. Instead, there is a gap **135** that is about 590 nm (in the y-axis direction) separating the bus waveguide **120** (SiN 1) and the lower waveguide **130** (Si). This gap **135** corresponds to a minimum threshold distance (D1) between the bus waveguide **120** (SiN 1) and the lower waveguide **130** (Si) for avoiding the TE.sub.1-TM.sub.0 mode hybridization described above. The lower waveguide **130** (Si) translates (bends inward towards the longitudinal axis **115**) in the x-axis direction (from right to left in FIGS. **5**A and **5**B). In this variation, (bend in) first region **102** has a length (in the z-axis direction) of about ˜70 μm, to ensure low TE.sub.0.fwdarw.TE.sub.1 cross-talk (e.g., less than −40 dB). Insertion loss is also very low.
(48) FIG. **5**B shows (taper) second region **106** at cross section C-C of FIG. **1**. In FIG. **5**B, the bus waveguide **120** maintains the same width of 1.6 μm in the x-axis direction, while the lower waveguide **130** (Si) narrows (tapers) in width in the x-direction (e.g., from about ˜450 nm down to about ˜100 nm). In this variation, (taper) second region **106** has a length (in the z-axis direction) of about ˜140 μm, to have minimal loss at longer wavelengths with no cross-talk (theoretically).
(49) In a wavelength division multiplexing (WDM) filter application, longer wavelength insertion loss is more important than shorter wavelength insertion loss, so this may be tolerable. Otherwise, a length of 180 μm (instead of 140 μm) may be useful for (taper) second region **106** according to the second example embodiment to achieve low loss across the whole O-band. It is also noted that the large gap **135** (e.g., threshold distance (D1)) between the silicon layer (e.g., lower waveguide **130**

(Si)) and the nitride layer (e.g., bus waveguide **120** (SiN 1)) according to the second example embodiment makes for a long and, therefore, potentially sensitive transition (e.g., with respect to fabrication tolerances).

(50) In some example embodiments, an adiabatic optimization algorithm can be used to calculate the profile (shape) of the silicon bend in (e.g., the lower waveguide **130** from untapered end **132** at cross-section A-A to **134** at cross-section C-C in FIG. **1**). The adiabatic algorithm calculates an estimated length of ˜234 μm to achieve more than 99% TE.sub.0 and TE.sub.1 transmission without the second nitride layer (e.g., the upper waveguide **140**) according to the second example embodiment, compared to ˜45 μm for the first example embodiment with the extra nitride layer (e.g., the upper waveguide **140**). Thus, the addition of the upper waveguide **140** (SiN 2) in the first example embodiment of FIGS. **1** and **2**A-**2**C results in a device that is about five times shorter in length compared to the second example embodiment of FIGS. **5**A-**5**B. In addition, cross-talk (TE.sub.1.fwdarw.TE.sub.0) may be considered acceptable without the second nitride layer (upper waveguide **140**), but may not be good enough unless (taper) second region **106** of the device is about ˜140-150 μm long. Further, a device configured according to the second example embodiment of FIGS. **5**A-**5**B may exhibit higher TE.sub.1 insertion loss (scattering into TM.sub.0 and TM.sub.1 modes) compared to a device that is configured according to the first example embodiment of FIGS. **1** and **2**A-**2**C.

(51) FIGS. **6**A and **6**B are functional block diagrams of a modemux **100**, according to an example embodiment. As noted, a standard mux (not shown) converts TE.sub.0 to TE.sub.1. However, the modemux **100** of the present disclosure does not convert TE.sub.0 to TE.sub.1, as shown in FIG. **6**A. Also, if TE.sub.0 is launched into the nitride port (e.g., bus waveguide **120** (SiN 1)) of the modemux **100**, the TE.sub.0 will radiate out from modemux **100**, as shown in FIG. **6**B. This is not true for a standard mux in which TE.sub.0 would not radiate out, but is instead converted to TE.sub.1).

(52) In some example embodiments, the bus waveguide **120** and the upper waveguide **140** may be made of dielectric materials, such as silicon nitride (SiN) or silicon oxynitride (SiON), and the lower waveguide **130** may be made of crystalline materials, such as silicon (Si), LiNbO.sub.3 or InP. Bus waveguide **120**, lower waveguide **130** and upper waveguide **140** may have identical or different thicknesses (in the y-axis direction).

(53) Also, it is noted that modemux **100** can operate in either direction. From left to right in FIG. **1**, modemux **100** operates as a multiplexer (one mode on each of two waveguides to two modes on one waveguide). From right to left in FIG. **1**, modemux **100** operates as a demultiplexer (two modes on one waveguide to one mode of each of two waveguides). This functionality is also easily seen in FIGS. **6**A and **6**B.

(54) FIG. **7** is a flowchart showing a method **700** that includes a series of operations for processing light with a modemux **100**, according to an example embodiment. At step **710**, a photonic component (e.g., modemux **100**) receives a TE.sub.1 mode optical signal on a bus waveguide (SiN). At step **720**, the photonic component receives a TE.sub.0 mode optical signal on a lower waveguide (Si) disposed below the bus waveguide (SiN). At step **730**, the photonic component mode multiplexes the TE.sub.1 mode optical signal and the TE.sub.0 mode optical signal, without converting the TE.sub.0 mode optical signal or the TE.sub.1 mode optical signal to another mode. At step **740**, the photonic component outputs the mode multiplexed TE.sub.0 mode optical signal and TE.sub.1 mode optical signal on the bus waveguide (SiN). The structure and operation of the photonic component (e.g., modemux **100**) are configured to prevent/avoid TE.sub.1-TM.sub.0 mode hybridization of an optical signal that traverses the bus waveguide (SiN).

(55) In this example, the bus waveguide (SiN) is arranged linearly from a first end (e.g., input end) to a second end (e.g., output end) of the photonic component (e.g., modemux **100**). The second waveguide (Si) is arranged non-linearly from the first end to the second end and includes a bend-in section that translates towards the longitudinal axis and over a first portion of the bus waveguide

(SiN), and a tapered section that overlaps with a second portion of the bus waveguide (SiN). The lower waveguide (Si) does not overlap with the first portion of the bus waveguide (SiN) at the first end of the photonic component. The lower waveguide (Si) tapers along a substantially linear portion thereof that extends along the longitudinal axis. The lower waveguide (Si) narrows at the second end of the photonic component.
(56) In one variation of this example (refer to FIGS. **5**A-**5**B), the lower waveguide (Si) and the bus waveguide (SiN) are separated (disposed apart from each other) by at least a minimum threshold distance, which is effective to prevent/avoid (or at least limit/inhibit/reduce) TE.sub.1-TM.sub.0 mode hybridization of an optical signal that traverses the bus waveguide (SiN).
(57) In another variation of this example (refer to FIGS. **1** and **2**A-**2**C), the photonic component (e.g., modemux **100**) further includes an upper waveguide (SiN 2) disposed in the bend-in region on an opposite side above the bus waveguide (SiN 1) relative to the lower waveguide (Si). The upper waveguide (SiN 2) includes a bend-in section that translates towards the longitudinal axis and over the first portion of the bus waveguide (SiN), does not overlap with the first portion of the bus waveguide (SiN 1) at the first end of the device, and substantially matches a path of the bend-in section of the lower waveguide (Si). In an embodiment, the lower waveguide and the upper waveguide are asymmetrically distanced from the bus waveguide, although these waveguides may be similarly distanced in another embodiment. The upper waveguide (SiN 2) and the lower waveguide (Si) create a pseudo-symmetry about the longitudinal axis of the bus waveguide (SiN 1) to prevent/avoid TE.sub.1-TM.sub.0 mode hybridization of an optical signal that traverses the bus waveguide (SiN 1). In this variation, the lower waveguide (Si) and the upper waveguide (SiN 2) may not be disposed apart from the bus waveguide (SiN 1) by some minimum threshold distance in order to effectively prevent/avoid the TE.sub.1-TM.sub.0 mode hybridization.
(58) In an embodiment, the bus waveguide (SiN 1), the lower waveguide (Si) and the upper waveguide (SiN 2) are configured to mode multiplex a first TE.sub.0 mode optical signal with a first TE.sub.1 mode optical signal, without converting the first TE.sub.0 mode optical signal into a second TE mode optical signal. Additionally, or alternatively, the bus waveguide (SiN 1), the lower waveguide (Si) and the upper waveguide (SiN 2) are configured to mode multiplex the first TE.sub.0 mode optical signal with the first TE.sub.1 mode optical signal, without converting the first TE.sub.1 mode optical signal into a second TE.sub.0 mode optical signal.
(59) Example Use Case Device (Bragg-Based Demultiplexer)
(60) Example applications for the design of the modemux **100** of this disclosure, which may be implemented according to either the first example embodiment of FIGS. **1** and **2**A-**2**C or the second example embodiment of FIGS. **5**A-**5**B, are described below with reference to FIGS. **8-12**.
(61) TE.sub.HO represents a “higher order TE-mode” (TE.sub.A where A integer and A>0), where a “TE-mode” is defined as a mode that is substantially TE-polarized. This notation is used to indicate the architecture is compatible with all higher-order modes, not just TE.sub.1, which is typically used in many instances. The example embodiments described herein and illustrated in the drawings generally use TE.sub.HO=TE.sub.1. However, this is not a requirement and does not imply any loss of generality to the architecture described herein for other higher order TE-modes.
(62) An example architecture for a Bragg-based WDM may use some form of modemux and a Bragg grating. The Bragg converts TE.sub.0 to TE.sub.HO (e.g., TE.sub.1), and the modemux multiplexes inputs from two single-mode (TE.sub.0) waveguides onto two modes (TE.sub.0 and TE.sub.HO) of one multimode output waveguide. TE.sub.0 from input A is passed through to TE.sub.0 on the output, and TE.sub.0 from input B is converted to TE.sub.HO on the output (TE.sub.0,A<.fwdarw.TE.sub.0,B and TE.sub.0,B<.fwdarw.TE.sub.HO). An existing architecture may rely on a modemux that performs the TE.sub.0,A<.fwdarw.TE.sub.0 and the TE.sub.0,B<.fwdarw.TE.sub.HO in a single component, in which multiplexing and mode conversion are done as a single step.
(63) A first typical Bragg-based demultiplexing architecture consists of a Bragg grating that

converts TE.sub.0<.fwdarw.TE.sub.1 excited through a directional coupler style multiplexer. The directional coupler style multiplexer (or “coupler mux”) couples TE.sub.0 from one port to TE.sub.1 on output (conversion), and passes TE.sub.0 from the other port as TE.sub.0 on output (pass). The multiplexing principle behind this typical architecture is that the multiplexing directional coupler relies on phase-matching the TE.sub.0 mode of a single waveguide to the TE.sub.1 of a multimode waveguide. However, this style of coupler mux is essentially unusable for integrated WDM receiver requirements because phase matching of TE.sub.0 of a single-mode waveguide to TE.sub.1 of a multimode waveguide will generally occur precisely at one wavelength, resulting in an unacceptable bandwidth, and there will still be phase matching from TE.sub.0 in the single-mode waveguide to TE.sub.0 in the multimode waveguide, causing large cross-talk.

(64) A second typical Bragg-based demultiplexing architecture consists of a Bragg grating that converts TE.sub.0<.fwdarw.TE.sub.1 excited through an adiabatic modemux. The “modemux” couples TE.sub.0 from one port to TE.sub.1 on output (conversion), and passes TE.sub.0 from the other port as TE.sub.0 on output (pass). The multiplexing principle behind this typical architecture is that the modemux relies on a single component to convert TE.sub.0 to TE.sub.1 of a multimode waveguide, while transmitting TE.sub.0 to that multimode waveguide. On one side of the modemux, there are two single mode waveguides, which give rise to a pair of “degenerate” (or very similar) waveguide TE.sub.0-like modes. These modes are phase matched, and can easily couple unless well isolated. To perform the modemuxing operation, converting one of these two modes to TE.sub.1 is to be performed, in some manner without causing cross-talk. In other words, a device may be designed to perturb a first input TE.sub.0 mode signal into an output TE.sub.1 mode signal, without causing any scattering into an output TE.sub.0 mode signal. However, this is a difficult task when the first input TE.sub.0 mode signal and a second input TE.sub.0 mode signal are phase matched towards one side of the modemux. Furthermore, because this is all done in SiN, the index contrast between the output TE.sub.0 mode signal and the output TE.sub.1 mode signal cannot be that high. This architecture requires at least a 200 um long modemux (likely 300-400 um), and is reliant on stable nitride thickness, etc. Most of the “length” in this modemux is due to the output bends of the modemux. It is very difficult to get low cross-talk as the waveguide becomes degenerate.

(65) Thus, some typical architectures may use a regular modemux (e.g., a standard, traditional, or conventional modemux), in which TE.sub.0 is multiplexed into a multimode waveguide at the same time that TE.sub.0 is converted into TE.sub.1 of the multimode waveguide. However, because both operations occur at once, cross-talk is compromised. In some typical schemes, the whole block (i.e., standard modemux and Bragg) ideally has very low cross-talk (‘TE.sub.0’.fwdarw.TE.sub.1 and ‘TE.sub.1’.fwdarw.TE.sub.0 cross talks are ideally both extremely low). Therefore, the typical Bragg-based demultiplexing architectures described above struggle to deliver low return loss due to difficulty implementing a compact, robust, low cross-talk modemux.

(66) Accordingly, the present disclosure provides a wavelength division multiplexing (WDM) architecture based on an integrated Bragg (e.g., Bragg grating **810**) and adiabatic mode add/drop filter (e.g., modemux **100**), also referred to herein as a Bragg-based demultiplexer **800** as described below with reference to FIG. **8**. As shown in FIG. **8**, a Bragg-based demultiplexer **800** utilizes a novel multiplexing (or “modemuxing”) functionality through a combination of two distinct components that: (1) adiabatically transmit TE.sub.0 from A to TE.sub.0 on a multimode waveguide, while also transmitting a B input that is TE.sub.HO to TE.sub.HO on the same multimode waveguide (via the “adiabatic TE.sub.0 mode add/drop filter” **100** functionality), and (2) separately convert a TE.sub.0-like input to the input B TE.sub.HO mode (via the “TE1.fwdarw.TE0 mode converter” **850** functionality).

(67) FIG. **8** is a block diagram of a use case device for an adiabatic TE.sub.0 mode add/drop filter (modemux) **100** to provide a Bragg-based demultiplexer (also referred to as an integrated Bragg-

based WDM architecture), according to an example embodiment. In particular, as shown in FIG. **8**, the Bragg-based demultiplexer **800** (or simply, apparatus **800**) includes a (backward-reflecting) Bragg grating **810**, and is further implemented using a multimode waveguide with an adiabatic TE.sub.0 mode add/drop filter **100** (modemux **100** as described above), along with a TE.sub.1.fwdarw.TE.sub.0 mode converter **850** component as further described below. The TE.sub.0 add/drop filter (modemux) **100** has a unique design, in that it does not convert a TE.sub.0 mode optical signal to a TE.sub.1 mode optical signal and/or does not convert a TE.sub.1 mode optical signal to a TE.sub.0 mode optical signal when performing a multiplexing (or modemuxing) operation. The mode converter **850** may be connected to a photodetector **870** (GePD) via one or more waveguides **852**, **854** (waveguide **854** may be optional in some example embodiments). The mode converter **850** is a component that is configured to convert TE.sub.1 in a multi-mode SiN waveguide into an optical signal (e.g., TE.sub.0 mode light or ˜99% TE.sub.0-like mode light) that can be detected by the photodetector **870** (GePD), for example.
(68) More specifically, referring to FIG. **8**, the TE.sub.0 add/drop filter **100** includes a lower waveguide **130** (e.g., a single-mode Si waveguide) that is configured to receive a TE.sub.0 mode optical signal having two or more wavelengths (e.g., λ.sub.1, λ.sub.2, . . . , λ.sub.N), and a bus waveguide **120** (e.g., a multimode SiN waveguide) that is connected with the Bragg **810** and is configured to (modemux and) transmit the TE.sub.0 mode optical signal (all wavelengths λ.sub.1-λ.sub.N) to the Bragg **810**, without converting the TE.sub.0 mode optical signal to another mode (e.g., TE.sub.1).
(69) The Bragg **810** is configured to receive the TE.sub.0 mode optical signal (all as) from the TE.sub.0 add/drop filter **100** on the multimode (SiN) bus waveguide **120**, and reflect a first portion of the TE.sub.0 mode optical signal having a particular wavelength (e.g., λ.sub.P, which is one of λ.sub.1, λ.sub.2, . . . , λ.sub.N) back to the TE.sub.0 add/drop filter **100** on the bus waveguide **120**. The operation of reflecting the first portion of the TE.sub.0 mode optical signal (λ.sub.P) converts this optical signal to a (drop-band) TE.sub.1 mode optical signal having that particular wavelength (λ.sub.P). The TE.sub.0 add/drop filter **100** is further configured to receive the reflected (drop-band) TE.sub.1 mode optical signal at the particular wavelength (λ.sub.P) from the Bragg **810** on the bus waveguide **120**, and (modemux and) transmit the reflected (drop-band) TE.sub.1 mode optical signal (λ.sub.P) on the bus waveguide **120** towards a photodetector (GePD) **870** (i.e., via the mode converter **850**), without converting the reflected (drop-band) TE.sub.1 mode optical signal (λ.sub.P) to another mode (e.g., TE.sub.0).
(70) The TE.sub.1.fwdarw.TE.sub.0 mode converter **850** is configured to receive the (drop-band) TE.sub.1 mode optical signal at the particular wavelength (λ.sub.P) from the TE.sub.0 add/drop filter **100** on the bus waveguide **120**, and convert the (drop-band) TE.sub.1 mode optical signal having the particular wavelength (λ.sub.P) to a (drop-band) TE.sub.0 mode optical signal having the particular wavelength (λ.sub.P). The mode converter **850** is connected with the photodetector (GePD) **870** via a waveguide **852** (e.g., a single-mode Si waveguide), and is further configured to transmit the converted (drop-band) TE.sub.0 mode optical signal at the particular wavelength (λ.sub.P) to the photodetector (GePD) **870** on the single-mode (Si) waveguide **852**. The photodetector (GePD) **870** is configured to receive and detect the converted (drop-band) TE.sub.0 mode optical signal at the particular wavelength (λ.sub.P) that is received from the mode converter **850**.
(71) In some example embodiments, the Bragg **810** may be further connected with an inter-layer transition **814** via a waveguide **812** (e.g., a multimode SiN waveguide), and is configured to transmit a (pass-band) TE.sub.0 mode optical signal to the inter-layer transition **814** on the multimode (SiN) waveguide **812**, where the (pass-band) TE.sub.0 mode optical signal corresponds to a second portion of the TE.sub.0 mode optical signal having one or more wavelengths (e.g., λ.sub.1, λ.sub.2, . . . , λ.sub.N) other than the particular wavelength (λ.sub.P) that is not reflected by (and passes through) the Bragg **810**.

(72) Thus, multiple Bragg-based demultiplexers may be cascaded together in stages, as further described below with reference to FIG. **10**, in order to reflect and detect a (drop-band) optical signal having a respective wavelength in a given stage, while allowing a (pass-band) optical signal having other wavelengths to pass through to the next stage for further processing. Instead of performing multiplexing (modemuxing) and mode conversion (TE.sub.1.fwdarw.TE.sub.0 or TE.sub.0.fwdarw.TE.sub.1) in a single device/operation (which may result in undesirable cross-talk as described above), the apparatus **800** has a device structure that separately performs multiplexing/modemuxing and mode conversion in two distinct devices/operations in a manner that minimizes or reduces cross-talk.
(73) The modemux **100** shown in FIG. **8** avoids any potential degeneracies between waveguides, in contrast to the second typical architecture (standard modemux) described above. n.sub.eff of TE.sub.0 never matches (or nearly matches) n.sub.eff of TE.sub.1. Also, the modemux **100** shown in FIG. **8** is, in one embodiment, operated entirely in the adiabatic regime, remaining broadband, in contrast to the first typical architecture (coupler mux) described above. The modemux **100** of FIG. **8** may use multiple waveguiding materials (SiN and Si) to ensure that there is minimal phase matching between TE.sub.0 and TE.sub.1, so cross-talk is extremely low.
(74) Unlike the typical architectures described above, the proposed architecture (e.g., apparatus **800**) described herein uses two different adiabatic components having a configuration that separately muxes TE.sub.0 and TE.sub.1 in one component (adiabatic TE.sub.0 mode add/drop filter **100**), and converts TE.sub.1 to TE.sub.0-like mode(s) in another component (TE.sub.1-TE.sub.0 mode converter **850**, as shown in FIG. **8**). Thus, the device of FIG. **8** converts TE.sub.0<.fwdarw.TE.sub.1 independently of muxing onto the multimode waveguide. Notably, TE.sub.0 is muxed onto the multimode waveguide once TE.sub.1 is fully present. In this device, cross-talk is irrelevant at the TE.sub.1.fwdarw.TE.sub.0 mode converter **850** block of FIG. **8**, where there is an arbitrary number of ports on the output side shown on the left (depending on implementation/requirements). In the present embodiments, the adiabatic TE.sub.0 mode add/drop filter **100** block (modemux component) of FIG. **8** is designed to have very low cross-talk (for TE.sub.0.fwdarw.TE.sub.1 and T.sub.1.fwdarw.TE.sub.0 conversion), which can be achieved using different materials to create a large phase mismatch according to one example embodiment, and/or to create symmetry according to another example embodiment, as described above with reference to FIGS. **1**-**7**, for example. One advantage of the proposed architecture (apparatus **800**) described herein is that, by utilizing the modemux **100** described above, the apparatus **800** (Bragg-based demultiplexer) can be made very low cross-talk (meeting the return loss specification), is low insertion loss, and is compact.
(75) According to an aspect of the present disclosure, an inter-layer transition may be used to convert from the modemux **100**/Bragg **810** layer (on a multimode SiN waveguide) to the photodetector (GePD) **870** layer (on a single-mode Si waveguide). The typical architectures described above (e.g., using a standard modemux) make use of a transition block with one input (e.g., SiN or Si) and one output (e.g., Si or SiN). However, in the proposed architecture (apparatus **800** of FIG. **8**), a TE.sub.1.fwdarw.TE.sub.0 mode converter **850** is utilized in addition to the TE.sub.0 add/drop filter (modemux) **100**, as shown in FIG. **8**.
(76) Next, three example implementations (options A, B, and C) for the "TE.sub.1.fwdarw.TE.sub.0 mode converter" **850** of FIG. **8**, which converts TE.sub.1 in multimode SiN waveguide into TE.sub.0, are described in further detail below with reference to FIGS. **9**A, **9**B, and **9**C, respectively. FIG. **9**A shows a mode converter **950**(A) (option A) including a "3 dB transition" **951**, which provides an adiabatic splitter/transition (SiN/Si) all in one, and is compact (e.g., ˜50 um). The mode converter **950**(A) may also be referred to as a "bilayer photonic 3 dB y-splitter," for example. FIG. **9**B shows a mode converter **950**(B) (option B) including a straight-forward "3 dB multimode y-splitter" **953** (SiN), with standard interlayer (SiN.fwdarw.Si) transitions **955**(**1**), **955**(**2**). FIG. **9**C shows a mode converter **950**(C) (option C) including a standard

modemux **957** (SiN) with standard interlayer (SiN.fwdarw.Si) transitions **955**(**1**), **955**(**2**), but without a stringent cross-talk requirement. Hence, it will be very compact. As indicated with dashed lines in FIG. **9**C, the “TE.sub.0” port is optionally routed to the photodetector (GePD) **870** of FIG. **8**, which may slightly boost power to the photodetector **870** if cross-talk is particularly bad. Otherwise, the mode converter **950**(C) may have one output (the “TE.sub.1” port) in this example.
(77) As described above, the integrated Bragg-based WDM architecture of FIG. **8** utilizes the novel multiplexing (or modemuxing) functionality embodied by adiabatic TE.sub.0 mode add/drop filter (modemux) **100**, in which the modemux **100** does not attempt to convert an input TE.sub.0 mode optical signal of an individual (or “single-mode”) waveguide into an output TE.sub.1 mode optical signal (or vice versa) as described above, in contrast to some typical architectures (e.g., using a standard modemux). Instead, the adiabatic TE.sub.0 mode add/drop filter (modemux) **100** shown in FIG. **8** has both a multimode input (bus waveguide **120**) and a single-mode input (lower waveguide **130**), for transmitting a TE.sub.1 mode optical signal as a TE.sub.1 mode optical signal, while adiabatically transferring the TE.sub.0 mode optical signal (or vice versa). As used herein, the phrase “without converting” or “does not convert” may comprise not only full/complete (100%) avoidance of mode conversion, but also something that substantially/significantly/nearly completely (e.g., 90%, 95%, 98%, 99.9%, etc.) avoids mode conversion. The modemux **100** described herein can be used for an integrated Bragg-based WDM architecture on a receiver, for example, as described below with reference to FIG. **10**.
(78) FIG. **10** shows a proposed integrated Bragg-based WDM architecture using the example implementations described above. FIG. **10** is a block diagram of a full Bragg-based WDM architecture **1000** that provides a three-stage demultiplexing architecture for separating out four wavelengths, according to an example embodiment. The full Bragg-based WDM architecture **1000** (or simply, apparatus **1000**) includes a first Bragg-based demultiplexer **800**(**1**), a second Bragg-based demultiplexer **800**(**2**), and a third Bragg-based demultiplexer **800**(**3**) each having an identical or substantially similar configuration as apparatus **800** of FIG. **8** and designed for a respective wavelength.
(79) More specifically, referring to FIG. **10**, the first apparatus **800**(**1**) includes a first adiabatic TE.sub.0 mode add/drop filter (modemux) **100**(**1**), a first Bragg **810**(**1**), and a first TE.sub.1.fwdarw.TE.sub.0 mode converter **850**(**1**). The first TE.sub.0 add/drop filter **100**(**1**) includes a first lower waveguide **130**(**1**) (e.g., a single-mode Si waveguide) that is configured to receive a TE.sub.0 mode optical signal having two or more wavelengths (e.g., four wavelengths in the example of FIG. **10**, which are collectively denoted as “all as”), and a first bus waveguide **120**(**1**) (e.g., a multimode SiN waveguide) that is connected with the first Bragg **810**(**1**) and is configured to (modemux and) transmit the TE.sub.0 mode optical signal (all as) to the first Bragg **810**(**1**) without converting the TE.sub.0 mode optical signal to another mode (e.g., TE.sub.1).
(80) The first Bragg **810**(**1**) is configured to receive the TE.sub.0 mode optical signal (all as) from the first TE.sub.0 add/drop filter **100**(**1**) on the first bus waveguide **120**(**1**), and reflect a first portion of the TE.sub.0 mode optical signal having a first wavelength (λ.sub.1) back to the first TE.sub.0 add/drop filter **100**(**1**) on the first bus waveguide **120**(**1**). The operation of reflecting the first portion of the TE.sub.0 mode optical signal (λ.sub.1) converts this optical signal to a first (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1). The first TE.sub.0 add/drop filter **100**(**1**) is further configured to receive the reflected first (drop-band) TE.sub.1 mode optical signal at the first wavelength (λ.sub.1) from the first Bragg **810**(**1**) on the first bus waveguide **120**(**1**), and (modemux and) transmit the reflected first (drop-band) TE.sub.1 mode optical signal (λ.sub.1) on the first bus waveguide **120**(**1**) towards a first photodetector (GePD) **870**(**1**) (i.e., via the first mode converter **850**(**1**)), without converting the reflected first (drop-band) TE.sub.1 mode optical signal (λ.sub.1) to another mode (e.g., TE.sub.0).
(81) The first TE.sub.1.fwdarw.TE.sub.0 mode converter **850**(**1**) is configured to receive the first (drop-band) TE.sub.1 mode optical signal at the first wavelength (λ.sub.1) from the first TE.sub.0

add/drop filter **100**(**1**) on the first bus waveguide **120**(**1**), and convert the first (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1) to a first (drop-band) TE.sub.0 mode optical signal having the first wavelength (λ.sub.1). The first mode converter **850**(**1**) is connected with the first photodetector (GePD) **870**(**1**) via a waveguide **852**(**1**) (e.g., a single-mode Si waveguide), and is further configured to transmit the converted first (drop-band) TE.sub.0 mode optical signal (λ.sub.1) to the first photodetector (GePD) **870**(**1**) on the waveguide **852**(**1**). The first photodetector (GePD) **870**(**1**) is configured to receive and detect the converted first (drop-band) TE.sub.0 mode optical signal at the first wavelength (λ.sub.1) that is received from the first mode converter **850**(**1**).
(82) In the example embodiment of FIG. **10**, the first Bragg **810**(**1**) is further connected with a first inter-layer transition **814**(**1**) via a waveguide **812**(**1**) (e.g., a multimode SiN waveguide), and is configured to transmit a first (pass-band) TE.sub.0 mode optical signal to the first transition **814**(**1**) on the waveguide **812**(**1**), where the first (pass-band) TE.sub.0 mode optical signal corresponds to a second portion of the TE.sub.0 mode optical signal having one or more wavelengths (e.g., three wavelengths denoted as λ.sub.2, λ.sub.3, λ.sub.4) other than the first wavelength (λ.sub.1) that is not reflected by (and passes through) the first Bragg **810**(**1**).
(83) The first transition **814**(**1**) is configured to receive the first (pass-band) TE.sub.0 mode optical signal having the other wavelengths (λ.sub.2, λ.sub.3, λ.sub.4) on the waveguide **812**(**1**), and transmit the first (pass-band) TE.sub.0 mode optical signal (λ.sub.2, λ.sub.3, λ.sub.4) towards a second adiabatic TE.sub.0 mode add/drop filter **100**(**2**) of the second apparatus **800**(**2**). The first transition **814**(**1**) is connected to the second TE.sub.0 add/drop filter **100**(**2**) via one or more waveguides (e.g., waveguide **816**(**1**) and waveguide **818**(**1**)) connected with a second lower waveguide **130**(**2**) (e.g., a single-mode Si waveguide) of the second TE.sub.0 add/drop filter **100**(**2**). The waveguide **816**(**1**) and the waveguide **818**(**2**) may be single-mode (Si) waveguides, for example, where the waveguide **818**(**2**) forms a bend or curve (denoted as "180 degree Si clothoid" **818**(**1**) in FIG. **10**). Thus, in this manner the first apparatus **800**(**1**) and the second apparatus **800**(**2**) are cascaded together in stages in order to reflect and detect a (drop-band) optical signal having a first wavelength (λ.sub.1) in the first stage, while allowing a (pass-band) optical signal having other wavelengths (λ.sub.2, λ.sub.3, λ.sub.4) to pass through (to the second stage) for further processing, and effectively limiting cross-talk.
(84) Likewise, the second apparatus **800**(**2**) includes the second adiabatic TE.sub.0 mode add/drop filter (modemux) **100**(**2**), a second Bragg **810**(**2**), and a second TE.sub.1.fwdarw.TE.sub.0 mode converter **850**(**2**). The second TE.sub.0 add/drop filter **100**(**2**) includes the second lower waveguide **130**(**2**) (e.g., a single-mode Si waveguide) that is configured to receive the first (pass-band) TE.sub.0 mode optical signal having the other wavelengths (e.g., λ.sub.2, λ.sub.3, λ.sub.4) other than the first wavelength (λ.sub.1) from the first Bragg **810**(**1**) via the first transition **814**(**1**) and the waveguides **816**(**1**), **818**(**1**). The second TE.sub.0 add/drop filter **100**(**2**) also includes a second bus waveguide **120**(**2**) (e.g., a multimode SiN waveguide) that is connected with the second Bragg **810**(**2**) and is configured to (modemux and) transmit the first (pass-band) TE.sub.0 mode optical signal at the other wavelengths (λ.sub.2, λ.sub.3, λ.sub.4) to the second Bragg **810**(**2**), without converting the first (pass-band) TE.sub.0 mode optical signal (λ.sub.2, λ.sub.3, λ.sub.4) to another mode (e.g., TE.sub.1). The second Bragg **810**(**2**) receives the first (pass-band) TE.sub.0 mode optical signal (λ.sub.2, λ.sub.3, λ.sub.4) from the second TE.sub.0 add/drop filter **100**(**2**) on the second bus waveguide **120**(**2**), and reflects a first portion of the first (pass-band) TE.sub.0 mode optical signal having a second wavelength (λ.sub.2) back to the second TE.sub.0 add/drop filter **100**(**2**) on the second bus waveguide **120**(**2**), while also converting this optical signal to a second (drop-band) TE.sub.1 mode optical signal having the second wavelength (λ.sub.2). The second TE.sub.0 add/drop filter **100**(**2**) receives the reflected second (drop-band) TE.sub.1 mode optical signal having the second wavelength (λ.sub.2) from the second Bragg **810**(**2**) on the second bus waveguide **120**(**2**), and transmits the reflected second (drop-band) TE.sub.1 mode optical signal

(λ.sub.2) on the second bus waveguide **120**(**2**) towards a second photodetector (GePD) **870**(**2**) (i.e., via the second mode converter **850**(**2**)), without converting the second (drop-band) TE.sub.1 mode optical signal (λ.sub.2) to another mode (e.g., TE.sub.0).

(85) The second TE.sub.1.fwdarw.TE.sub.0 mode converter **850**(**2**) receives the second (drop-band) TE.sub.1 mode optical signal at the second wavelength (**0**.**2**) from the second TE.sub.0 add/drop filter **100**(**2**) on the second bus waveguide **120**(**2**), converts the second (drop-band) TE.sub.1 mode optical signal having the second wavelength (λ.sub.2) to a second (drop-band) TE.sub.0 mode optical signal having the second wavelength (λ.sub.2), and transmits the converted second (drop-band) TE.sub.0 mode optical signal (λ.sub.2) to the second photodetector (GePD) **870**(**2**) on the waveguide **852**(**2**), where the second photodetector (GePD) **870**(**2**) receive and detects the converted second (drop-band) TE.sub.0 mode optical signal at the second wavelength (λ.sub.2) that is received from the second mode converter **850**(**2**). The second Bragg **810**(**2**) is connected with a second inter-layer transition **814**(**2**) via a waveguide **812**(**2**) (e.g., a multimode SiN waveguide), and transmits a second (pass-band) TE.sub.0 mode optical signal to the second transition **814**(**2**) on the waveguide **812**(**2**), where the second (pass-band) TE.sub.0 mode optical signal corresponds to a second portion of the first (pass-band) TE.sub.0 mode optical signal having other wavelengths (e.g., λ.sub.3, λ.sub.4) other than the second wavelength (λ.sub.2) that is not reflected by (and passes through) the second Bragg **810**(**2**). The second transition **814**(**2**) receives the second (pass-band) TE.sub.0 mode optical signal at the other wavelengths (λ.sub.3, λ.sub.4) on the waveguide **812**(**2**), and transmits the second (pass-band) TE.sub.0 mode optical signal (λ.sub.3, λ.sub.4) towards a third adiabatic TE.sub.0 mode add/drop filter **100**(**3**) via one or more waveguides (e.g., a single-mode Si waveguide **816**(**2**), and a bent/curved (180 degree single-mode Si clothoid) waveguide **818**(**2**)) connected with a third lower waveguide **130**(**3**) (e.g., a single-mode Si waveguide) of the third TE.sub.0 add/drop filter **100**(**3**). Thus, the second apparatus **800**(**2**) and the third apparatus **800**(**3**) are cascaded together in stages in order to reflect and detect a (drop-band) optical signal having a second wavelength (λ.sub.2) in the second stage, while allowing a (pass-band) optical signal having other wavelengths (λ.sub.3, λ.sub.4) to pass through (to the third stage) for further processing, and effectively limiting cross-talk.

(86) Likewise, the third apparatus **800**(**3**) includes the third adiabatic TE.sub.0 mode add/drop filter (modemux) **100**(**3**), a third Bragg **810**(**3**), and a third TE.sub.1.fwdarw.TE.sub.0 mode converter **850**(**3**). The third TE.sub.0 add/drop filter **100**(**3**) includes the third lower waveguide **130**(**3**) (e.g., a single-mode Si waveguide) that is configured to receive the second (pass-band) TE.sub.0 mode optical signal having the other wavelengths (e.g., λ.sub.3, λ.sub.4) other than the second wavelength (λ.sub.2) from the second Bragg **810**(**2**) via the second transition **814**(**2**) and the waveguides **816**(**2**), **818**(**2**). The third TE.sub.0 add/drop filter **100**(**3**) also includes a third bus waveguide **120**(**3**) (e.g., a multimode SiN waveguide) that is connected with the third Bragg **810**(**3**) and is configured to (modemux and) transmit the second (pass-band) TE.sub.0 mode optical signal at the other wavelengths (λ.sub.3, λ.sub.4) to the third Bragg **810**(**3**), without converting the second (pass-band) TE.sub.0 mode optical signal (λ.sub.3, λ.sub.4) to another mode (e.g., TE.sub.1). The third Bragg **810**(**3**) receives the second (pass-band) TE.sub.0 mode optical signal (λ.sub.3, λ.sub.4) from the third TE.sub.0 add/drop filter **100**(**3**) on the third bus waveguide **120**(**3**), and reflects a first portion of the second (pass-band) TE.sub.0 mode optical signal having a third wavelength (λ.sub.3) back to the third TE.sub.0 add/drop filter **100**(**3**) on the third bus waveguide **120**(**3**), while also converting this optical signal to a third (drop-band) TE.sub.1 mode optical signal having the third wavelength (λ.sub.3). The third TE.sub.0 add/drop filter **100**(**3**) receives the reflected third (drop-band) TE.sub.1 mode optical signal at the third wavelength (λ.sub.3) from the third Bragg **810**(**3**) on the third bus waveguide **120**(**3**), and (modemuxes and) transmits the reflected third (drop-band) TE.sub.1 mode optical signal (λ.sub.3) on the third bus waveguide **120**(**2**) towards a third photodetector (GePD) **870**(**3**) (i.e., via the third mode converter **850**(**3**)), without converting the third (drop-band) TE.sub.1 mode optical signal (λ.sub.3) to another mode (e.g., TE.sub.0).

(87) The third TE.sub.1.fwdarw.TE.sub.0 mode converter **850**(**3**) receives the third (drop-band) TE.sub.1 mode optical signal at the third wavelength (λ.sub.3) from the third TE.sub.0 add/drop filter **100**(**3**) on the third bus waveguide **120**(**3**), converts the third (drop-band) TE.sub.1 mode optical signal having the third wavelength (λ.sub.3) to a third (drop-band) TE.sub.0 mode optical signal having the third wavelength (λ.sub.3), and transmits the converted third (drop-band) TE.sub.0 mode optical signal (λ.sub.3) to the third photodetector (GePD) **870**(**3**) on the waveguide **852**(**3**), where the third photodetector (GePD) 870(3) receives and detects the converted third (drop-band) TE.sub.0 mode optical signal at the third wavelength (λ.sub.3) that is received from the third mode converter **850**(**3**). The third Bragg **810**(**3**) is further connected with a third inter-layer transition **814**(**3**) via a waveguide **812**(**3**) (e.g., a multimode SiN waveguide), and transmits a third (pass-band) TE.sub.0 mode optical signal to the third transition **814**(**3**) on the waveguide **812**(**3**), where the third (pass-band) TE.sub.0 mode optical signal corresponds to a second portion of the second (pass-band) TE.sub.0 mode optical signal having other wavelengths (e.g., λ.sub.4) other than the third wavelength (λ.sub.3) that is not reflected by (and passes through) the third Bragg **810**(**3**). The third transition **814**(**3**) receives the third (pass-band) TE.sub.0 mode optical signal (λ.sub.4) on the waveguide **812**(**3**), and transmits the third (pass-band) TE.sub.0 mode optical signal (λ.sub.4) (which, in this example corresponds to a fourth (drop-band) TE.sub.0 mode optical signal having the fourth wavelength (λ.sub.4)) to a fourth photodetector (GePD) **870**(**4**) on the waveguide **816**(**3**) (e.g., a single-mode Si waveguide), where the fourth photodetector **870**(**4**) receives and detects the third (pass-band) TE.sub.0 mode optical signal having the fourth wavelength (λ.sub.4) (i.e., receives and detects the fourth (drop-band) TE.sub.0 mode optical signal having the fourth wavelength (λ.sub.4)). Thus, the third apparatus **800**(**3**) reflects and detects a (drop-band) optical signal having a third wavelength (λ.sub.3) in the third stage, while allowing a (pass-band) optical signal having the other wavelengths (λ.sub.4) to pass through for further processing (to the fourth photodetector **870**(**4**) that detects the fourth (drop-band) TE.sub.0 optical signal having the fourth wavelength (λ.sub.4)), and effectively limiting cross-talk.
(88) Although three stages including three apparatuses **800** (Bragg-based demultiplexers, with three adiabatic TE.sub.0 mode add/drop filters (modemuxes) **100**, three Braggs **810**, and three TE.sub.1.fwdarw.TE.sub.0 mode converters **850**) are shown in FIG. **10**, this is intended to be illustrative only and is non-limiting in nature. Other example embodiments could comprise fewer or more (two, fourth, five, etc.) stages and corresponding apparatuses **800**, depending on the specific implementation and/or the number of distinct wavelengths (as) to be detected, for example.
(89) As shown in FIG. **10**, three Bragg-based demultiplexers **800** (e.g., apparatus **800**(**1**), **800**(**2**), **800**(**3**) of FIG. **10** with Braggs **810**(**1**), **810**(**2**), and **810**(**3**), respectively) are utilized in a full Bragg-based WDM architecture **1000**, where each Bragg-based demultiplexer **800** is connected using silicon (Si) waveguides forming 180 degree bends (e.g., 180 degree Si clothoids **818**(**1**), **818**(**2**) of FIG. **10**). Since the adiabatic TE.sub.0 mode add/drop filter (modemux) **100** has a silicon (Si) input (lower waveguide **130**), an added benefit of the proposed architectures described herein is that a silicon.fwdarw.nitride interlayer transition (or “Si.fwdarw.SiN transition”) is not needed, since it is already built into the TE.sub.0 mode add/drop filter **100**. As described above with reference to FIGS. **1**, **2**A-**2**C, **3**A-**3**B, and **4**A-**4**B, an example implementation of a modemux **100** of FIG. **8** (the “TE.sub.0 mode add/drop filters” **100**(**1**), **100**(**2**), **100**(**3**) of FIG. **10**) is expected to have cross-talk (TE.sub.0.Math.TE.sub.1) of <−45 dB, an insertion loss (excluding propagation loss)<0.03 dB, and a total length of about ˜100 um.
(90) The proposed full Bragg-based WDM architecture shown in FIG. **10** (apparatus **1000**, with three Bragg-based demultiplexers **800**) and described above assumes the usage of the following components: (1) the example implementation of the “adiabatic TE.sub.0 mode add/drop filter” **100** for modemux **100**) described above with reference to FIGS. **1**, **2**A-**2**B, **3**A-**3**B, and **4**A-**4**B, and (2) the example implementation of the “TE.sub.1.fwdarw.TE.sub.0 mode converter” **950**(A) (option A for mode converter **850**) described above with reference to FIG. **9**A. However, this is merely

intended to be illustrative and non-limiting in nature, and other example implementations are also possible, such as the second example embodiment of the modemux **100** described above with reference to FIGS. **5**A-**5**B, and/or the "TE.sub.1.fwdarw.TE.sub.0 mode converter" **950**(B) or **950**(C) (options B or C for mode converter **850**) described above with reference to FIGS. **9**B and **9**C), for example.

(91) FIG. **11** is a block diagram of another use case device for an adiabatic TE.sub.0 mode add/drop filter (modemux) **100** to provide a forward Bragg-based demultiplexer, according to an example embodiment. As shown in FIG. **11**, the forward Bragg-based demultiplexer **1100** (or simply, apparatus **1100**) includes a forward Bragg grating **1110**, an adiabatic TE.sub.0 mode add/drop filter (modemux) **100**, and a mode converter **1150** (i.e., TE.sub.1.fwdarw.TE.sub.0). The mode converter **1150** is connected to a photodetector (GePD) **1170** via one or more waveguides **1152**, **1154** (the waveguide **1154** may be optional in some example embodiments). Similar to the mode converter **850** of FIG. **8**, the mode converter **1150** of FIG. **11** may be implemented by any of the mode converters **950**(A), **950**(B) and/or **950**(C) of FIGS. **9**A-**9**C, for example. The proposed architecture of FIG. **11** (apparatus **1100**, with a forward Bragg **1110**) functions very similarly to the proposed architecture of FIG. **8** (apparatus **800**, with a backward-reflecting Bragg **810**), except that the forward Bragg **1110** of FIG. **11** scatters forward-propagating TE.sub.0 (received via waveguide **1112**) to forward-propagating TE.sub.1, and consequently, the adiabatic components (e.g., TE.sub.0 add/drop filter **100** and TE.sub.1.fwdarw.TE.sub.0 mode converter **1150**) precede the Bragg in this example embodiment. In the forward Bragg-based demultiplexing scheme of FIG. **11**, return loss is not of significant concern; rather, an ultra-low cross-talk mux may be employed to ensure minimal channel cross-talk.

(92) Thus, as described above with reference to FIGS. **8**, **9**A-**9**C, **10** and **11**, the present disclosure describes various proposed architectures (e.g., Bragg-based demultiplexer **800** of FIG. **8**, full Bragg-based WDM architecture **1000** of FIG. **10**, and/or forward Bragg-based demultiplexer **1100** of FIG. **11**) that facilitate low cross-talk and are expected to remove return loss (RL) challenges, while minimizing the device footprint and keeping insertion loss (IL) low.

(93) FIGS. **12**A-**12**C illustrate a flowchart showing a method **1200** that includes a series of operations for processing light with a Bragg-based demultiplexer **800** of FIG. **8**, with an integrated adiabatic TE.sub.0 mode add/drop filter (modemux) **100** and Bragg grating **810**, as well as a TE.sub.1.fwdarw.TE.sub.0 mode converter **850** that operates independently of the TE.sub.0 mode add/drop filter **100**, according to an example embodiment. FIG. **12**A shows operations from the perspective of the TE.sub.0 mode add/drop filter **100**, FIG. **12**B shows operations from the perspective of the Bragg grating **810**, and FIG. **12**C shows operations from the perspective of the TE.sub.1.fwdarw.TE.sub.0 mode converter **850**.

(94) As shown in FIG. **12**A, at step **1210**, a TE.sub.0 mode add/drop filter (e.g., the TE.sub.0 mode add/drop filter **100** of FIG. **8**) receives a TE.sub.0 mode optical signal on a lower waveguide (e.g., a single-mode (Si) waveguide **130**), where the TE.sub.0 mode optical signal has at least a first wavelength (λ.sub.1) and a second wavelength (λ.sub.2) (i.e., light modulating at different frequencies (e.g., λ.sub.1, λ.sub.2, . . . , λ.sub.N)). At step **1220**, the TE.sub.0 add/drop filter transmits the TE.sub.0 mode optical signal having the first wavelength and the second wavelength (λ.sub.1, λ.sub.2) towards a Bragg grating (e.g., the Bragg grating **810** of FIG. **8**) on a bus waveguide (e.g., a multimode (SiN) waveguide **120**) disposed above the lower waveguide. In step **1220**, the TE.sub.0 add/drop filter modemuxes and transmits without converting the TE.sub.0 mode optical signal having the first wavelength and the second wavelength (λ.sub.1, λ.sub.2) to another mode (e.g., TE.sub.1).

(95) As shown in FIG. **12**B, at step **1230**, the Bragg grating receives the TE.sub.0 mode optical signal having the first wavelength and the second wavelength (λ.sub.1, λ.sub.2) from the TE.sub.0 add/drop filter on the bus waveguide (SiN). At step **1240**, the Bragg grating transmits a reflected (drop-band) TE mode optical signal to the TE.sub.0 mode add/drop filter on the bus waveguide

(SiN). The reflected (drop-band) TE.sub.1 mode optical signal corresponds to a first portion of the TE.sub.0 mode optical signal having the first wavelength (λ.sub.1) that is reflected by the Bragg grating back to the TE.sub.0 mode add/drop filter, where the operation of reflecting converts the first portion of the TE.sub.0 mode optical signal having the first wavelength (λ.sub.1) to the reflected (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1).
(96) Also shown in FIG. **12**B, at step **1235** (which may occur before, after, or concurrently with step **1240**), the Bragg grating transmits a non-reflected (pass-band) TE.sub.0 mode optical signal having the second wavelength (λ.sub.2) towards a second TE.sub.0 mode add/drop filter. The non-reflected (pass-band) TE.sub.0 mode optical signal having the second wavelength (λ.sub.2) corresponds to a second portion of the TE.sub.0 mode optical signal having one or more other wavelengths (e.g., λ.sub.2, . . . , λ.sub.N) other than the first wavelength (λ.sub.1), that is not reflected by (and passes through) the Bragg grating. For example, the Bragg grating may transmit the non-reflected (pass-band) TE.sub.0 mode optical signal having the second wavelength (λ.sub.2) to the second TE.sub.0 mode add/drop filter via a transition (e.g., inter-layer transition **814** on a multimode (SiN) waveguide **812** of FIG. **8**), for further transmission (by the second TE.sub.0 mode add/drop filter), reflection (by a second Bragg grating), conversion (by a second TE1-TE0 mode converter), and/or processing (by a second photodetector configured to detect the second wavelength (λ.sub.2)).
(97) Referring again to FIG. **12**A, at step **1250**, the TE.sub.0 mode add/drop filter receives the reflected (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1) from the Bragg grating on the bus waveguide (SiN). At step **1260**, the TE.sub.0 mode add/drop filter transmits the reflected (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1) towards a photodetector (e.g., the photodetector (GePD) **870** of FIG. **8**) on the bus waveguide (SiN). In step **1260**, the TE.sub.0 mode add/drop filter modemuxes and transmits without converting the (drop-band) TE.sub.1 mode optical signal (λ.sub.1) to another mode (e.g., TE.sub.0).
(98) As shown in FIG. **12**C, at step **1270**, a TE.sub.1.fwdarw.TE.sub.0 mode converter (e.g., TE.sub.1.fwdarw.TE.sub.0 mode converter **850** of FIG. **8**) receives the (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1) from the TE.sub.0 add/drop filter on the bus waveguide (SiN). At step **1275**, the TE.sub.1.fwdarw.TE.sub.0 mode converter converts the (drop-band) TE.sub.1 mode optical signal having the first wavelength (λ.sub.1) to a (drop-band) TE.sub.0 mode optical signal having the first wavelength (λ.sub.1). At step **1280**, the TE.sub.1.fwdarw.TE.sub.0 mode converter transmits the converted (drop-band) TE.sub.0 mode optical signal having the first wavelength (λ.sub.1) to the photodetector (e.g., to the photodetector (GePD) **870** on the single-mode (Si) waveguide **852** of FIG. **8**). The photodetector then receives and detects (processes) the converted (drop-band) TE.sub.0 mode optical signal having the first wavelength (λ.sub.1) that is received from the TE.sub.1.fwdarw.TE.sub.0 mode converter.
(99) In the example of FIG. **12**A, the TE.sub.0 mode add/drop filter (modemux) component is configured to mode multiplex TE.sub.1 mode optical signals and TE.sub.0 mode optical signals, without converting either the TE.sub.0 mode optical signal or the TE.sub.1 mode optical signal to a different mode, respectively. The conversion operation is performed separately by the TE.sub.1.fwdarw.TE.sub.0 mode converter component, as shown in the example of FIG. **12**C. The structure and operation of the TE.sub.0 mode add/drop filter are designed to prevent/avoid TE.sub.1-TM.sub.0 mode hybridization of an optical signal that traverses the bus waveguide (multimode SiN waveguide), for example.
(100) Variations and Implementations
(101) Embodiments described herein may include one or more networks, which can represent a series of points and/or network elements of interconnected communication paths for receiving and/or transmitting messages (e.g., packets of information) that propagate through the one or more networks. These network elements offer communicative interfaces that facilitate communications

between the network elements. A network can include any number of hardware and/or software elements coupled to (and in communication with) each other through a communication medium. Such networks can include, but are not limited to, any local area network (LAN), virtual LAN (VLAN), wide area network (WAN) (e.g., the Internet), software defined WAN (SD-WAN), wireless local area (WLA) access network, wireless wide area (WWA) access network, metropolitan area network (MAN), Intranet, Extranet, virtual private network (VPN), Low Power Network (LPN), Low Power Wide Area Network (LPWAN), Machine to Machine (M2M) network, Internet of Things (IoT) network, Ethernet network/switching system, any other appropriate architecture and/or system that facilitates communications in a network environment, and/or any suitable combination thereof.

(102) Networks through which communications propagate can use any suitable technologies for communications including wireless communications (e.g., 4G/5G/nG, IEEE 802.11 (e.g., Wi-Fi®/Wi-Fi6®), IEEE 802.16 (e.g., Worldwide Interoperability for Microwave Access (WiMAX)), Radio-Frequency Identification (RFID), Near Field Communication (NFC), Bluetooth™, mm.wave, Ultra-Wideband (UWB), etc.), and/or wired communications (e.g., T1 lines, T3 lines, digital subscriber lines (DSL), Ethernet, Fibre Channel, etc.). Generally, any suitable means of communications may be used such as electric, sound, light, infrared, and/or radio to facilitate communications through one or more networks in accordance with embodiments herein. Communications, interactions, operations, etc. as discussed for various embodiments described herein may be performed among entities that may directly or indirectly connected utilizing any algorithms, communication protocols, interfaces, etc. (proprietary and/or non-proprietary) that allow for the exchange of data and/or information.

(103) In various example implementations, any entity or apparatus for various embodiments described herein can encompass network elements (which can include virtualized network elements, functions, etc.) such as, for example, network appliances, forwarders, routers, servers, switches, gateways, bridges, loadbalancers, firewalls, processors, modules, radio receivers/transmitters, or any other suitable device, component, element, or object operable to exchange information that facilitates or otherwise helps to facilitate various operations in a network environment as described for various embodiments herein. Note that with the examples provided herein, interaction may be described in terms of one, two, three, or four entities. However, this has been done for purposes of clarity, simplicity and example only. The examples provided should not limit the scope or inhibit the broad teachings of systems, networks, etc. described herein as potentially applied to a myriad of other architectures.

(104) Communications in a network environment can be referred to herein as ‘messages’, ‘messaging’, ‘signaling’, ‘data’, ‘content’, ‘objects’, ‘requests’, ‘queries’, ‘responses’, ‘replies’, etc. which may be inclusive of packets. As referred to herein and in the claims, the term ‘packet’ may be used in a generic sense to include packets, frames, segments, datagrams, and/or any other generic units that may be used to transmit communications in a network environment. Generally, a packet is a formatted unit of data that can contain control or routing information (e.g., source and destination address, source and destination port, etc.) and data, which is also sometimes referred to as a ‘payload’, ‘data payload’, and variations thereof. In some embodiments, control or routing information, management information, or the like can be included in packet fields, such as within header(s) and/or trailer(s) of packets. Internet Protocol (IP) addresses discussed herein and in the claims can include any IP version 4 (IPv4) and/or IP version 6 (IPv6) addresses.

(105) To the extent that embodiments presented herein relate to the storage of data, the embodiments may employ any number of any conventional or other databases, data stores or storage structures (e.g., files, databases, data structures, data or other repositories, etc.) to store information.

(106) Note that in this Specification, references to various features (e.g., elements, structures, nodes, modules, components, engines, logic, steps, operations, functions, characteristics, etc.)

included in ‘one embodiment’, ‘example embodiment’, ‘an embodiment’, ‘another embodiment’, ‘certain embodiments’, ‘some embodiments’, ‘various embodiments’, ‘other embodiments’, ‘alternative embodiment’, and the like are intended to mean that any such features are included in one or more embodiments of the present disclosure, but may or may not necessarily be combined in the same embodiments. Note also that a module, engine, client, controller, function, logic or the like as used herein in this Specification, can be inclusive of an executable file comprising instructions that can be understood and processed on a server, computer, processor, machine, compute node, combinations thereof, or the like and may further include library modules loaded during execution, object files, system files, hardware logic, software logic, or any other executable modules.

(107) It is also noted that the operations and steps described with reference to the preceding figures illustrate only some of the possible scenarios that may be executed by one or more entities discussed herein. Some of these operations may be deleted or removed where appropriate, or these steps may be modified or changed considerably without departing from the scope of the presented concepts. In addition, the timing and sequence of these operations may be altered considerably and still achieve the results taught in this disclosure. The preceding operational flows have been offered for purposes of example and discussion. Substantial flexibility is provided by the embodiments in that any suitable arrangements, chronologies, configurations, and timing mechanisms may be provided without departing from the teachings of the discussed concepts.

(108) As used herein, unless expressly stated to the contrary, use of the phrase ‘at least one of’, ‘one or more of’, ‘and/or’, variations thereof, or the like are open-ended expressions that are both conjunctive and disjunctive in operation for any and all possible combination of the associated listed items. For example, each of the expressions ‘at least one of X, Y and Z’, ‘at least one of X, Y or Z’, ‘one or more of X, Y and Z’, ‘one or more of X, Y or Z’ and ‘X, Y and/or Z’ can mean any of the following: 1) X, but not Y and not Z; 2) Y, but not X and not Z; 3) Z, but not X and not Y; 4) X and Y, but not Z; 5) X and Z, but not Y; 6) Y and Z, but not X; or 7) X, Y, and Z.

(109) Each example embodiment disclosed herein has been included to present one or more different features. However, all disclosed example embodiments are designed to work together as part of a single larger system or method. This disclosure explicitly envisions compound embodiments that combine multiple previously-discussed features in different example embodiments into a single system or method.

(110) Additionally, unless expressly stated to the contrary, the terms ‘first’, ‘second’, ‘third’, etc., are intended to distinguish the particular nouns they modify (e.g., element, condition, node, module, activity, operation, etc.). Unless expressly stated to the contrary, the use of these terms is not intended to indicate any type of order, rank, importance, temporal sequence, or hierarchy of the modified noun. For example, ‘first X’ and ‘second X’ are intended to designate two ‘X’ elements that are not necessarily limited by any order, rank, importance, temporal sequence, or hierarchy of the two elements. Further as referred to herein, ‘at least one of’ and ‘one or more of’ can be represented using the ‘(s)’ nomenclature (e.g., one or more element(s)).

(111) In some aspects, the techniques described herein relate to a method including: receiving, at a TE.sub.0 mode add/drop filter, a TE.sub.0 mode optical signal having a first wavelength and a second wavelength; transmitting, from the TE.sub.0 mode add/drop filter, the TE.sub.0 mode optical signal having the first wavelength and the second wavelength towards a Bragg grating, without converting the TE.sub.0 mode optical signal having the first wavelength and the second wavelength to another mode; receiving, at the TE.sub.0 mode add/drop filter, a reflected TE.sub.1 mode optical signal having the first wavelength from the Bragg grating; and transmitting, from the TE.sub.0 mode add/drop filter, the reflected TE.sub.1 mode optical signal having the first wavelength towards a photodetector, without converting the reflected TE.sub.1 mode optical signal having the first wavelength to another mode.

(112) In some aspects, the TE.sub.0 mode add/drop filter is an adiabatic TE.sub.0 mode add/drop

filter.
(113) In some aspects, the method further includes: receiving the TE.sub.0 mode optical signal having the first wavelength and the second wavelength on a lower waveguide; and transmitting the TE.sub.0 mode optical signal having the first wavelength and the second wavelength towards the Bragg grating on a bus waveguide disposed above the lower waveguide.
(114) In some aspects, the method further includes: receiving the reflected TE.sub.1 mode optical signal having the first wavelength from the Bragg grating on the bus waveguide; and transmitting the reflected TE.sub.1 mode optical signal having the first wavelength towards the photodetector on the bus waveguide.
(115) In some aspects, the lower waveguide is a single-mode waveguide comprised of silicon (Si) and the bus waveguide is a multimode waveguide comprised of silicon nitride.
(116) In some aspects, the method further includes: establishing a pseudo-symmetry about a longitudinal axis of the bus waveguide to prevent TE.sub.1-TM.sub.0 mode hybridization of optical signals that traverse the bus waveguide.
(117) In some aspects, the method further includes: mode multiplexing, by the TE.sub.0 mode add/drop filter, the TE.sub.0 mode optical signal having the first wavelength and the second wavelength with the reflected TE.sub.1 mode optical signal having the first wavelength.
(118) In some aspects, the method further includes: receiving, at a TE.sub.1.fwdarw.TE.sub.0 mode converter, the reflected TE.sub.1 mode optical signal having the first wavelength from the TE.sub.0 mode add/drop filter; converting, by the TE.sub.1.fwdarw.TE.sub.0 mode converter, the reflected TE.sub.1 mode optical signal having the first wavelength to a converted TE.sub.0 mode optical signal having the first wavelength; and transmitting, from the TE.sub.1.fwdarw.TE.sub.0 mode converter, the converted TE.sub.0 mode optical signal having the first wavelength to the photodetector.
(119) In some aspects, the method further includes: transmitting, from the Bragg grating, a non-reflected (pass-band) TE.sub.0 mode optical signal having the second wavelength towards a second TE.sub.0 mode add/drop filter.
(120) In some aspects, the techniques described herein relate to a method including: passing an optical signal through a plurality of TE.sub.0 mode add/drop filters; reflecting respective wavelengths of the optical signal using respective Bragg gratings; and detecting powers of the respective wavelengths using respective photodetectors, wherein each TE.sub.0 mode add/drop filter in the plurality of TE.sub.0 mode add/drop filters passes the optical signal without converting the optical signal to a different mode. In some aspects, at least one TE.sub.0 mode add/drop filter in the plurality of TE.sub.0 mode add/drop filters is an adiabatic TE.sub.0 mode add/drop filter.
(121) In some aspects, the techniques described herein relate to an apparatus including: a TE.sub.0 mode add/drop filter; and a Bragg grating connected with the TE.sub.0 mode add/drop filter; wherein the TE.sub.0 mode add/drop filter is configured to: receive a TE.sub.0 mode optical signal having a first wavelength and a second wavelength; transmit the TE.sub.0 mode optical signal having the first wavelength and the second wavelength towards the Bragg grating, without converting the TE.sub.0 mode optical signal having the first wavelength and the second wavelength to another mode; receive a reflected TE.sub.1 mode optical signal having the first wavelength from the Bragg grating; and transmit the reflected TE.sub.1 mode optical signal having the first wavelength towards a photodetector, without converting the reflected TE.sub.1 mode optical signal having the first wavelength to another mode.
(122) In some aspects, the TE.sub.0 mode add/drop filter is an adiabatic TE.sub.0 mode add/drop filter.
(123) In some aspects, the TE.sub.0 mode add/drop filter is configured to: receive the TE.sub.0 mode optical signal having the first wavelength and the second wavelength on a lower waveguide; and transmit the TE.sub.0 mode optical signal having the first wavelength and the second wavelength towards the Bragg grating on a bus waveguide disposed above the lower waveguide.

(124) In some aspects, the TE.sub.0 mode add/drop filter is configured to: receive the reflected TE.sub.1 mode optical signal having the first wavelength from the Bragg grating on the bus waveguide; and transmit the reflected TE.sub.1 mode optical signal having the first wavelength towards the photodetector on the bus waveguide.
(125) In some aspects, the lower waveguide is a single-mode waveguide comprised of silicon (Si) and the bus waveguide is a multimode waveguide comprised of silicon nitride.
(126) In some aspects, the techniques described herein relate to an apparatus, wherein the TE.sub.0 mode add/drop filter further establishes a pseudo-symmetry about a longitudinal axis of the bus waveguide to prevent TE.sub.1-TM.sub.0 mode hybridization of optical signals that traverse the bus waveguide.
(127) In some aspects, the techniques described herein relate to an apparatus, wherein the TE.sub.0 mode add/drop filter is configured to mode multiplex the TE.sub.0 mode optical signal having the first wavelength and the second wavelength with the reflected TE.sub.1 mode optical signal having the first wavelength.
(128) In some aspects, the techniques described herein relate to an apparatus, further including: a TE.sub.1.fwdarw.TE.sub.0 mode converter configured to: receive the reflected TE.sub.1 mode optical signal having the first wavelength from the TE.sub.0 mode add/drop filter; convert the reflected TE.sub.1 mode optical signal having the first wavelength to a converted TE.sub.0 mode optical signal having the first wavelength; and transmit the converted TE.sub.0 mode optical signal having the first wavelength to the photodetector.
(129) In some aspects, the techniques described herein relate to an apparatus, wherein the Bragg grating is configured to transmit a non-reflected TE.sub.0 mode optical signal having the second wavelength towards a second TE.sub.0 add/drop filter.
(130) One or more advantages described herein are not meant to suggest that any one of the embodiments described herein necessarily provides all of the described advantages or that all the embodiments of the present disclosure necessarily provide any one of the described advantages. Numerous other changes, substitutions, variations, alterations, and/or modifications may be ascertained to one skilled in the art and it is intended that the present disclosure encompass all such changes, substitutions, variations, alterations, and/or modifications as falling within the scope of the appended claims.

Claims

1. A method comprising: receiving, at a TE.sub.0 mode add/drop filter, a TE.sub.0 mode optical signal having a first wavelength and a second wavelength; transmitting, from the TE.sub.0 mode add/drop filter, the TE.sub.0 mode optical signal having the first wavelength and the second wavelength towards a Bragg grating, without converting the TE.sub.0 mode optical signal having the first wavelength and the second wavelength to another mode; receiving, at the TE.sub.0 mode add/drop filter, a reflected TE.sub.1 mode optical signal having the first wavelength from the Bragg grating; and transmitting, from the TE.sub.0 mode add/drop filter, the reflected TE.sub.1 mode optical signal having the first wavelength towards a photodetector, without converting the reflected TE.sub.1 mode optical signal having the first wavelength to another mode, wherein the TE.sub.0 mode add/drop filter comprises: a bus waveguide; a lower waveguide disposed on a first side of the bus waveguide; and an upper waveguide disposed on a second side of the bus waveguide opposite to the first side of the bus waveguide, wherein the upper waveguide follows at least a portion of a path of the lower waveguide, and opposing longitudinal edges of both the lower waveguide and the upper waveguide, along the at least a portion of the path, are located between longitudinal edges of the bus waveguide.
2. The method of claim 1, wherein the TE.sub.0 mode add/drop filter is an adiabatic TE.sub.0 mode add/drop filter.

3. The method of claim 1, further comprising: receiving the TE.sub.0 mode optical signal having the first wavelength and the second wavelength on the lower waveguide; and transmitting the TE.sub.0 mode optical signal having the first wavelength and the second wavelength towards the Bragg grating on the bus waveguide disposed above the lower waveguide.
4. The method of claim 3, further comprising: receiving the reflected TE.sub.1 mode optical signal having the first wavelength from the Bragg grating on the bus waveguide; and transmitting the reflected TE.sub.1 mode optical signal having the first wavelength towards the photodetector on the bus waveguide.
5. The method of claim 4, wherein the lower waveguide is a single-mode waveguide comprised of silicon and the bus waveguide is a multimode waveguide comprised of silicon nitride.
6. The method of claim 5, further comprising: establishing, using the upper waveguide, a pseudo-symmetry about a longitudinal axis of the bus waveguide to prevent TE.sub.1-TM.sub.0 mode hybridization of optical signals that traverse the bus waveguide.
7. The method of claim 1, further comprising: mode multiplexing, by the TE.sub.0 mode add/drop filter, the TE.sub.0 mode optical signal having the first wavelength and the second wavelength with the reflected TE.sub.1 mode optical signal having the first wavelength.
8. The method of claim 1, further comprising: receiving, at a TE.sub.1.fwdarw.TE.sub.0 mode converter, the reflected TE.sub.1 mode optical signal having the first wavelength from the TE.sub.0 mode add/drop filter; converting, by the TE.sub.1.fwdarw.TE.sub.0 mode converter, the reflected TE.sub.1 mode optical signal having the first wavelength to a converted TE.sub.0 mode optical signal having the first wavelength; and transmitting, from the TE.sub.1.fwdarw.TE.sub.0 mode converter, the converted TE.sub.0 mode optical signal having the first wavelength to the photodetector.
9. The method of claim 1, further comprising: transmitting, from the Bragg grating, a non-reflected TE.sub.0 mode optical signal having the second wavelength towards a second TE.sub.0 mode add/drop filter.
10. An apparatus comprising: a TE.sub.0 mode add/drop filter; and a Bragg grating connected with the TE.sub.0 mode add/drop filter; wherein the TE.sub.0 mode add/drop filter is configured to: receive a TE.sub.0 mode optical signal having a first wavelength and a second wavelength; transmit the TE.sub.0 mode optical signal having the first wavelength and the second wavelength towards the Bragg grating, without converting the TE.sub.0 mode optical signal having the first wavelength and the second wavelength to another mode; receive a reflected TE.sub.1 mode optical signal having the first wavelength from the Bragg grating; and transmit the reflected TE.sub.1 mode optical signal having the first wavelength towards a photodetector, without converting the reflected TE.sub.1 mode optical signal having the first wavelength to another mode, wherein the TE.sub.0 mode add/drop filter comprises: a bus waveguide; a lower waveguide disposed on a first side of the bus waveguide; and an upper waveguide disposed on a second side of the bus waveguide opposite to the first side of the bus waveguide, wherein the upper waveguide follows at least a portion of a path of the lower waveguide, and opposing longitudinal edges of both the lower waveguide and the upper waveguide, along the at least a portion of the path, are located between longitudinal edges of the bus waveguide.
11. The apparatus of claim 10, wherein the TE.sub.0 mode add/drop filter is an adiabatic TE.sub.0 mode add/drop filter.
12. The apparatus of claim 10, wherein the TE.sub.0 mode add/drop filter is configured to: receive the TE.sub.0 mode optical signal having the first wavelength and the second wavelength on the lower waveguide; and transmit the TE.sub.0 mode optical signal having the first wavelength and the second wavelength towards the Bragg grating on the bus waveguide disposed above the lower waveguide.
13. The apparatus of claim 12, wherein the TE.sub.0 mode add/drop filter is configured to: receive the reflected TE.sub.1 mode optical signal having the first wavelength from the Bragg grating on

the bus waveguide; and transmit the reflected TE.sub.1 mode optical signal having the first wavelength towards the photodetector on the bus waveguide.
14. The apparatus of claim 13, wherein the lower waveguide is a single-mode waveguide comprised of silicon and the bus waveguide is a multimode waveguide comprised of silicon nitride.
15. The apparatus of claim 14, wherein the TE.sub.0 mode add/drop filter further establishes, using the upper waveguide, a pseudo-symmetry about a longitudinal axis of the bus waveguide to prevent TE.sub.1-TM.sub.0 mode hybridization of optical signals that traverse the bus waveguide.
16. The apparatus of claim 10, wherein the TE.sub.0 mode add/drop filter is configured to mode multiplex the TE.sub.0 mode optical signal having the first wavelength and the second wavelength with the reflected TE.sub.1 mode optical signal having the first wavelength.
17. The apparatus of claim 12, further comprising: a TE.sub.1.fwdarw.TE.sub.0 mode converter configured to: receive the reflected TE.sub.1 mode optical signal having the first wavelength from the TE.sub.0 mode add/drop filter; convert the reflected TE.sub.1 mode optical signal having the first wavelength to a converted TE.sub.0 mode optical signal having the first wavelength; and transmit the converted TE.sub.0 mode optical signal having the first wavelength to the photodetector.
18. The apparatus of claim 10, wherein the Bragg grating is configured to transmit a non-reflected TE0 mode optical signal having the second wavelength towards a second TE0 add/drop filter.
19. A method comprising: receiving a TE.sub.0 mode optical signal having a first wavelength and a second wavelength; transmitting the TE.sub.0 mode optical signal having the first wavelength and the second wavelength towards a Bragg grating, without converting the TE.sub.0 mode optical signal having the first wavelength and the second wavelength to another mode; receiving a reflected TE.sub.1 mode optical signal having the first wavelength from the Bragg grating; and transmitting the reflected TE.sub.1 mode optical signal having the first wavelength towards a photodetector, without converting the reflected TE.sub.1 mode optical signal having the first wavelength to another mode, wherein receiving the TE.sub.0 mode optical signal having a first wavelength and a second wavelength comprises receiving the TE.sub.0 mode optical signal having a first wavelength and a second wavelength at a TE.sub.0 mode add/drop filter, which comprises: a bus waveguide; a lower waveguide disposed on a first side of the bus waveguide; and an upper waveguide disposed on a second side of the bus waveguide opposite to the first side of the bus waveguide, wherein the upper waveguide follows at least a portion of a path of the lower waveguide, and opposing longitudinal edges of both the lower waveguide and the upper waveguide, along the at least a portion of the path, are located between longitudinal edges of the bus waveguide.
20. The method of claim 19, wherein receiving the TE.sub.0 mode optical signal, transmitting the TE.sub.0 mode optical signal, receiving reflected TE.sub.1 mode optical signal, and transmitting the reflected TE.sub.1 mode optical signal are performed by the TE.sub.0 mode add/drop filter.