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(54) **2X2 COUPLER**

(71) Applicant: **Cisco Technology, Inc.**, San Jose, CA (US)

(72) Inventors: **Jean-Luc J. TAMBASCO**, Macungie, PA (US); **Dominic F. SIRIANI**, Lansdale, PA (US)

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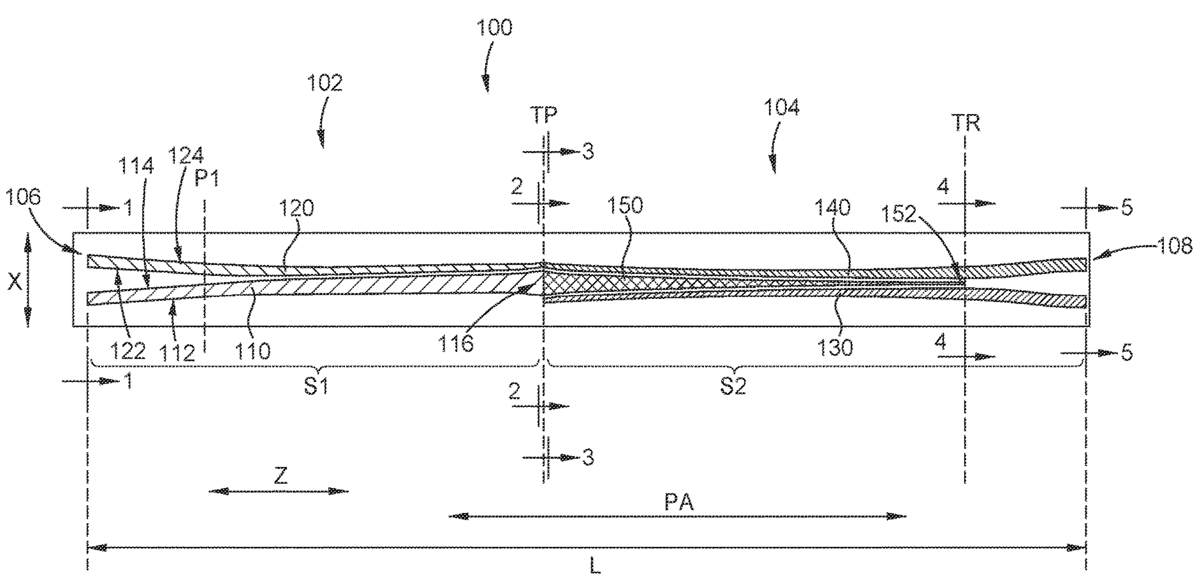
(57) **ABSTRACT**

A 2×2 coupler is disclosed. In one aspect, the 2×2 coupler includes a first stage configured as a mode multiplexer. The mode multiplexer includes two input waveguides that transition asymmetrically along a propagation axis of the 2×2 coupler so that an optical signal input into either of the two input waveguides traverses into the input waveguide that transitions from a single mode waveguide to a multimode waveguide. The 2×2 coupler also includes a second stage configured as a multimode splitter. The multimode splitter includes two single mode output waveguides and a multimode waveguide arranged in communication with the multimode waveguide of the mode multiplexer. The output waveguides and the multimode waveguide transition symmetrically along the propagation axis so that the optical signal traversing in the multimode waveguide of the mode multiplexer is received by the multimode waveguide of the multimode splitter and split into the two single mode output waveguides.



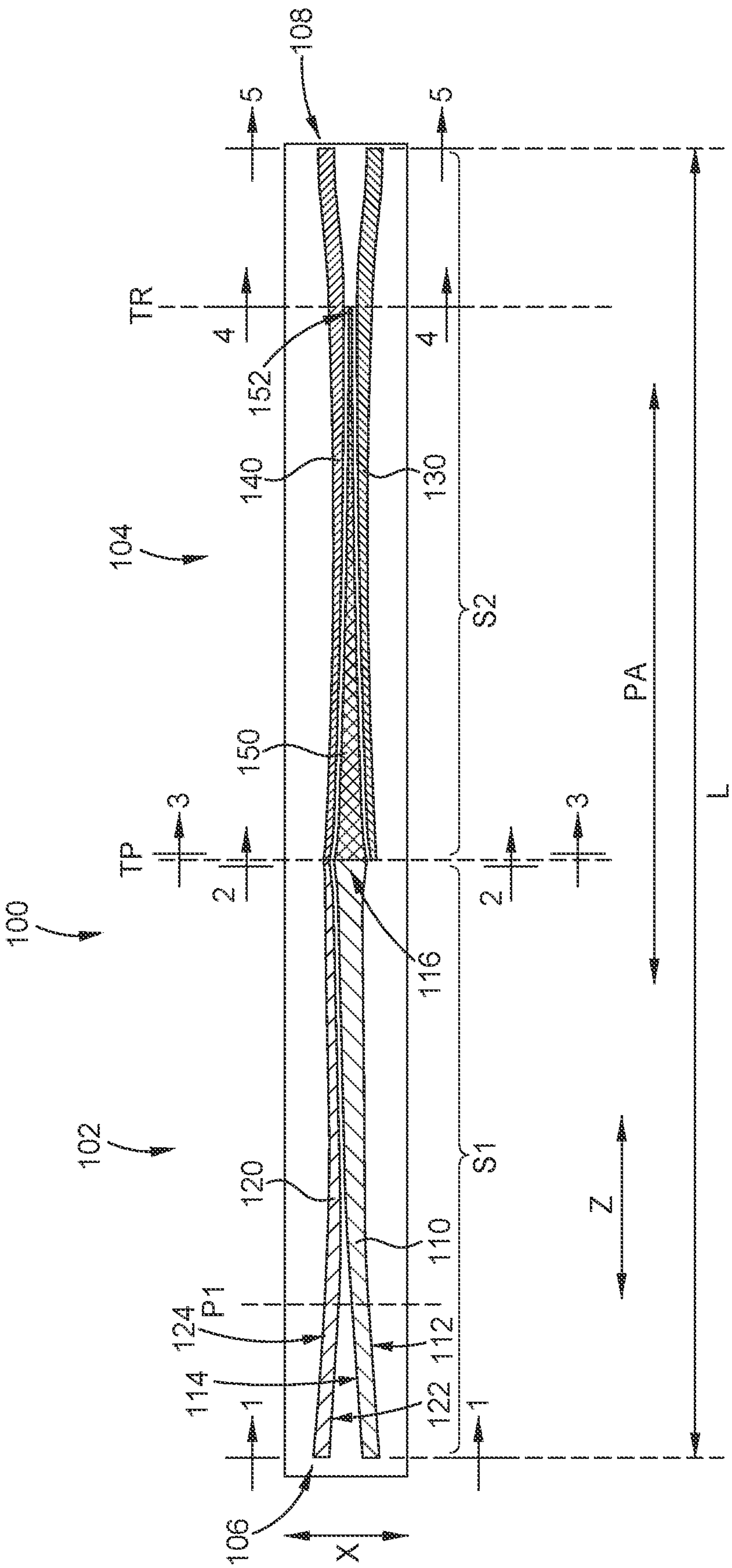

108
5
5
TR
4
4
152
140
130
104
S2
PA
150
TP
3
3
2
2
100
116
L
102
S1
120
Z
110
P1
124
112
114
122
1
1
106
X

FIG. 1

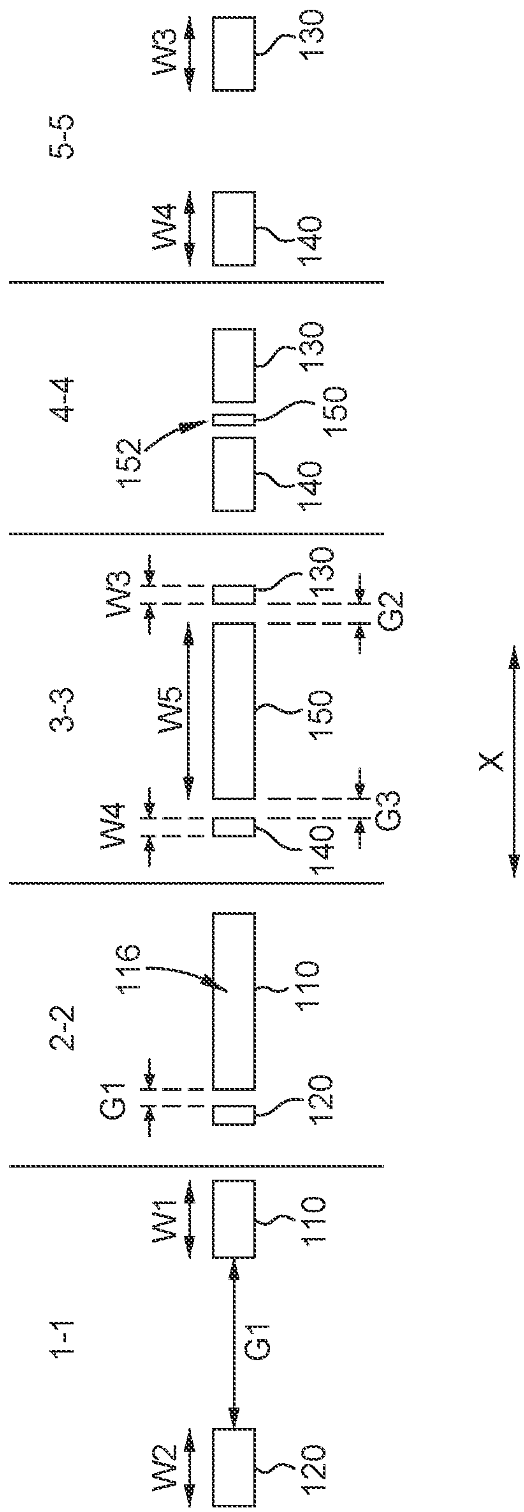

5-5
W3
130
W4
140
4-4
130
150
152
140
3-3
W3
130
G2
W5
150
W4
140
G3
X
2-2
116
110
G1
120
1-1
W1
110
G1
W2
120

FIG. 2

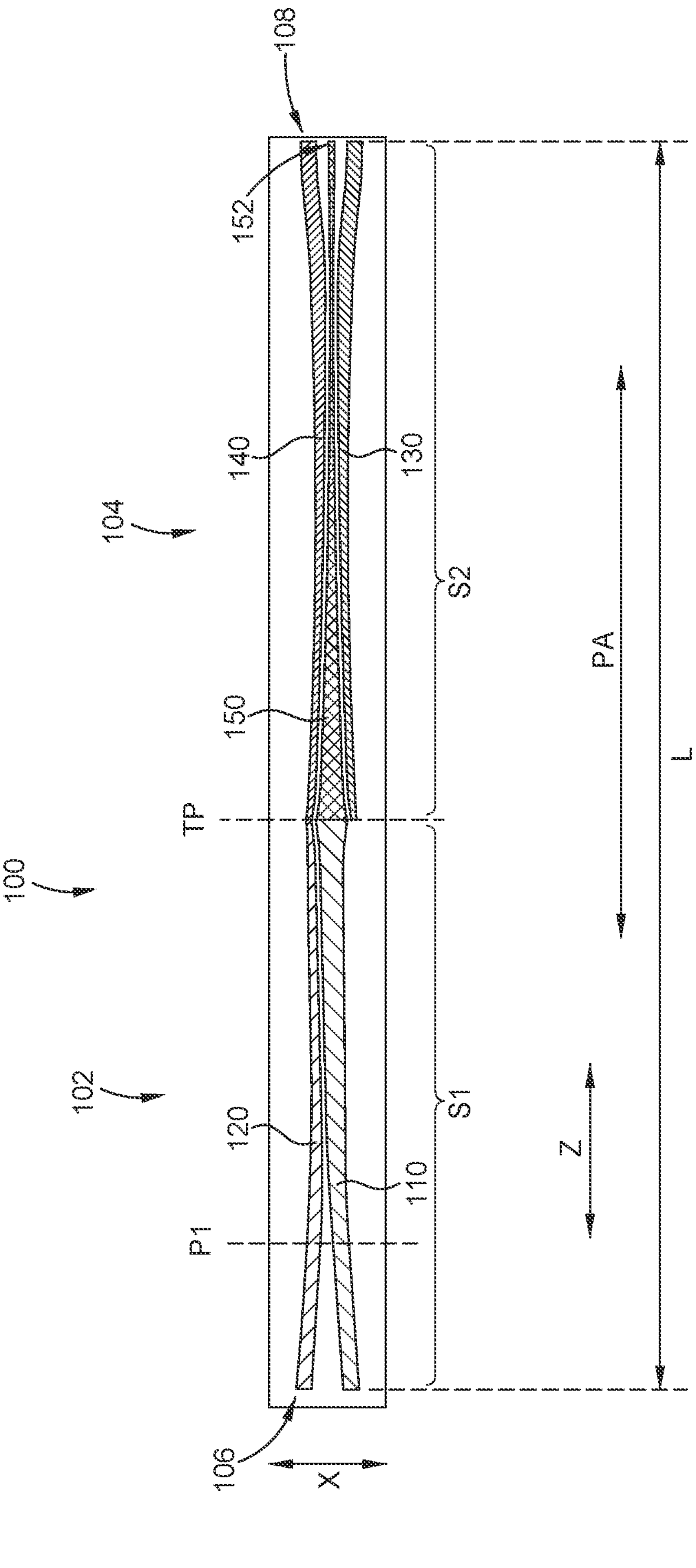


FIG. 3

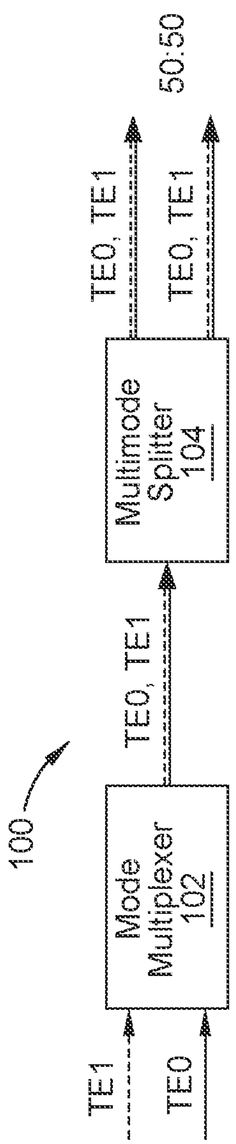

100
TE1
TE0
Mode Multiplexer 102
TE0, TE1
Multimode Splitter 104
TE0, TE1
TE0, TE1
50:50

FIG. 4

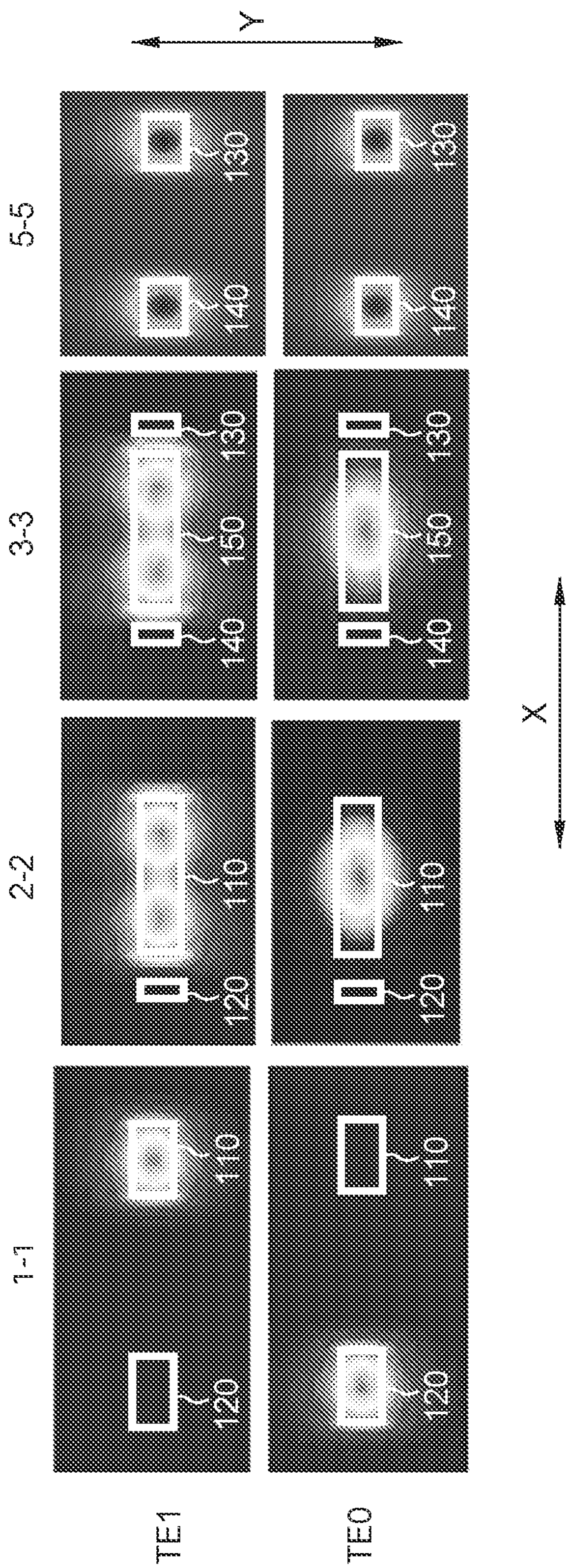

Y
1-1
2-2
3-3
5-5
TE1
TE0
120
110
120
110
120
110
120
110
140
150
130
140
150
130
140
130
140
130
X

FIG. 5

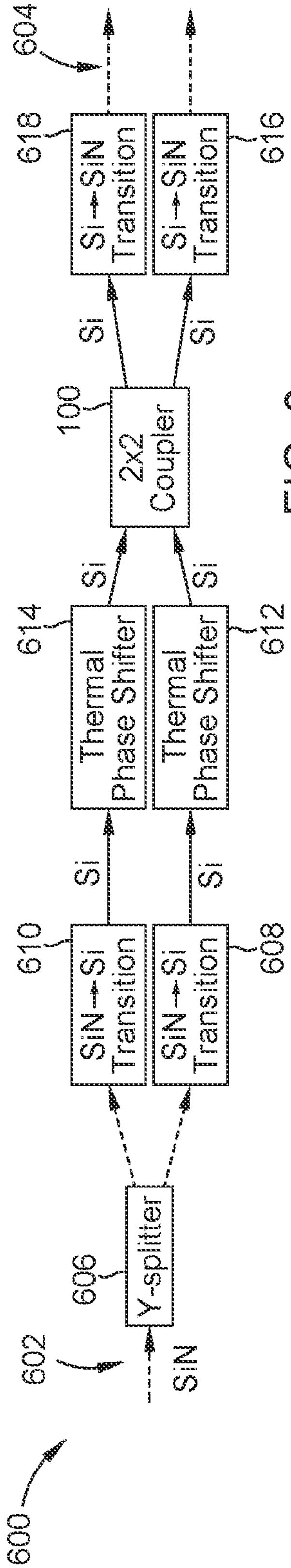


FIG. 6

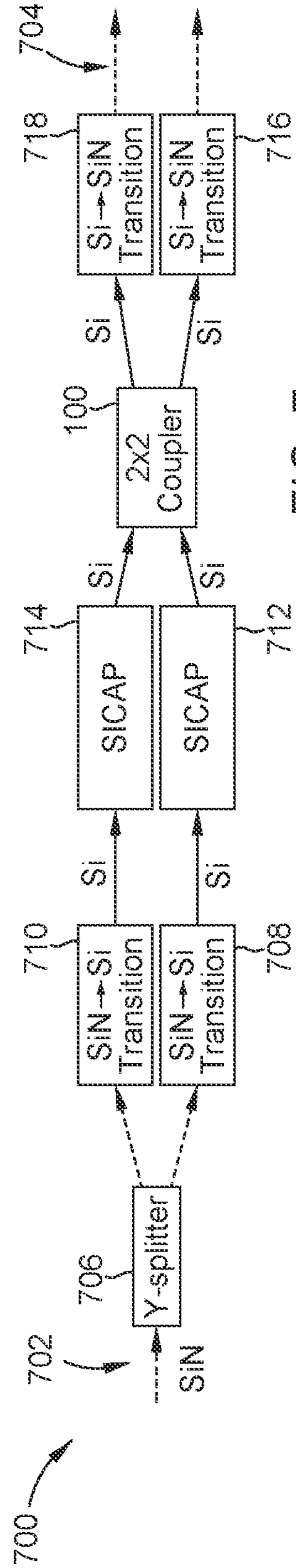


FIG. 7

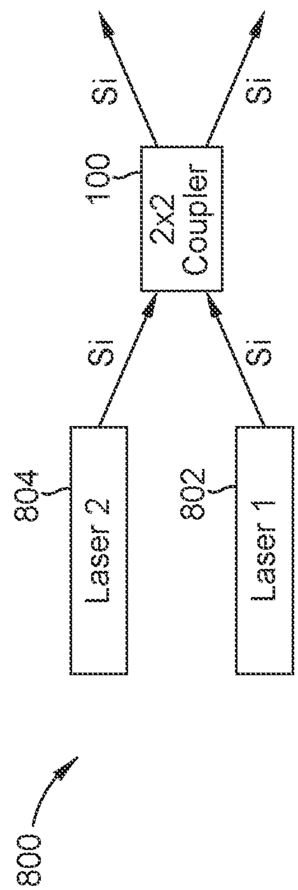


FIG. 8

2X2 COUPLER

TECHNICAL FIELD

[0001] Embodiments presented in this disclosure generally relate to photonic components. More specifically, embodiments disclosed herein relate to 2×2 couplers.

BACKGROUND

[0002] 2×2 couplers, such as adiabatic 2×2 3 dB splitters, are photonic components used to split or cross optical signals. 2×2 couplers can be implemented in a number of applications, including switches, modulators, interferometers, etc. As one example, an adiabatic 2×2 3 dB splitter can be used as an input and/or an output splitter of a photonic switch. Further, adiabatic splitters can be used as standalone devices. Generally, adiabatic splitters are desired to be minimal loss, compact, and fabrication tolerant. Adiabatic splitters are also designed to have a precise split ratio. Improvements to these metrics is desirable as improved optical performance, packaging, and/or manufacturability can result.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] So that the manner in which the above-recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate typical embodiments and are therefore not to be considered limiting; other equally effective embodiments are contemplated.

[0004] FIG. **1** is a top view of a 2×2 coupler according to one embodiment of the present disclosure.

[0005] FIG. **2** depicts various cross-sectional views of the 2×2 coupler of FIG. **1**.

[0006] FIG. **3** is a top view of a 2×2 coupler according to another embodiment of the present disclosure.

[0007] FIG. **4** is a schematic flow diagram depicting an example manner in which optical signals can be split by the 2×2 coupler of FIG. **1**.

[0008] FIG. **5** illustrates a matrix of cross-sections of the 2×2 coupler of FIG. **1** that demonstrate an example manner in which the 2×2 coupler can split optical signals.

[0009] FIG. **6** is a schematic view of a thermo-optic switch incorporating a 2×2 coupler according to one embodiment of the present disclosure.

[0010] FIG. **7** is a schematic view of an electro-optic switch incorporating a 2×2 coupler according to one embodiment of the present disclosure.

[0011] FIG. **8** is a schematic view of a laser switch incorporating a 2×2 coupler according to one embodiment of the present disclosure.

[0012] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements disclosed in one embodiment may be beneficially used in other embodiments without specific recitation.

DESCRIPTION OF EXAMPLE EMBODIMENTS

Overview

[0013] One embodiment presented in this disclosure is a 2×2 coupler. The 2×2 coupler includes a first stage configured as a mode multiplexer and a second stage configured as a multimode splitter.

[0014] Another embodiment presented in this disclosure is a 2×2 coupler. The 2×2 coupler includes a first stage having two input waveguides that transition asymmetrically along a propagation axis of the 2×2 coupler so that an optical signal input into one of the two input waveguides traverses into, or remains in, a first input waveguide of the two input waveguides that transitions from a single mode waveguide to a multimode waveguide. Further, the 2×2 coupler includes a second stage having two single mode output waveguides and a multimode waveguide arranged in communication with the multimode waveguide of the first stage. The two single mode output waveguides and the multimode waveguide transition symmetrically along the propagation axis so that the optical signal traversing in the multimode waveguide of the first stage is received by the multimode waveguide of the second stage and split into the two single mode output waveguides.

[0015] Yet another embodiment presented in this disclosure is a 2×2 coupler. The 2×2 coupler includes a first stage having two input waveguides that transition asymmetrically along a propagation axis of the 2×2 coupler so that an optical signal input into a first input waveguide or a second input waveguide of the two input waveguides traverses into, or remains in, the first input waveguide that transitions from a single mode waveguide to a multimode waveguide. The first input waveguide inverse tapers while the second input waveguide tapers over at least a portion of the first stage as the first and second waveguides extend away from an inlet of the 2×2 coupler. The 2×2 coupler also includes a second stage having two single mode output waveguides and a multimode waveguide arranged in communication with the multimode waveguide of the first stage. The two single mode output waveguides and the multimode waveguide transition symmetrically along the propagation axis so that the optical signal traversing in the multimode waveguide of the first stage is received by the multimode waveguide of the second stage and split into the two single mode output waveguides.

Example Embodiments

[0016] Various embodiments of 2×2 couplers are disclosed herein that can provide improved optical performance, packaging, and/or manufacturability over conventional 2×2 couplers. The disclosed 2×2 couplers can be used as standalone devices or can be implemented into various products, including, without limitation, switches (e.g., thermo-optic switches, electro-optic switches, laser switches, etc.), modulators, interferometers, other FR4 standard products, Co-Packaged Optics (CPO) applications, etc., and can be used in receiver, transmitter, and/or transceiver applications, among others.

[0017] In at least one example aspect, a 2×2 coupler having a mode multiplexer followed by a multimode splitter is disclosed. Specifically, the 2×2 coupler includes two stages, including a first stage configured as a mode multiplexer and a second stage configured as a multimode splitter.

The mode multiplexer of the first stage functions to robustly move all or nearly all of an optical signal (or its optical power), which is input into one of two single mode input waveguides of the mode multiplexer, into a single multimode waveguide. In this way, the optical signal is prepared in the first stage for the sensitive part of the process-the splitting of the optical signal that takes place in the multimode splitter of the second stage. The mode multiplexer includes two input waveguides that transition asymmetrically along a propagation axis of the 2×2 coupler so that an optical signal input into one of the two input waveguides traverses into, or remains in, the input waveguide of the two input waveguides that transitions from a single mode waveguide to a multimode waveguide. The multimode splitter of the second stage includes two single mode output waveguides and a multimode waveguide arranged in communication with the multimode waveguide of the mode multiplexer. The output waveguides and the multimode waveguide transition symmetrically along the propagation axis so that the optical signal traversing in the multimode waveguide of the mode multiplexer is received by the multimode waveguide of the multimode splitter and split into the two single mode output waveguides, e.g., 50:50.

[0018] Accordingly, the sensitive process of splitting the optical signal takes place along a symmetric transition, which can improve the performance of the 2×2 coupler, including providing improved split ratio, lower insertion loss, and higher bandwidth. The symmetry of the multimode splitter of the second stage can eliminate or provide for an ultra-low crosstalk 2×2 coupler. Moreover, the 2×2 coupler disclosed herein can be fabricated with a reduced footprint and a more robust design that is more tolerant to fabrication deviations than conventional 2×2 designs. In addition, the 2×2 coupler disclosed herein can enable the use of silicon to form an adiabatic 2×2 coupler. Further, when the 2×2 coupler of the present disclosure is implemented as a Si adiabatic 2×2 coupler in devices that utilize phase-shifting devices, the 2×2 coupler disclosed herein can eliminate or reduce the need for additional interlayer transitions as the phase-shifting devices positioned relative to the 2×2 coupler are typically formed of silicon as well.

[0019] As used herein, the term "substantially" or a like word of approximation means within ten percent (10%) of a stated value, unless otherwise specified.

[0020] With reference to FIGS. **1** and **2**, a 2×2 coupler **100** according to one example embodiment of the present disclosure is depicted. FIG. **1** is a top view of the 2×2 coupler **100** and FIG. **2** depicts various cross-sectional views of the 2×2 coupler **100**. For reference, the 2×2 coupler **100** defines a longitudinal direction Z, a lateral direction X, and a vertical direction Y. The longitudinal direction Z, the lateral direction X, and the vertical direction Y are mutually perpendicular to one another and form an orthogonal direction system.

[0021] The 2×2 coupler **100** has a length L, a first stage **S1** extending along a first portion of the length L, and a second stage **S2** extending along a second portion of the length L. The second stage **S2** follows or is adjacent to the first stage **S1** as shown in FIG. **1**. The first stage **S1** transitions to the second stage **S2** at a transition plane TP. For this example embodiment, the first stage **S1** is configured as a mode multiplexer **102** and the second stage **S2** is configured as a multimode 50:50 splitter, or multimode splitter **104**. Generally, the mode multiplexer **102** of the first stage **S1** prepares and feeds optical signals to the multimode splitter **104**. The multimode splitter **104** splits the optical signals, e.g., 50:50 into separate output waveguides. The 2×2 coupler **100** has an input **106** and an output **108**. In at least some embodiments, the 2×2 coupler **100** is made entirely of silicon. In this regard, the 2×2 coupler **100** can be an adiabatic 2×2 coupler. In some embodiments, the first stage **S1** or the second stage **S2** can be formed of silicon while the other stage can be formed of a different composition, such as silicon nitride. In this manner, in such embodiments, the 2×2 coupler **100** can be adiabatic in part.

[0022] The mode multiplexer **102** of the first stage **S1** is configured as a two-mode multiplexer and is arranged asymmetrically along a propagation axis PA of the 2×2 coupler **100**. The propagation axis PA extends along the longitudinal direction Z in this example embodiment. The mode multiplexer **102** has a first input waveguide **110** and a second input waveguide **120** that each traverse from the input **106** of the 2×2 coupler **100** to the transition plane TP. The first input waveguide **110** has a first width **W1** and the second input waveguide **120** has a second width **W2**, e.g., as shown at **1-1** in FIG. **2**, which is a cross section taken from line **1-1** in FIG. **1** at the input **106**. The first input waveguide **110** has a first edge **112** and a second edge **114**, which are spaced from one another along the lateral direction X. Likewise, the second input waveguide **120** has a first edge **122** and a second edge **124**, which are spaced from one another along the lateral direction X. The first and second input waveguides **110**, **120** have respective thicknesses extending along the vertical direction Y.

[0023] The first and second input waveguides **110**, **120** are both single mode waveguides at the input **106** and for at least a portion of the first stage **S1**. For instance, the first input waveguide **110** can be configured to receive optical signals each having a first mode (e.g., TE**0** mode optical signals, wherein TE denotes "Transverse Electric") and the second input waveguide **120** can be configured to receive optical signals each having a second mode (e.g., TE**1** mode optical signals). The first mode can be different than the second mode. Accordingly, the first and second input waveguides **110**, **120** are configured to receive different mode optical signals.

[0024] In an initial portion of the first stage **S1**, the first and second input waveguides **110**, **120** converge toward one another as depicted in FIG. **1**. In this manner, a gap **G1** defined between the first and second input waveguides **110**, **120** decreases during the initial portion of the first stage **S1**. Once the first and second input waveguides **110**, **120** are fully converged, the gap **G1** between the first and second input waveguides **110**, **120** can be maintained substantially constant until the transition plane TP. That is, the edge-to-edge gap **G1** between the second edge **114** of the first input waveguide **110** and the first edge **122** of the second input waveguide **120** can be held substantially constant over at least a portion of the first stage **S1**.

[0025] As further shown in FIG. **1**, the first and second input waveguides **110**, **120** are arranged asymmetrically along the first stage **S1** so that the first input waveguide **110** transitions from a single mode waveguide to a multimode waveguide, which can receive and guide first mode optical signals, e.g., TE**0** mode optical signals received by the first input waveguide **110**, or receive and guide second mode optical signals, e.g., TE**1** mode optical signals received by the second input waveguide **120**. Stated differently, the first and second input waveguides **110**, **120** transition along the first stage S**1** so as to render a single multimode waveguide at the transition plane TP. The first input waveguide **110** becomes the single multimode waveguide at least by the transition plane TP. In this regard, the first input waveguide **110** is a single mode waveguide at the input **106** but transitions into a multimode waveguide at least by the transition plane TP. The portion of the first input waveguide **110** arranged as a single multimode waveguide is denoted in FIG. **1** as single multimode waveguide **116** (see also the cross section **2-2** in FIG. **2**).

[0026] The first input waveguide **110** becomes a "multi-mode" waveguide in that, at least by the transition plane TP, the first input waveguide **110** is operable to receive and guide optical signals having a first mode (e.g., TE**0** mode optical signals), which are input into the first input waveguide **110** at the input **106**, and also operable to receive and guide optical signals having a second mode (e.g., TE**1** mode optical signals), which are input into the second input waveguide **120** at the input **106**. For instance, when an optical signal having a first mode (e.g., a TE**0** mode) is input into the first input waveguide **110** at the input **106**, the optical signal having the first mode effectively remains within the same waveguide (i.e., the first input waveguide **110** that transitions from a single mode waveguide to a multimode waveguide) along the first stage S**1**. When an optical signal having a second mode (e.g., a TE**1** mode) is input into the second input waveguide **120** at the input **106**, the optical signal having the second mode effectively "jumps" over to the first input waveguide **110** at least by the transition plane TP.

[0027] The first input waveguide **110** transitions from a single mode waveguide to a multimode waveguide due to the geometry of the first and second input waveguides **110**, **120** in a transition region of the first stage S**1** (the transition region spans between the first plane P**1** and the transition plane TP). The first plane P**1** can be positioned between the input **106** and the transition plane TP along the longitudinal direction Z as shown in FIG. **1**, or in other embodiments, the first plane P**1** can be at the input **106**. As illustrated in FIG. **1**, the first input waveguide **110** inverse tapers (e.g., generally from the first plane P**1** of the 2×2 coupler **100** to the transition plane TP) while the second input waveguide **120** tapers (e.g., generally from the first plane P**1** to the transition plane TP). In this regard, the first width W**1** of the first input waveguide **110** increases (e.g., gradually) while the second width W**2** of the second input waveguide **120** decreases (e.g., gradually) during this transition region of the first stage S**1**. The second input waveguide **120** can taper so as to "disappear" or nearly disappear at the transition plane TP. This ensures that substantially all optical power (e.g., at least 95%) of an optical signal input into the second input waveguide **120** is contained in the single multimode waveguide at the transition plane TP (i.e., the first input waveguide **110** at the transition plane TP). The first and second waveguides **110**, **120** are also arranged so that substantially all optical power (e.g., at least 95%) of an optical signal input into the first input waveguide **110** is contained in the single multimode waveguide at the transition plane TP (i.e., the first input waveguide **110** at the transition plane TP).

[0028] At **2-2** in FIG. **2**, which is a cross section taken from line **2-2** in FIG. **1** at the transition plane TP, the second input waveguide **120** is shown having nearly disappeared while the first input waveguide **110** is at its widest width. Stated another way, the first width W**1** of the first input waveguide **110** is greatest at the transition plane TP while the second width W**2** of the second input waveguide **120** is smallest at the transition plane TP. The close edge-to-edge gap G**1** and relatively large width of the first input waveguide **110** and relatively small width of the second input waveguide **120** allows an optical signal input into the second input waveguide **120** at the input **106** to "jump" or move to the first input waveguide **110** at least by the transition plane TP.

[0029] The multimode splitter **104** of the second stage S**2** is arranged symmetrically along the propagation axis PA of the 2×2 coupler **100**. For this example embodiment, the multimode splitter **104** is arranged as a multimode 50:50 y-splitter. However, in other embodiments, the multimode splitter **104** can have other symmetric arrangements.

[0030] As shown in FIG. **1**, the multimode splitter **104** has a first output waveguide **130** and a second output waveguide **140**. The first and second output waveguides **130**, **140** each traverse from the transition plane TP to the output **108**. The first and second output waveguides **130**, **140** generally converge toward one another along the lateral direction X over an initial portion of the second stage S**2** and then eventually diverge from one another along the lateral direction X as they approach the output **108** of the 2×2 coupler **100** over a latter portion of the second stage S**2**. The first and second output waveguides **130**, **140** are each single mode waveguides. The first output waveguide **130** has a third width W**3** and the second output waveguide **140** has a fourth width W**4**, e.g., as shown at **3-3** in FIG. **2**, which is a cross section taken from line **3-3** in FIG. **1** at the transition plane TP. The widths W**3**, W**4** of the first and second output waveguides **130**, **140** can vary over their longitudinal lengths. The first and second output waveguides **130**, **140** inverse taper (e.g., generally from the transition plane TP to the output **108**). In some embodiments, the first and second output waveguides **130**, **140** can inverse taper along a portion of the longitudinal length of the second stage S**2**. For instance, in some embodiments, the widths W**3**, W**4** of the first and second output waveguides **130**, **140** can inverse taper from the transition plane TP to a termination plane TR but then can remain substantially constant between the termination plane TR and the output **108**. Accordingly, the widths W**3**, W**4** of the first and second output waveguides **130**, **140** can increase (e.g., gradually) over at least a portion of the second stage S**2**. The first and second output waveguides **130**, **140** have respective thicknesses extending along the vertical direction Y.

[0031] The multimode splitter **104** also has a multimode waveguide **150** arranged between the first and second output waveguides **130**, **140**, e.g., along the lateral direction X. An edge-to-edge gap G**2** is defined between the first output waveguide **130** and a first edge of the multimode waveguide **150** and an edge-to-edge gap G**3** is defined between the second output waveguide **140** and a second edge of the multimode waveguide **150**, e.g., as shown at **3-3** in FIG. **2**. The gaps G**2**, G**3** can remain substantially constant over the longitudinal length of the multimode waveguide **150**. The multimode waveguide **150** has a fifth width W**5**, e.g., as shown at **3-3** in FIG. **2**. The width W**5** of the multimode waveguide **150** can vary over its longitudinal length. Indeed, the multimode waveguide **150** tapers (e.g., generally from the transition plane TP to the termination plane TR). In this regard, the fifth width W**5** of the multimode waveguide **150**

decreases (e.g., gradually) as the multimode waveguide **150** extends toward the output **108**. The multimode waveguide **150** has a thickness extending along the vertical direction Y.

[0032] Moreover, the multimode waveguide **150** traverses from the transition plane TP to the termination plane TR. A terminal end **152** of the multimode waveguide **150** and the first and second output waveguides **130**, **140** in relation to the terminal end **152** are shown at **4-4** in FIG. **2**, which is a cross section taken from line **4-4** in FIG. **1** at the termination plane TR. The termination plane TR is arranged between the transition plane TP and the output **108** in the example embodiment. In this regard, the multimode waveguide **150** terminates before the output **108** of the 2×2 coupler **100**. At **5-5** in FIG. **2**, which is a cross section taken from line **5-5** in FIG. **1** at the output **108**, the multimode waveguide **150** is not present and the widths W**3**, W**4** of the first and second output waveguides **130**, **140** are shown substantially equal.

[0033] In some alternative embodiments, as shown in FIG. **3**, the multimode waveguide **150** of the 2×2 coupler **100** can traverse longitudinally from the transition plane TP to the output **108**. The terminal end **152** of the multimode waveguide **150** is depicted at the output **108**. In this regard, the multimode waveguide **150** can have an "extended tip" in some embodiments. Such an arrangement can be advantageous for fabrication robustness, e.g., to avoid discontinuities until the first and second output waveguides **130**, **140** are substantially decoupled, e.g., as they are arranged at the output **108**.

[0034] As illustrated in FIG. **1**, the multimode splitter **104** is also arranged in communication with the single multimode waveguide of the first stage S**1** (i.e., the first input waveguide **110** at the transition plane TP). That is, at the transition plane TP, the multimode waveguide **150** is in communication with the single multimode waveguide of the mode multiplexer **102** (i.e., the first input waveguide **110** at the transition plane TP). In some embodiments, the width W**5** of the multimode waveguide **150** is substantially equal to the width of the single multimode waveguide of the mode multiplexer **102** at the transition plane TP (i.e., the width W**1** of the first input waveguide **110** at the transition plane TP). Stated another way, at the transition plane TP, the fifth width W**5** is substantially equal to the first width W**1**.

[0035] Notably, the first and second output waveguides **130**, **140** and the multimode waveguide **150** transition symmetrically along the second stage S**2** so that an optical signal traversing in the multimode waveguide of the first stage S**1** (i.e., the first input waveguide **110** at the transition plane TP) is received by the multimode waveguide **150** of the second stage S**2** and split substantially equally into the first and second output waveguides **130**, **140**. In this way, the splitting of an optical signal is accomplished with a splitter having a symmetric arrangement.

[0036] With reference now to FIGS. **4** and **5**, an example manner in which optical signals can be split by the 2×2 coupler **100** will be provided. FIG. **4** is a schematic flow diagram depicting an example manner in which optical signals can be split by the 2×2 coupler **100**. FIG. **5** illustrates a matrix of cross-sections of the 2×2 coupler **100** that demonstrate how the 2×2 coupler **100** splits light, according to an example embodiment.

[0037] As shown in FIGS. **4** and **5**, a first mode optical signal and a second mode optical signal can enter the 2×2 coupler **100**, e.g., through respective input ports of the first and second input waveguides **110**, **120**. In this example, the first mode optical signal is a TE**0** mode optical signal and the second mode optical signal is a TE**1** mode optical signal.

[0038] With respect to the TE**0** mode optical signal, the TE**0** mode optical signal is input into the first input waveguide **110** of the mode multiplexer **102** as illustrated in FIG. **5** at the cross section **1-1**. The first input waveguide **110** is a single mode waveguide at the input **106** (FIG. **1**), or at the cross section **1-1**. As described above, the first and second input waveguides **110**, **120** transition asymmetrically along the first stage S**1** (FIG. **1**) so that the first input waveguide **110** transitions from a single mode waveguide to a multimode waveguide. At the transition plane TP (FIG. **1**), or at cross section **2-2**, the first input waveguide **110** is a multimode waveguide and the second input waveguide **120** "disappears" or nearly disappears. Accordingly, all or nearly all of the optical power of the TE**0** mode optical signal traversing through the first stage S**1** is contained within the first input waveguide **110** at cross section **2-2**, e.g., as shown in FIG. **5**.

[0039] The TE**0** mode optical signal propagates across the transition plane TP (FIG. **1**) and into the multimode splitter **104**, and at the cross section **3-3** (which is just after the transition plane TP in the second stage S**2**), the TE**0** mode optical signal traverses along the multimode waveguide **150** as shown in FIG. **5**. As described above, the first and second output waveguides **130**, **140** and the multimode waveguide **150** transition symmetrically along the second stage S**2** and are arranged so that the TE**0** mode optical signal substantially equally splits into the first and second output waveguides **130**, **140**. As illustrated in FIG. **5** at the cross section **5-5**, the TE**0** mode optical signal has split 50:50 between the first output waveguide **130** and the second output waveguide **140** at the output **108** (FIG. **1**).

[0040] With respect to the TE**1** mode optical signal, the TE**1** mode optical signal is input into the second input waveguide **120** of the mode multiplexer **102** as illustrated in FIG. **5** at the cross section **1-1**. The second input waveguide **120** is a single mode waveguide at the input **106** (FIG. **1**), or at the cross section **1-1**. As noted above, the first and second input waveguides **110**, **120** transition asymmetrically along the first stage S**1** (FIG. **1**) so that the first input waveguide **110** transitions from a single mode waveguide to a multimode waveguide and so that the second input waveguide **120** "disappears" or nearly disappears as the second input waveguide **120** approaches the transition plane TP (FIG. **1**). The first input waveguide **110** can inverse taper along at least a portion of the first stage S**1** to increase in width and the second input waveguide **120** can taper along at least a portion of the first stage S**1** to decrease in width. Accordingly, the TE**1** mode optical signal input into the second input waveguide **120** "jumps" over or goes into the multimode section of the first input waveguide **110**. Thus, all or nearly all (e.g., at least 90%) of the optical power of the TE**1** mode optical signal traversing through the first stage S**1** is contained within the first input waveguide **110** at cross section **2-2** as shown in FIG. **5**.

[0041] The TE**1** mode optical signal propagates across the transition plane TP (FIG. **1**) and into the multimode splitter **104**, and at the cross section **3-3** (which is just after the transition plane TP in the second stage S**2**), the TE**1** mode optical signal traverses along the multimode waveguide **150** as shown in FIG. **5**. As described above, the first and second output waveguides **130**, **140** and the multimode waveguide **150** transition symmetrically along the second stage S**2** and are arranged so that the TE**1** mode optical signal substantially equally splits into the first and second output waveguides **130**, **140**. As illustrated in FIG. **5** at the cross section **5-5**, the TE**1** mode optical signal has split 50:50 between the first output waveguide **130** and the second output waveguide **140** at the output **108** (FIG. **1**).

[0042] Accordingly, the 2×2 coupler **100** outputs the TE**0** mode optical signal 50:50 between the first output waveguide **130** and the second output waveguide **140** and the TE**1** mode optical signal 50:50 between the first output waveguide **130** and the second output waveguide **140** as shown in FIGS. **4** and **5**.

[0043] Embodiments of the 2×2 coupler **100** disclosed herein can be used in a Mach Zehnder device, such as a switch, interferometer, or modulator. Examples are provided below.

[0044] As one example, FIG. **6** is a schematic view of a thermo-optic switch **600** incorporating the 2×2 coupler **100** therein. In this example, the thermo-optic switch **600** is a thermo-optic 1×2 switch having one input and two outputs. The thermo-optic switch **600** can be used in a receiver circuit, for example. As shown, the thermo-optic switch **600** has an input **602** and an output **604**. The thermo-optic switch **600** includes a y-splitter **606**, first and second transitions **608**, **610**, first and second thermal phase shifters **612**, **614**, the 2×2 coupler **100**, and third and fourth transitions **616**, **618**. Generally, the y-splitter **606** can split optical signals into two portions, the first and second transitions **608**, **610** can transition their respective optical paths from Silicon Nitride (SiN) to Silicon (Si), the first and second thermal phase shifters **612**, **614** can change the phase of their respective portions of the optical signals by locally controlling the temperature in a phase-shifting region, the 2×2 coupler **100** can receive different optical signals having different modes in its respective input waveguides and can split the modes equally between its output waveguides as described in detail herein, and the third and fourth transitions **616**, **618** can transition their respective optical paths from Si to SiN. Use of the 2×2 coupler **100** can improve the performance of the thermo-optic switch **600**. Moreover, such a configuration can enable the 2×2 coupler **100** to be entirely formed of Si, which make the 2×2 coupler **100** an adiabatic 2×2 coupler.

[0045] As another example, FIG. **7** is a schematic view of an electro-optic switch **700** incorporating the 2×2 coupler **100** therein. In this example, the electro-optic switch **700** is an electro-optic 1×2 switch having one input and two outputs. The electro-optic switch **700** can be used in a transmitter circuit, for example. As shown, the electro-optic switch **700** has an input **702** and an output **704**. The electro-optic switch **700** includes a y-splitter **706**, first and second transitions **708**, **710**, first and second electro-optic phase shifters **712**, **714**, the 2×2 coupler **100**, and third and fourth transitions **716**, **718**. Generally, the y-splitter **706** can split optical signals into two portions, the first and second transitions **708**, **710** can transition their respective optical paths from SiN to Si, the first and second electro-optic phase shifters **712**, **714** can change the phase of their respective portions of the optical signals, the 2×2 coupler **100** can receive different optical signals having different modes in its respective input waveguides and can split the modes equally between its output waveguides as described in detail herein, and the third and fourth transitions **716**, **718** can transition their respective optical paths from Si to SiN. Use of the 2×2 coupler **100** can improve the performance of the electro-optic switch **700**. Moreover, such a configuration can enable the 2×2 coupler **100** to be entirely formed of Si, which make the 2×2 coupler **100** an adiabatic 2×2 coupler.

[0046] As yet another example, FIG. **8** is a schematic view of a laser switch **800** incorporating the 2×2 coupler **100** therein. In this example, the laser switch **800** allows for selection between a first laser **802** and a second laser **804**. When the first laser **802** is selected, the first laser **802** emits an optical signal (or laser beam of a first mode), the 2×2 coupler **100** formed of Si can receive the optical signal. Particularly, the first stage of the 2×2 coupler configured as a mode multiplexer can have a first input waveguide and a second input waveguide that transition asymmetrically over the first stage. The optical signal can be received by the first input waveguide and can traverse through the first stage of the 2×2 coupler **100** so as to be contained in a single multimode waveguide before crossing the transition plane into the second stage of the 2×2 coupler. For instance, the optical signal can remain in the first input waveguide which transitions from a single mode input waveguide to a multimode waveguide. The second stage of the 2×2 coupler configured as a symmetric splitter can split the optical signal between its first and second output waveguides and output the split portions from the 2×2 coupler.

[0047] When the second laser **804** is selected, the second laser **804** emits an optical signal (or laser beam of a second mode), the 2×2 coupler **100** can receive the optical signal. Specifically, the optical signal can be received by the second input waveguide and can traverse through the first stage of the 2×2 coupler **100** so as to be contained in a single multimode waveguide before crossing the transition plane into the second stage of the 2×2 coupler. For instance, the optical signal can "jump" or go from the second input waveguide to a segment of the first input waveguide that has transitioned to a multimode waveguide. The second stage of the 2×2 coupler configured as a symmetric splitter can split the optical signal between its first and second output waveguides and output the split portions from the 2×2 coupler. Although the 2×2 coupler **100** is shown in FIG. **8** as being formed of Si, in other embodiments, the 2×2 coupler **100** of FIG. **8** can be formed of SiN.

[0048] It will be appreciated that the switches **600**, **700**, **800** depicted in FIGS. **6**, **7**, and **8** are provided by way of example and are not intended to be limiting. The 2×2 coupler disclosed herein can be implemented in other configurations, systems, circuits, as stand-alone devices, etc.

[0049] In the current disclosure, reference is made to various embodiments. However, the scope of the present disclosure is not limited to specific described embodiments. Instead, any combination of the described features and elements, whether related to different embodiments or not, is contemplated to implement and practice contemplated embodiments. Additionally, when elements of the embodiments are described in the form of "at least one of A and B," or "at least one of A or B," it will be understood that embodiments including element A exclusively, including element B exclusively, and including element A and B are each contemplated. Furthermore, although some embodiments disclosed herein may achieve advantages over other possible solutions or over the prior art, whether or not a particular advantage is achieved by a given embodiment is not limiting of the scope of the present disclosure. Thus, the aspects, features, embodiments and advantages disclosed herein are merely illustrative and are not considered elements or limitations of the appended claims except where explicitly recited in a claim(s).

[0050] In view of the foregoing, the scope of the present disclosure is determined by the claims that follow.

We claim:

1. A 2×2 coupler, comprising:

a first stage configured as a mode multiplexer; and

a second stage configured as a multimode splitter.

2. The 2×2 coupler of claim **1**, wherein the first stage transitions to the second stage at a transition plane, and wherein at the transition plane, substantially all optical power of an optical signal traversing through the 2×2 coupler is contained within a single multimode waveguide.

3. The 2×2 coupler of claim **1**, wherein the first stage transitions to the second stage at a transition plane, and wherein the mode multiplexer has a first input waveguide and a second input waveguide that each traverse from an input to the transition plane, and wherein the first and second input waveguides are arranged asymmetrically along a propagation axis of the 2×2 coupler.

4. The 2×2 coupler of claim **3**, wherein the first stage transitions to the second stage at a transition plane, and wherein the first input waveguide and the second input waveguide are single mode waveguides at an input of the 2×2 coupler and the first and second input waveguides transition along the first stage so as to render a single multimode waveguide at least at the transition plane.

5. The 2×2 coupler of claim **4**, wherein the first input waveguide becomes the single multimode waveguide at the transition plane while the second input waveguide tapers as the second input waveguide approaches the transition plane so that substantially all optical power of an optical signal input into the second input waveguide is contained in the single multimode waveguide at the transition plane.

6. The 2×2 coupler of claim **1**, wherein the mode multiplexer is arranged as a two-mode multiplexer.

7. The 2×2 coupler of claim **1**, wherein the multimode splitter is arranged symmetrically along a propagation axis of the 2×2 coupler.

8. The 2×2 coupler of claim **1**, wherein the multimode splitter is arranged as a multimode y-splitter.

9. The 2×2 coupler of claim **8**, wherein the multimode y-splitter has a multimode waveguide that tapers and two output waveguides that inverse taper.

10. The 2×2 coupler of claim **9**, wherein the first stage transitions to the second stage at a transition plane, and wherein, at the transition plane, the multimode waveguide is in communication with a single multimode waveguide of the mode multiplexer.

11. The 2×2 coupler of claim **9**, wherein the multimode waveguide is arranged between the two output waveguides.

12. The 2×2 coupler of claim **9**, wherein the multimode waveguide terminates before an output of the 2×2 coupler.

13. The 2×2 coupler of claim **9**, wherein the two output waveguides diverge from one another as they approach an output of the 2×2 coupler.

14. The 2×2 coupler of claim **9**, wherein the 2×2 coupler is made entirely of silicon.

15. A 2×2 coupler, comprising:

a first stage having two input waveguides that transition asymmetrically along a propagation axis of the 2×2 coupler so that an optical signal input into one of the two input waveguides traverses into, or remains in, a first input waveguide of the two input waveguides, wherein the first input waveguide transitions from a single mode waveguide to a multimode waveguide; and

a second stage having two single mode output waveguides and a multimode waveguide arranged in communication with the multimode waveguide of the first stage, the two single mode output waveguides and the multimode waveguide transition symmetrically along the propagation axis so that the optical signal traversing in the multimode waveguide of the first stage is received by the multimode waveguide of the second stage and split into the two single mode output waveguides.

16. The 2×2 coupler of claim **15**, wherein the 2×2 coupler is an adiabatic 2×2 coupler.

17. The 2×2 coupler of claim **15**, wherein the first input waveguide inverse tapers along at least a portion of the first stage and a second input waveguide of the two input waveguides tapers along at least a portion of the first stage.

18. The 2×2 coupler of claim **17**, wherein the first input waveguide and the second input waveguide converge toward one another from an input of the 2×2 coupler to a first plane arranged between the input and a transition plane defined where the first stage transitions to the second stage.

19. The 2×2 coupler of claim **15**, wherein the multimode waveguide of the second stage is arranged between the two single mode output waveguides and tapers over at least a portion of the second stage as the multimode waveguide extends away from the first stage while the two single mode output waveguides both inverse taper over at least a portion of the second stage as the two single mode output waveguides extend away from the first stage.

20. A Mach Zehnder device, comprising:

a 2×2 coupler, comprising:

a first stage having two input waveguides that transition asymmetrically along a propagation axis of the 2×2 coupler so that an optical signal input into a first input waveguide or a second input waveguide of the two input waveguides traverses into, or remains in, the first input waveguide, wherein the first input waveguide transitions from a single mode waveguide to a multimode waveguide, and wherein the first input waveguide inverse tapers while the second input waveguide tapers over at least a portion of the first stage as the first and second waveguides extend away from an inlet of the 2×2 coupler; and

a second stage having two single mode output waveguides and a multimode waveguide arranged in communication with the multimode waveguide of the first stage, the two single mode output waveguides and the multimode waveguide transition symmetrically along the propagation axis so that the optical signal traversing in the multimode waveguide of the first stage is received by the multimode waveguide of the second stage and split into the two single mode output waveguides.

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