US012395263B2

(12) **United States Patent**
Tambasco et al.

(10) **Patent No.: US 12,395,263 B2**
(45) **Date of Patent: Aug. 19, 2025**

(54) **WAVELENGTH DIVISION MULTIPLEXING ARCHITECTURE BASED ON INTEGRATED BRAGG AND ADIABATIC TE0 MODE ADD/DROP FILTER**

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

(72) Inventors: **Jean-Luc Joseph Tambasco**, Macungie, PA (US); **Dominic Francis Siriani**, Souderton, PA (US)

(73) Assignee: **CISCO TECHNOLOGY, INC.**, San Jose, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 195 days.

(21) Appl. No.: **18/096,128**

(22) Filed: **Jan. 12, 2023**

(65) **Prior Publication Data**

US 2024/0243832 A1 Jul. 18, 2024

(51) **Int. Cl.**
H04J 14/02 (2006.01)
H04B 10/294 (2013.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H04J 14/0201*** (2013.01); ***H04B 10/294*** (2013.01); *H04B 10/25* (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC H04J 14/0201; H04J 14/0307; H04J 14/02; H04J 14/04; H04B 10/294; H04B 10/25;
(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

11,635,570 B1 4/2023 Thompson
11,747,559 B2 9/2023 Bian
(Continued)

FOREIGN PATENT DOCUMENTS

CN 105866893 A 1/2019
WO 2018014365 A1 1/2018
WO 2022062676 A1 3/2022

OTHER PUBLICATIONS

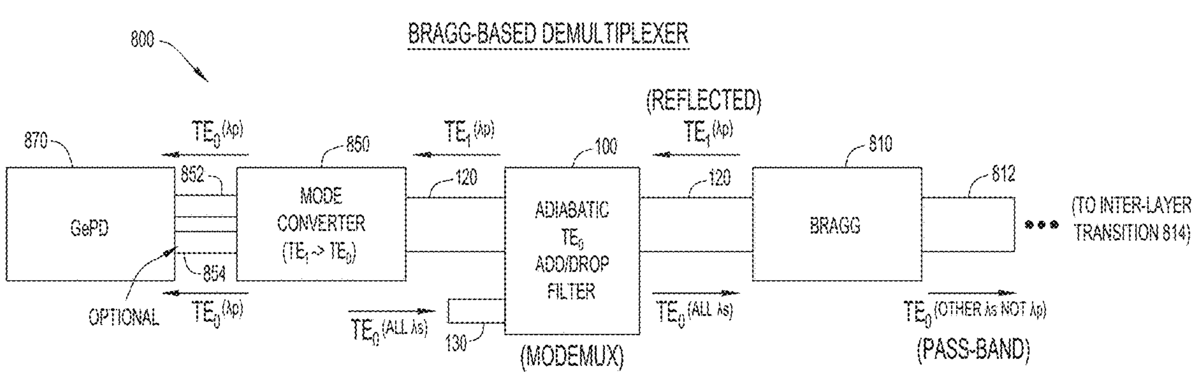
Shi et al, CN107167873A, Sep. 2017, Chinese Patent Office, All Document. (Year: 2017).*
(Continued)

Primary Examiner — Dibson J Sanchez
(74) *Attorney, Agent, or Firm* — Edell, Shapiro & Finnan, LLC

(57) **ABSTRACT**

A method and apparatus are provided. The method includes receiving, at a TE_0 mode add/drop filter, a TE_0 mode optical signal having a first wavelength and a second wavelength, and transmitting, from the TE_0 mode add/drop filter, the TE_0 mode optical signal having the first wavelength and the second wavelength towards a Bragg grating, without converting the TE_0 mode optical signal having the first wavelength and the second wavelength to another mode. The method further includes receiving, at the TE_0 mode add/drop filter, a reflected TE_1 mode optical signal having the first wavelength from the Bragg grating, and transmitting, from the TE_0 mode add/drop filter, the reflected TE_1 mode optical signal having the first wavelength towards a photodetector, without converting the reflected TE_1 mode optical signal having the first wavelength to another mode.

20 Claims, 17 Drawing Sheets



(51) **Int. Cl.**
H04B 10/25 (2013.01)
H04B 10/2581 (2013.01)
H04J 14/04 (2006.01)

(52) **U.S. Cl.**
CPC *H04B 10/2581* (2013.01); *H04J 14/02* (2013.01); *H04J 14/0307* (2023.08); *H04J 14/04* (2013.01)

(58) **Field of Classification Search**
CPC H04B 10/2581; G02B 2006/1215; G02B 6/12007; G02B 6/124; G02B 6/14
USPC 398/43–103, 140–172
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

12,158,607	B2	12/2024	Yamashita et al.	
2004/0258357	A1*	12/2004	De Barros	G02B 6/02085 385/28
2015/0104128	A1	4/2015	Oka et al.	
2015/0338577	A1*	11/2015	Shi	G02B 6/125 385/11
2018/0267237	A1*	9/2018	Oonawa	G02B 6/12004
2018/0284348	A1	10/2018	Lin	
2018/0314005	A1	11/2018	Lin et al.	
2019/0222309	A1	7/2019	Gross et al.	
2019/0243066	A1	8/2019	Mahgerefteh et al.	
2019/0384003	A1	12/2019	Painchaud et al.	
2020/0116939	A1*	4/2020	Wang	G02B 6/12007
2021/0109281	A1	4/2021	Ling et al.	
2023/0224040	A1*	7/2023	Lin	H04B 10/2519 398/147
2023/0268718	A1*	8/2023	Guo	G02F 1/21 372/20

OTHER PUBLICATIONS

Liu et al, Four-Channel CWDM (de)Multiplexers Using Cascaded Multimode Waveguide Gratings, Feb. 2020, IEEE, All Document. (Year: 2020).*

Xiao et al, Integrated Bragg Grating Filter With Reflection Light Dropped via Two Mode Conversions, May 2019, JOLWT, All Document. (Year: 2019).*

Jiang et al, Silicon lateral-apodized add-drop filter for on-chip optical interconnection, Oct. 2017, Applied Optics, vol. 56 No. 30, All Document. (Year: 2017).*

Shi, W., et al., "Silicon photonic Bragg-grating couplers for optical communications," Invited Paper, Proceedings of SPIE—The International Society for Optical Engineering, https://www.researchgate.net/publication/269323655_Silicon_photonic_Bragg-grating_couplers_for_optical_communications, Feb. 2014, 13 pages.

Okayama, H., et al., "Silicon wire waveguide TE0/TE1 mode conversion Bragg grating with resonant cavity section," Optics Express, Research Article, vol. 25, No. 14, https://opg.optica.org/oe/fulltext.cfm?uri=oe-25-14-16672&id=369014, Jul. 2017, 9 pages.

Qiu, H., et al., "Silicon add-drop filter based on multimode Bragg sidewall gratings and adiabatic couplers," Journal of Lightwave Technology, vol. 35, No. 9, https://ieeexplore.ieee.org/document/7851086/authors#authors, Feb. 2017, 5 pages.

Park, T., et al., "Optimization of Tilted Bragg Grating Tunable Filters Based on Polymeric Optical Waveguides," Current Optics and Photonics, vol. 1, No. 3, https://doi.org/10.3807/COPP.2017.1.3.214, Jun. 2017, 7 pages.

Jafari, O., et al., Mode-conversion-based silicon photonic modulator loaded by a combination of lateral and Interleaved p-n junctions, Research Article, vol. 9, No. 4, Photonics Research, https://doi.org/10.1364/PRJ.414400, Apr. 2021, 6 pages.

Wang, X., et al., "Hitless and gridless reconfigurable optical add drop (de)multiplexer based on looped waveguide sidewall Bragg gratings on silicon," Research Article, vol. 28, No. 10, Optics Express, https://opg.optica.org/oe/fulltext.cfm?uri=oe-28-10-14461&id=431329, May 2020, 15 pages.

Xie, S., et al., "Add-drop filter with complex waveguide Bragg grating and multimode interferometer operating on arbitrarily spaced channels," Optics Letters, vol. 43, No. 24, https://opg.optica.org/ol/abstract.cfm?uri=ol-43-24-6045, Dec. 2018, 4 pages.

Qiu, H., et al., "Silicon band-rejection and band-pass filter based on asymmetric Bragg sidewall gratings in a multimode waveguide," Optics Letters, vol. 41, Issue 11, https://opg.optica.org/ol/abstract.cfm?uri=ol-41-11-2450, Jun. 2016, 1 page.

* cited by examiner

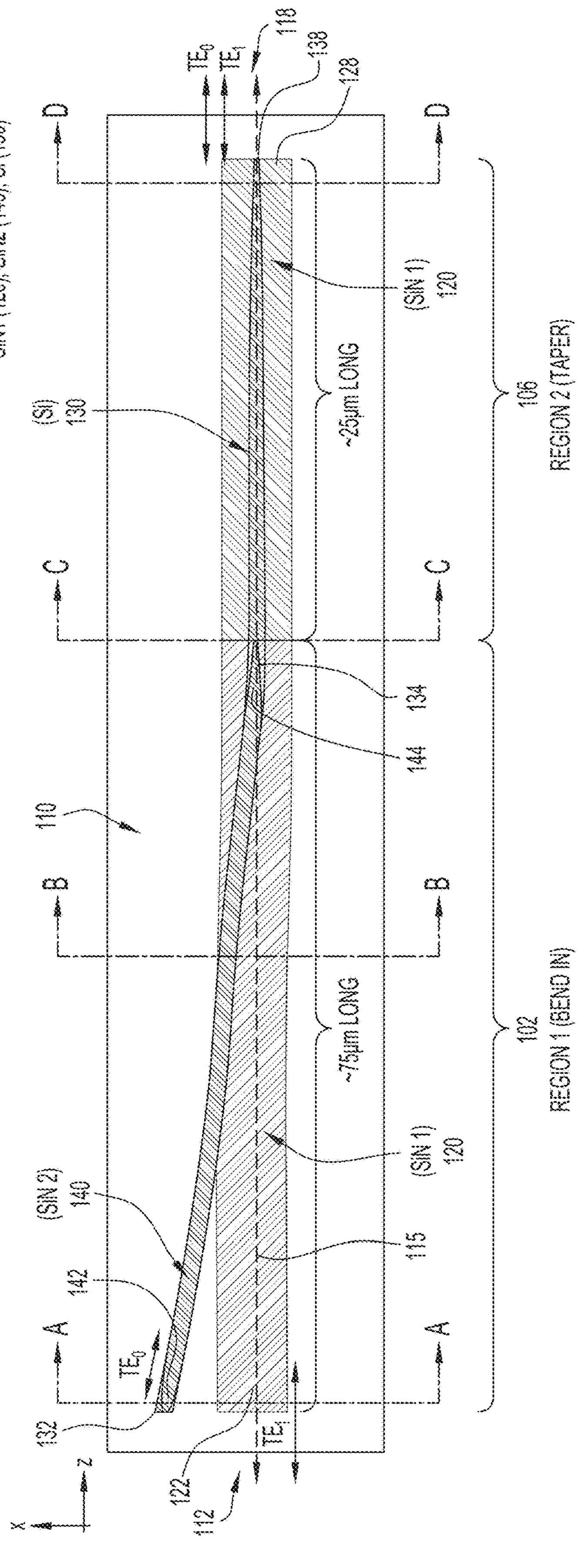

100
SIN1 (120), SIN2 (140), SI (130)
D
D
C
C
B
B
A
A
TE_0
TE_1
118
138
128
(SIN 1)
120
(Si)
130
~25μm LONG
106
REGION 2 (TAPER)
134
144
110
~75μm LONG
102
REGION 1 (BEND IN)
(SIN 1)
120
(SIN 2)
140
142
115
TE_0
132
TE_1
122
112
x
z

FIG.1

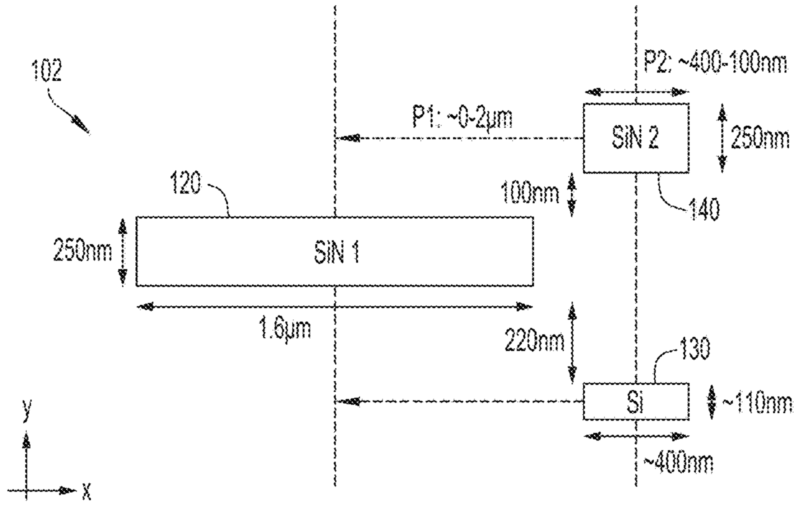


FIG.2A

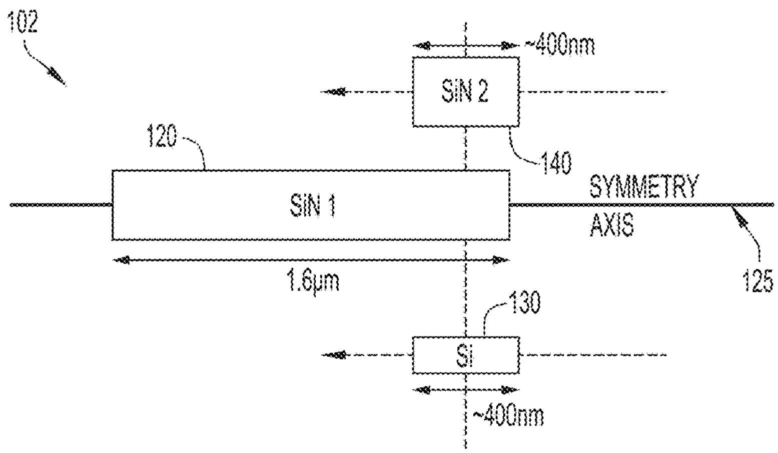


FIG.2B

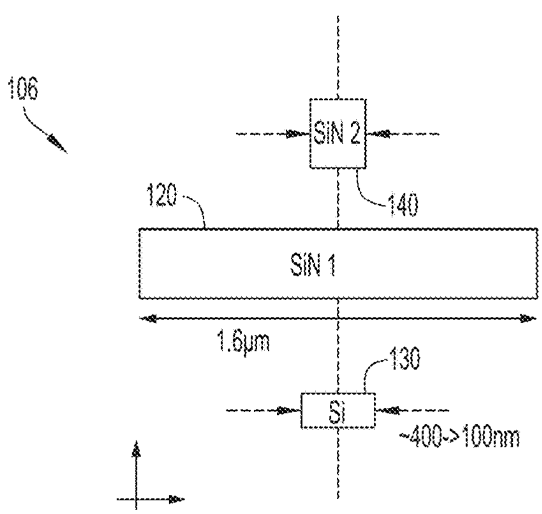


FIG.2C

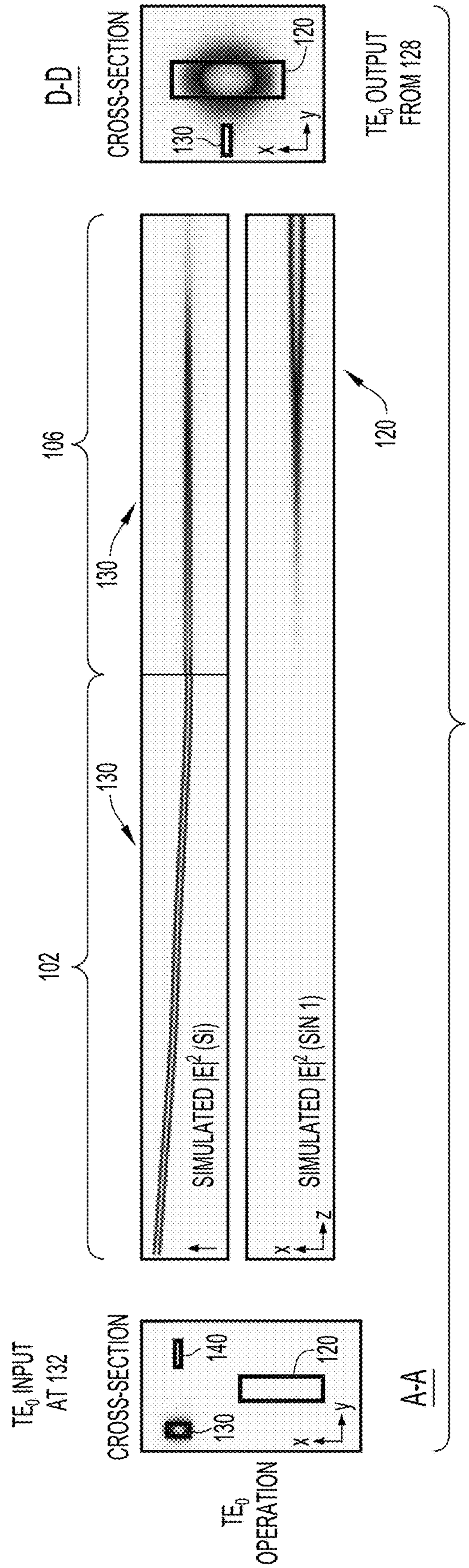
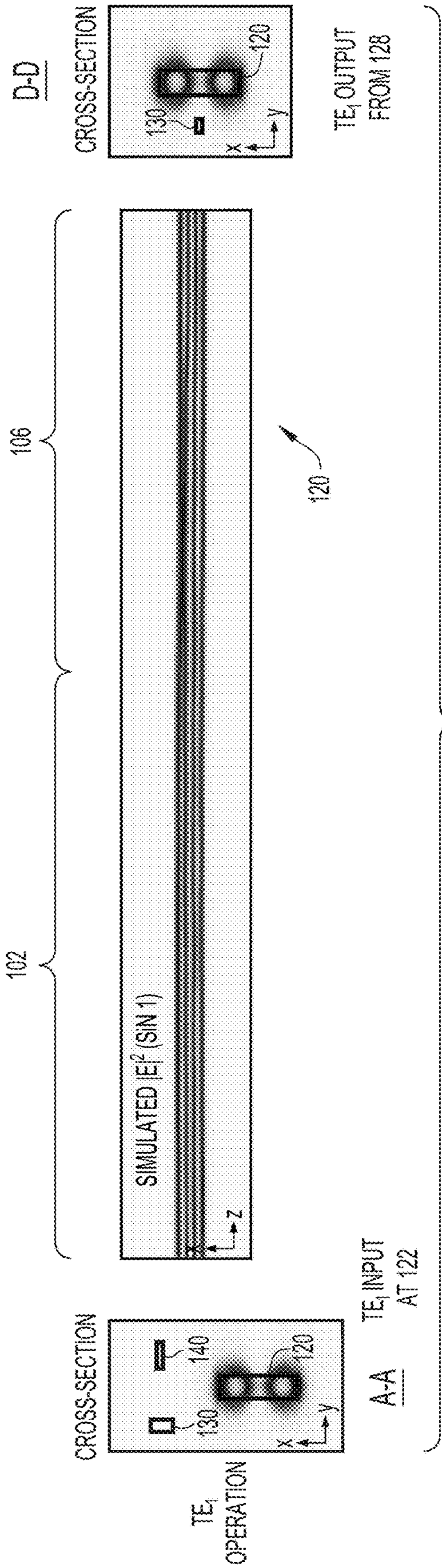
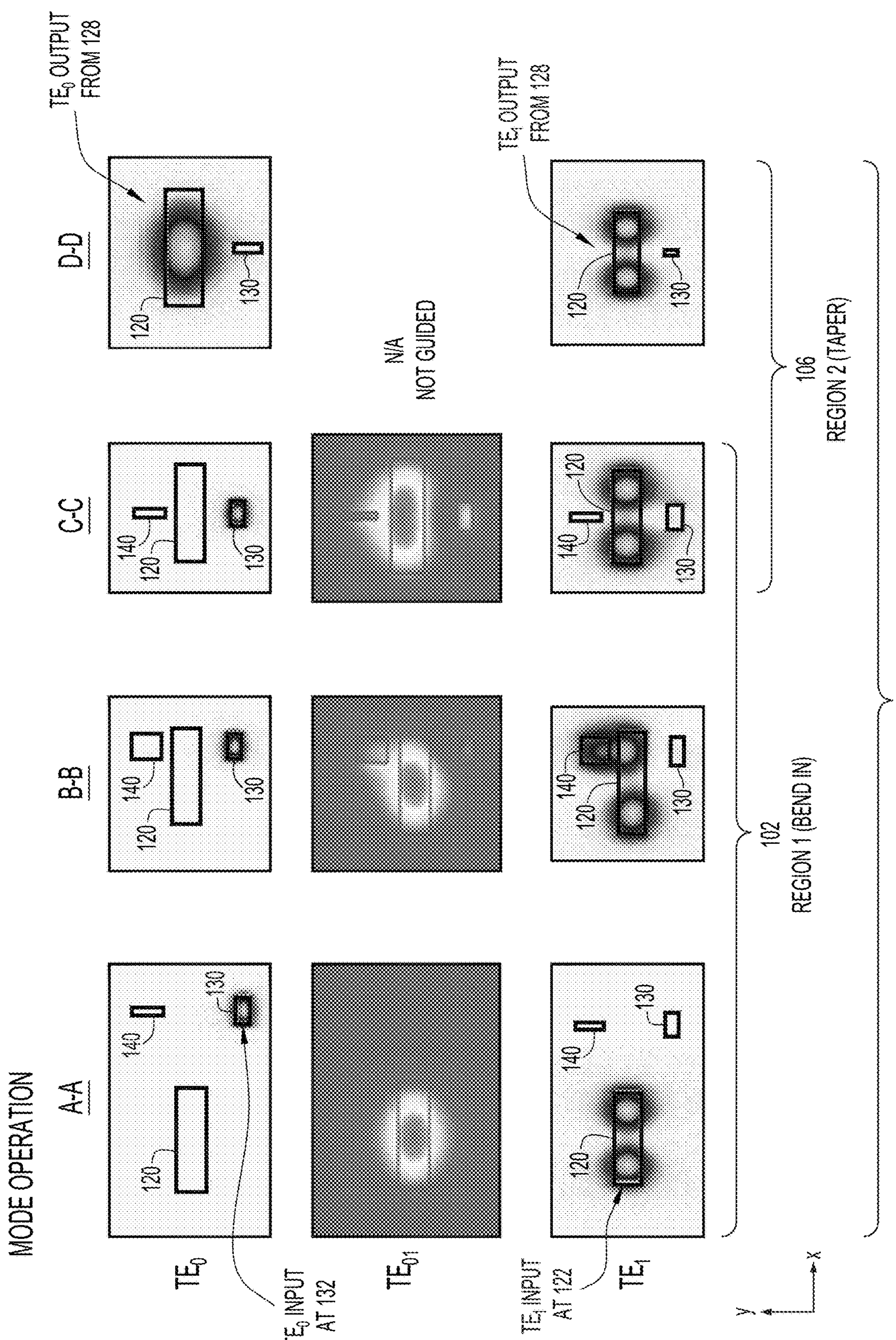

D-D
CROSS-SECTION
130
120
x
y
TE$_0$ OUTPUT FROM 128
106
102
130
130
120
SIMULATED $|E|^2$ (SI)
SIMULATED $|E|^2$ (SIN 1)
x
z
TE$_0$ INPUT AT 132
CROSS-SECTION
140
120
130
x
y
A-A
TE$_0$ OPERATION

FIG.3A



D-D
CROSS-SECTION
130
120
x
y
TE_1 OUTPUT FROM 128
106
120
102
SIMULATED $|E|^2$ (SIN 1)
z
TE_1 INPUT AT 122
CROSS-SECTION
140
130
120
x
y
A-A
TE_1 OPERATION

FIG.3B



MODE OPERATION
A-A
B-B
C-C
D-D
TE_0
TE_{01}
TE_1
TE_0 INPUT AT 132
TE_1 INPUT AT 122
TE_0 OUTPUT FROM 128
TE_1 OUTPUT FROM 128
N/A NOT GUIDED
120
130
140
102 REGION 1 (BEND IN)
106 REGION 2 (TAPER)
y
x

FIG.3C

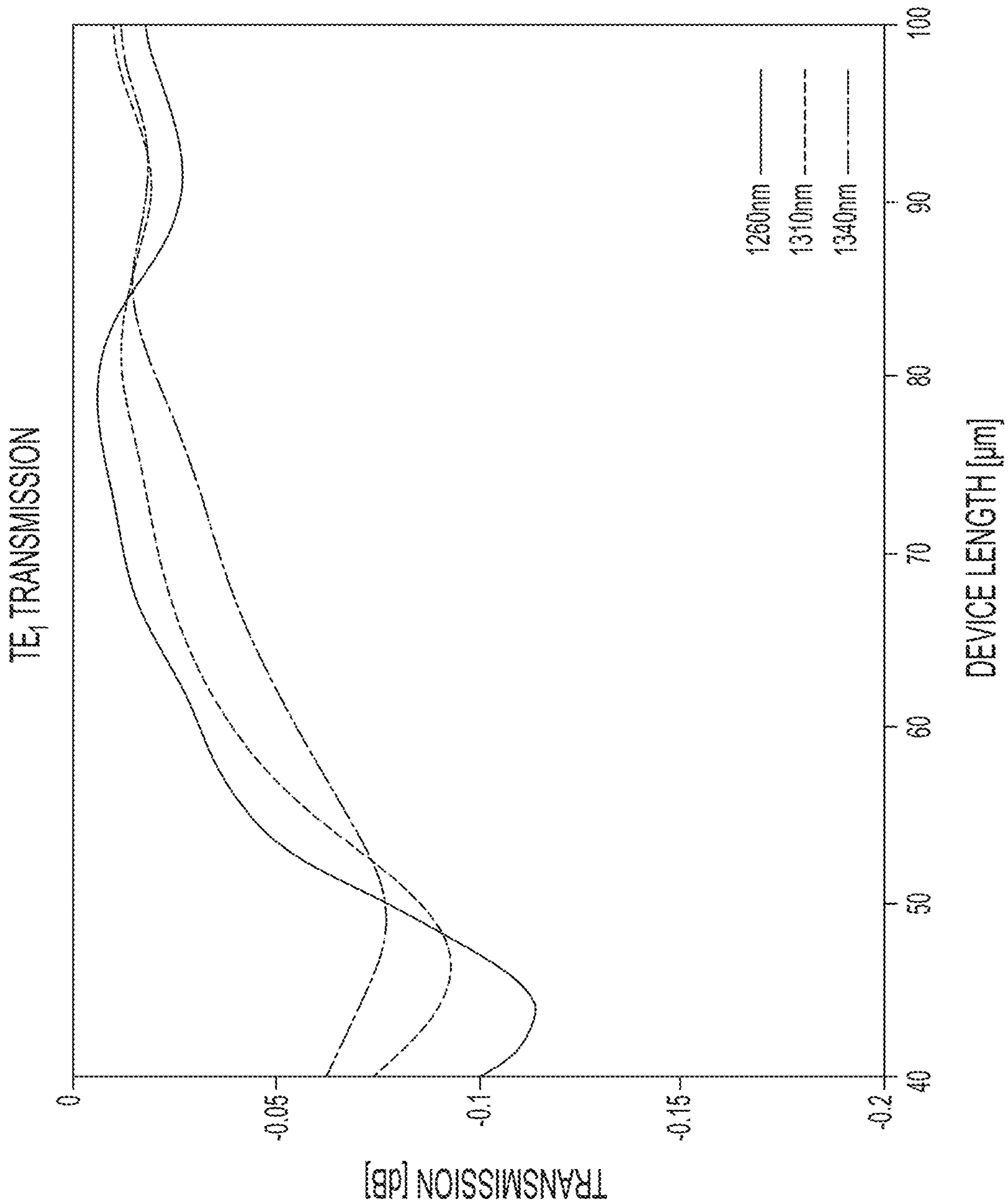

TE_1 TRANSMISSION
TRANSMISSION [dB]
0
-0.05
-0.1
-0.15
-0.2
40
50
60
70
80
90
100
DEVICE LENGTH [μm]
1260nm
1310nm
1340nm

FIG.4A

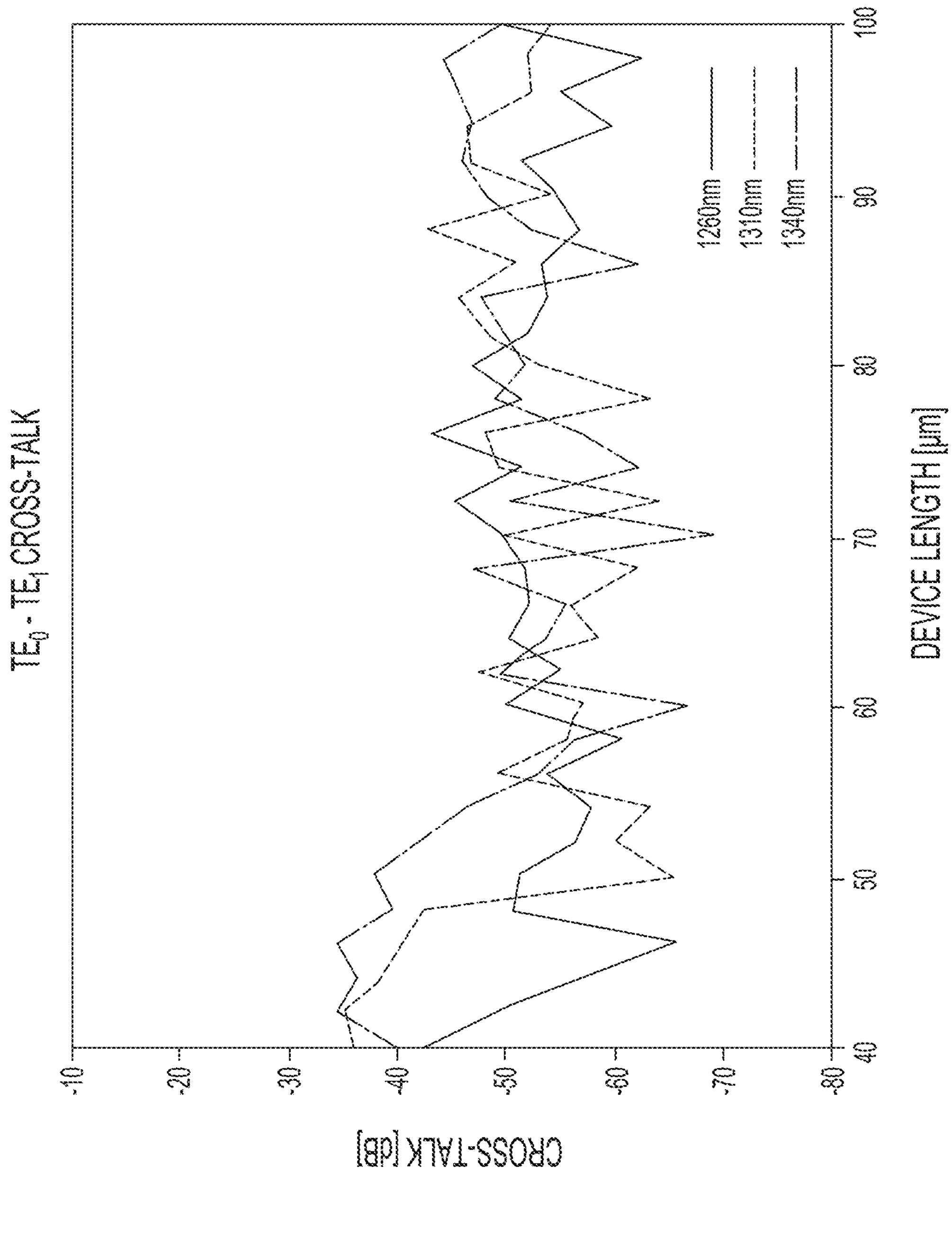

TE_0 - TE_1 CROSS-TALK
CROSS-TALK [dB]
-10
-20
-30
-40
-50
-60
-70
-80
40
50
60
70
80
90
100
DEVICE LENGTH [μm]
1260nm
1310nm
1340nm

FIG.4B

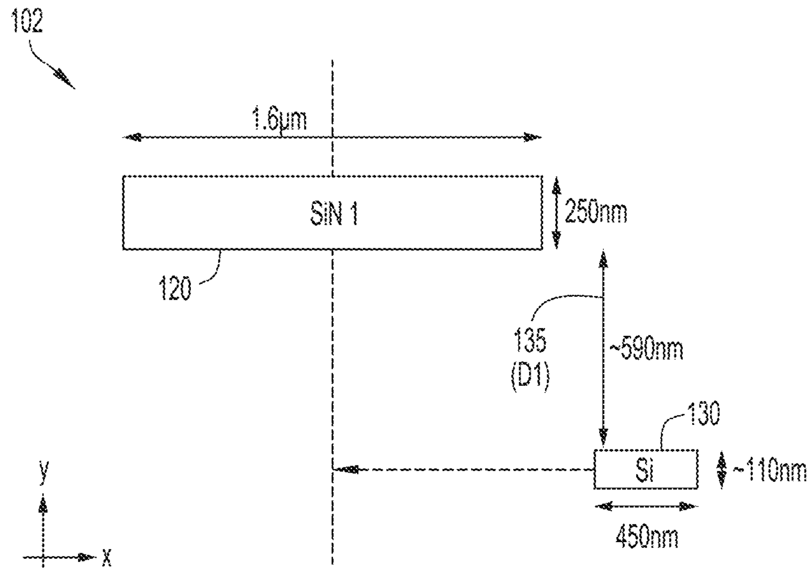

102
1.6μm
SiN 1
250nm
120
135
(D1)
~590nm
130
Si
~110nm
450nm
y
x

FIG.5A

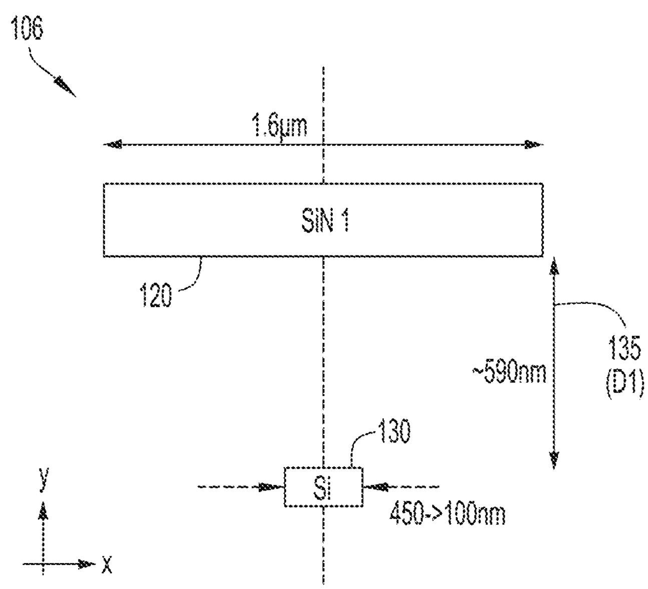
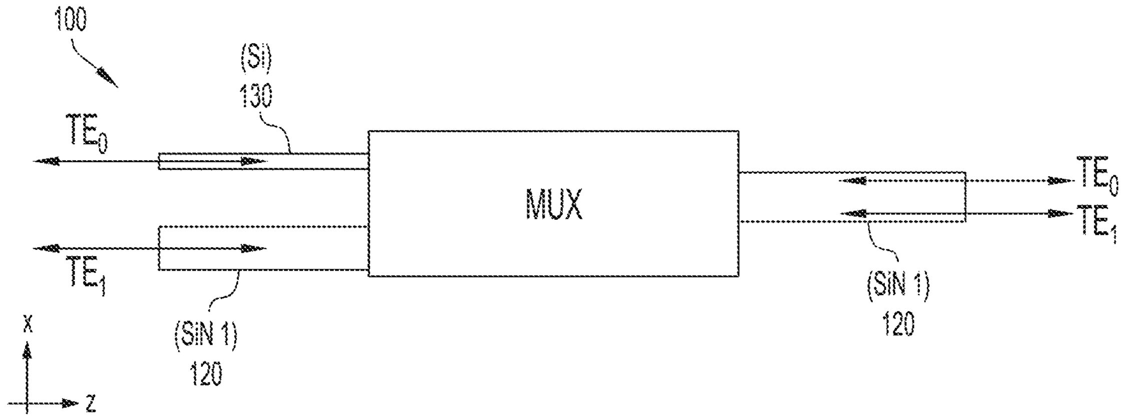
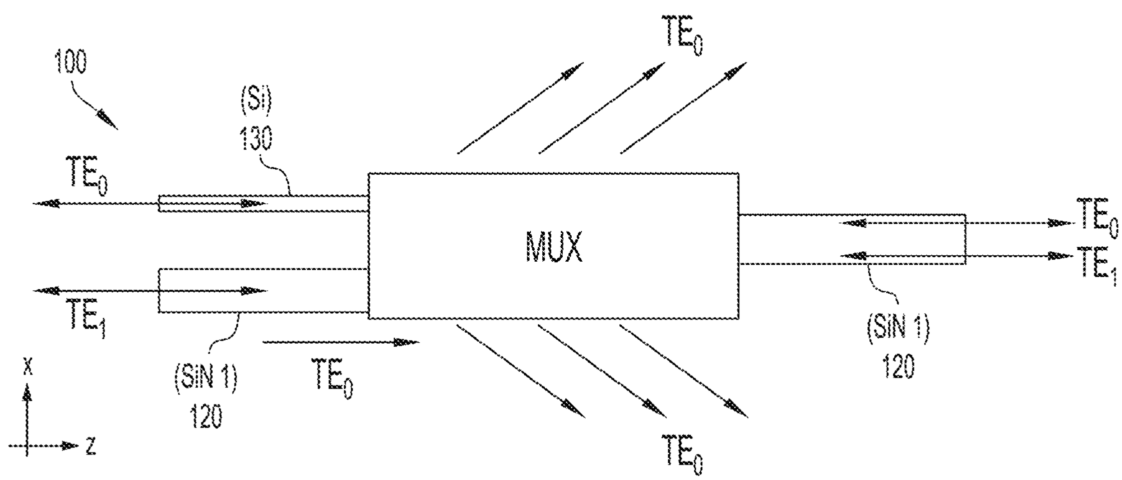

106
1.6μm
SiN 1
120
~590nm
135
(D1)
130
Si
450->100nm
y
x

FIG.5B



100
(Si)
130
TE_0
MUX
TE_0
TE_1
TE_1
(SiN 1)
120
x
z
(SiN 1)
120

FIG.6A



TE_0
100
(Si)
130
TE_0
MUX
TE_0
TE_1
TE_1
x
(SiN 1)
120
TE_0
(SiN 1)
120
z
TE_0

FIG.6B

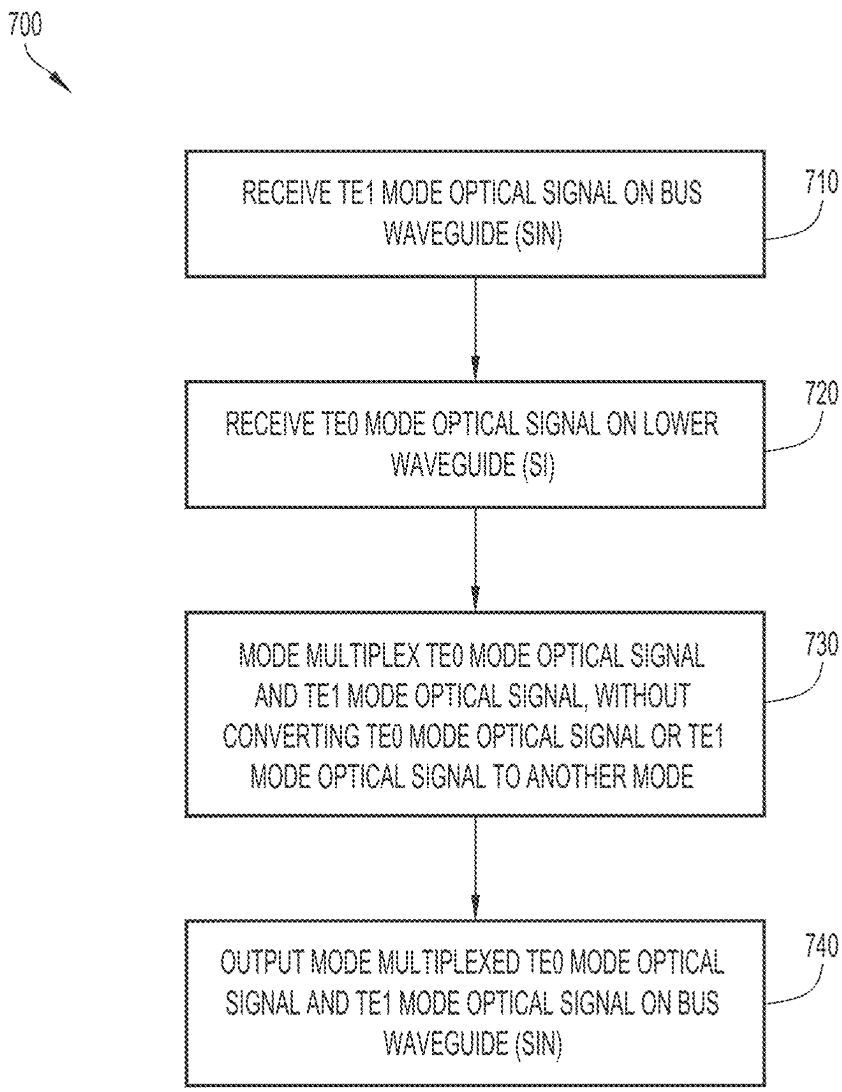

700
RECEIVE TE1 MODE OPTICAL SIGNAL ON BUS WAVEGUIDE (SIN)
710
RECEIVE TE0 MODE OPTICAL SIGNAL ON LOWER WAVEGUIDE (SI)
720
MODE MULTIPLEX TE0 MODE OPTICAL SIGNAL AND TE1 MODE OPTICAL SIGNAL, WITHOUT CONVERTING TE0 MODE OPTICAL SIGNAL OR TE1 MODE OPTICAL SIGNAL TO ANOTHER MODE
730
OUTPUT MODE MULTIPLEXED TE0 MODE OPTICAL SIGNAL AND TE1 MODE OPTICAL SIGNAL ON BUS WAVEGUIDE (SIN)
740

FIG.7

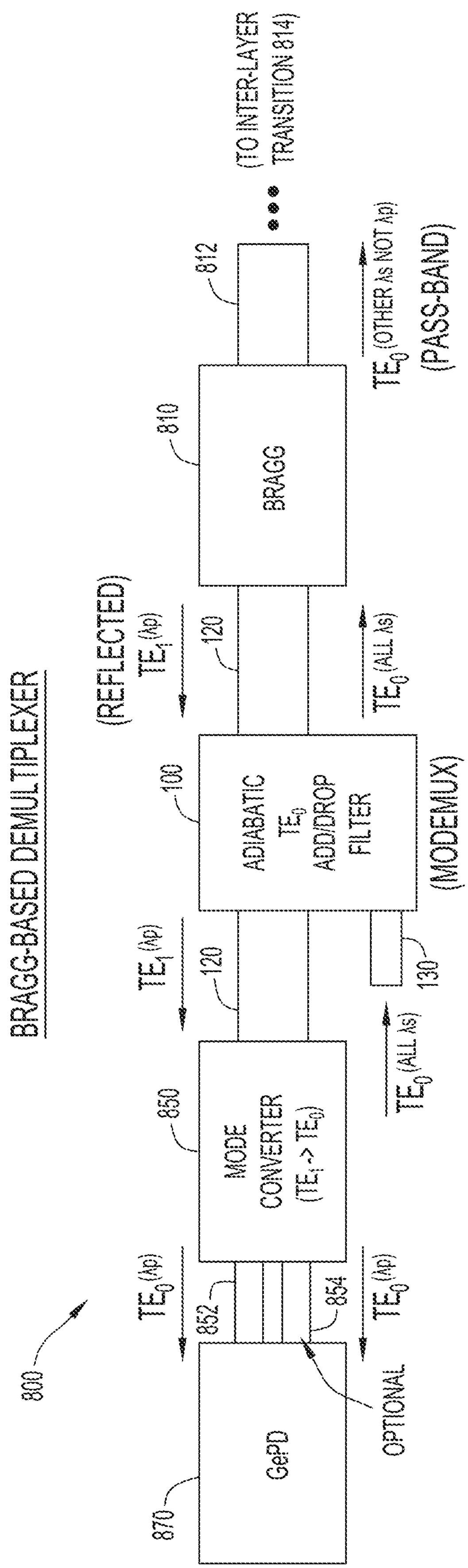

BRAGG-BASED DEMULTIPLEXER
800
870
GePD
852
854
OPTIONAL
TE0 (λp)
TE0 (λp)
850
MODE
CONVERTER
(TE1 -> TE0)
TE1 (λp)
120
TE0 (ALL λs)
100
ADIABATIC
TE0
ADD/DROP
FILTER
(MODEMUX)
130
(REFLECTED)
TE1 (λp)
120
TE0 (ALL λs)
810
BRAGG
812
TE0 (OTHER λs NOT λp)
(PASS-BAND)
(TO INTER-LAYER
TRANSITION 814)

FIG.8

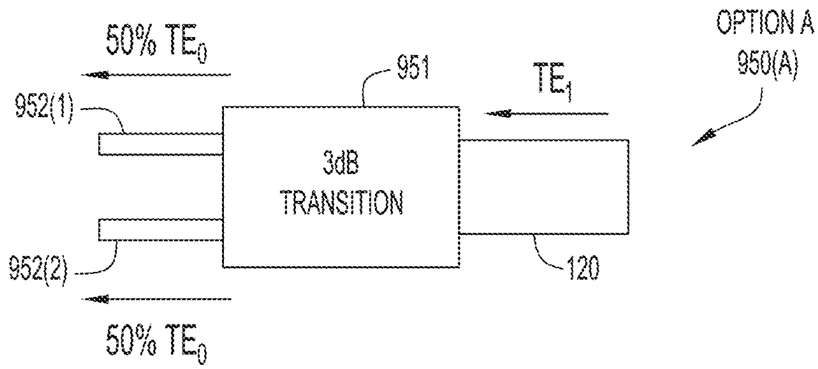


FIG.9A

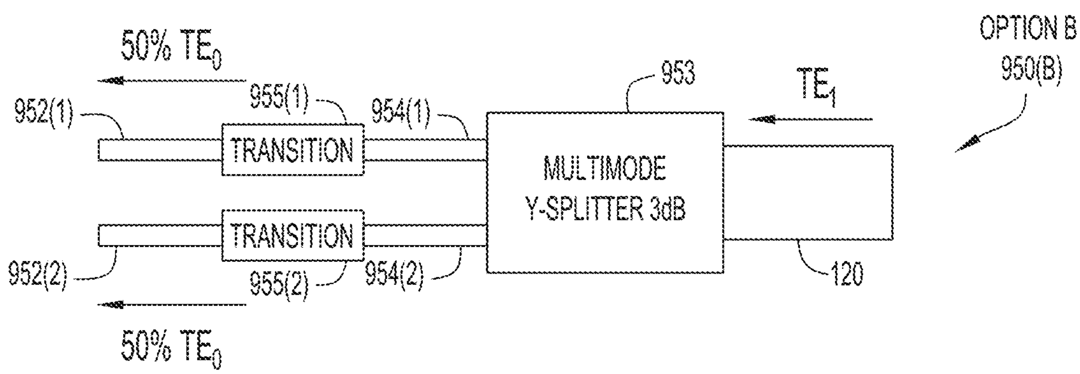


FIG.9B

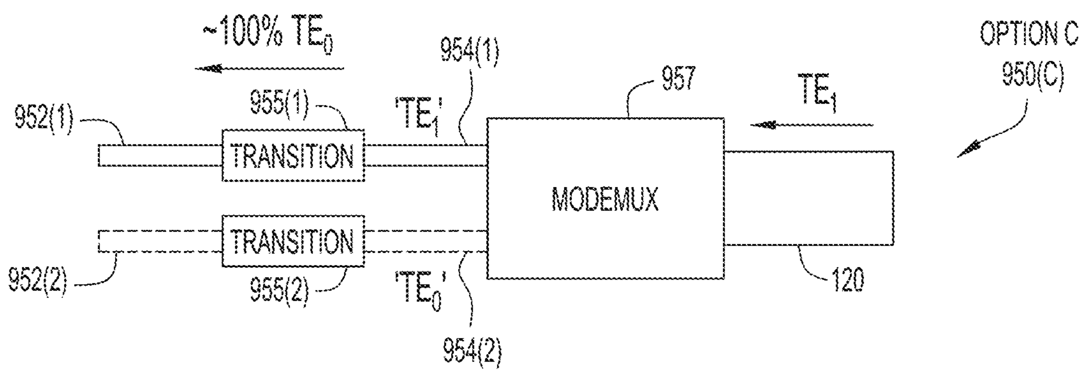


FIG.9C

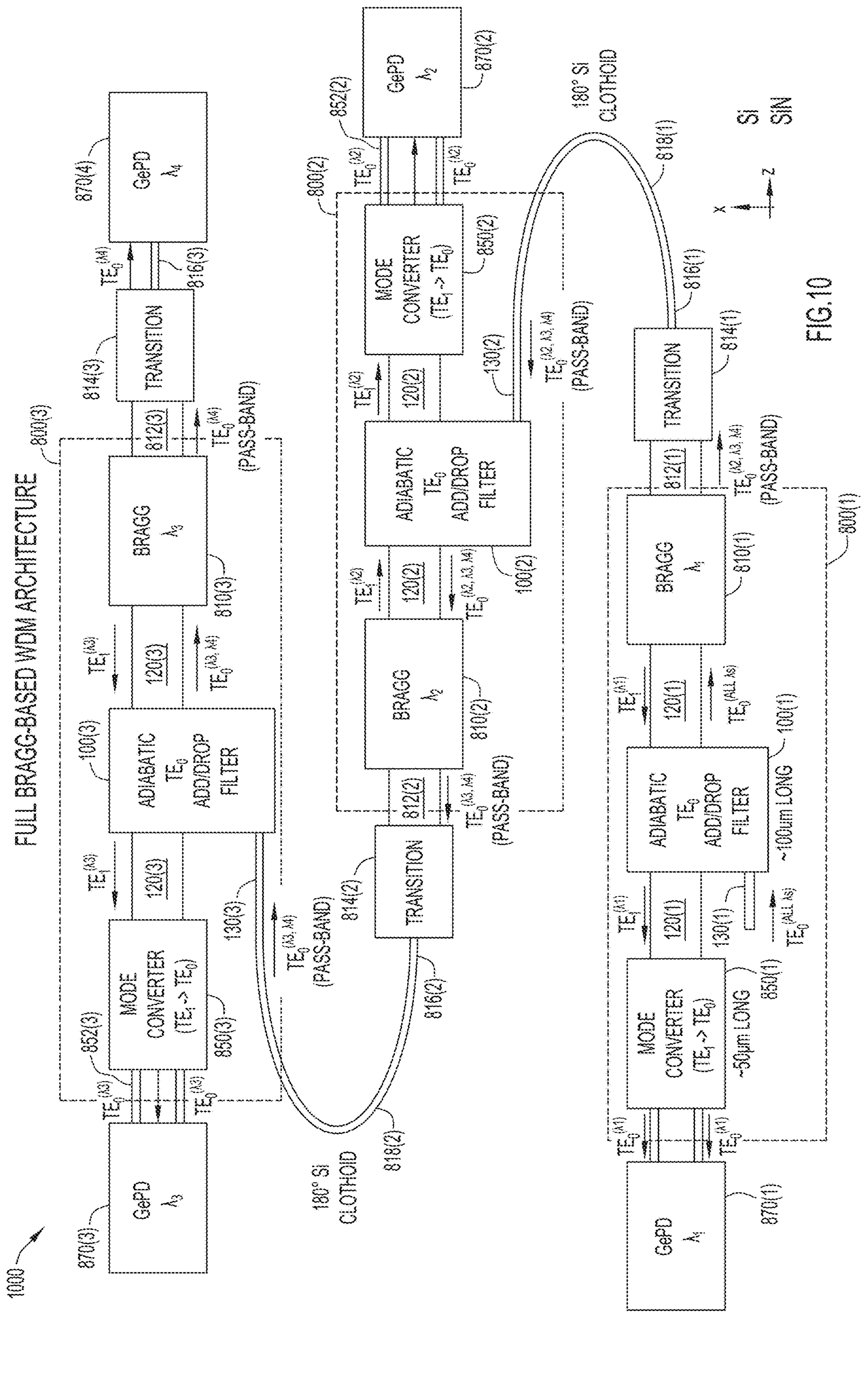

FULL BRAGG-BASED WDM ARCHITECTURE
1000
GePD
MODE CONVERTER (TE_1 -> TE_0)
ADIABATIC TE_0 ADD/DROP FILTER
BRAGG
TRANSITION
180° Si CLOTHOID
(PASS-BAND)
~50µm LONG
~100µm LONG
Si
SiN
x
z
870(1)
870(2)
870(3)
870(4)
850(1)
850(2)
850(3)
852(2)
852(3)
800(1)
800(2)
800(3)
100(1)
100(2)
100(3)
120(1)
120(2)
120(3)
130(1)
130(2)
130(3)
810(1)
810(2)
810(3)
812(1)
812(2)
812(3)
814(1)
814(2)
814(3)
816(1)
816(2)
816(3)
818(1)
818(2)

FIG. 10

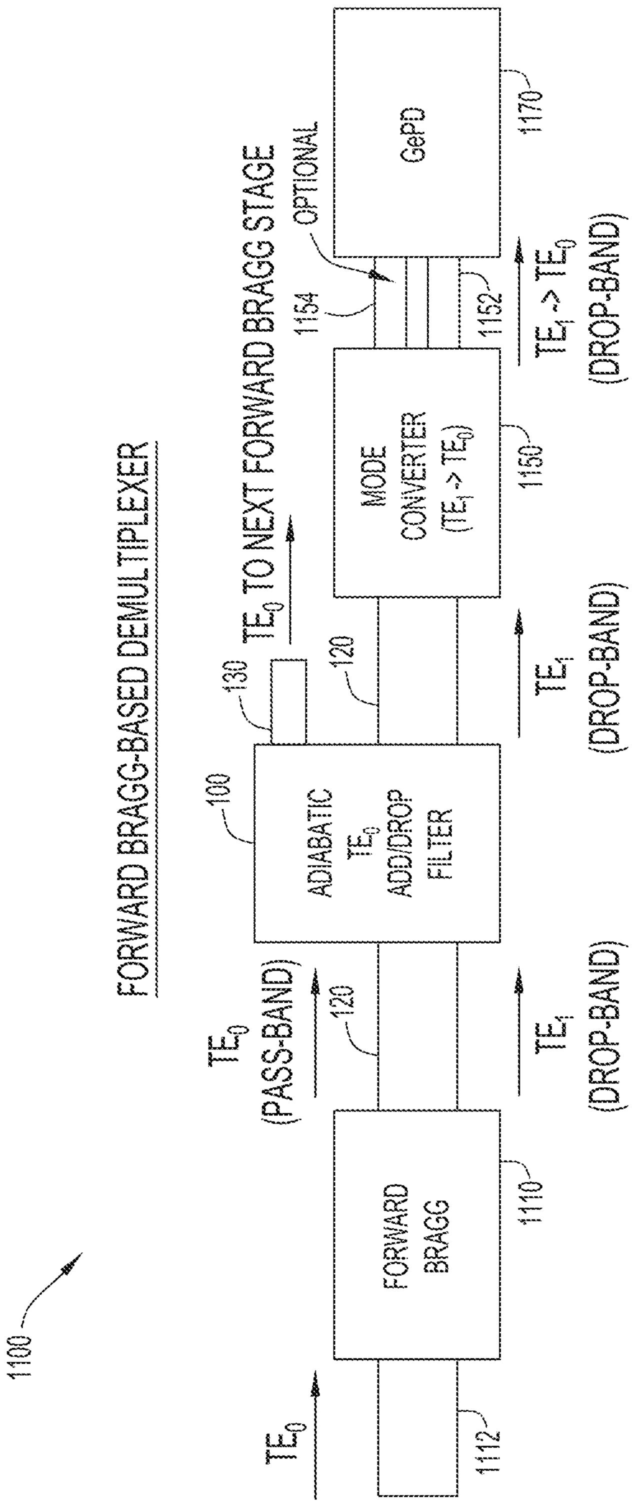

FORWARD BRAGG-BASED DEMULTIPLEXER
1100
TE_0
1112
FORWARD BRAGG
1110
TE_0 (PASS-BAND)
120
TE_1 (DROP-BAND)
ADIABATIC TE_0 ADD/DROP FILTER
100
130
TE_0 TO NEXT FORWARD BRAGG STAGE
120
TE_1 (DROP-BAND)
MODE CONVERTER (TE_1 -> TE_0)
1150
1154
OPTIONAL
1152
TE_1 -> TE_0 (DROP-BAND)
GePD
1170

FIG.11

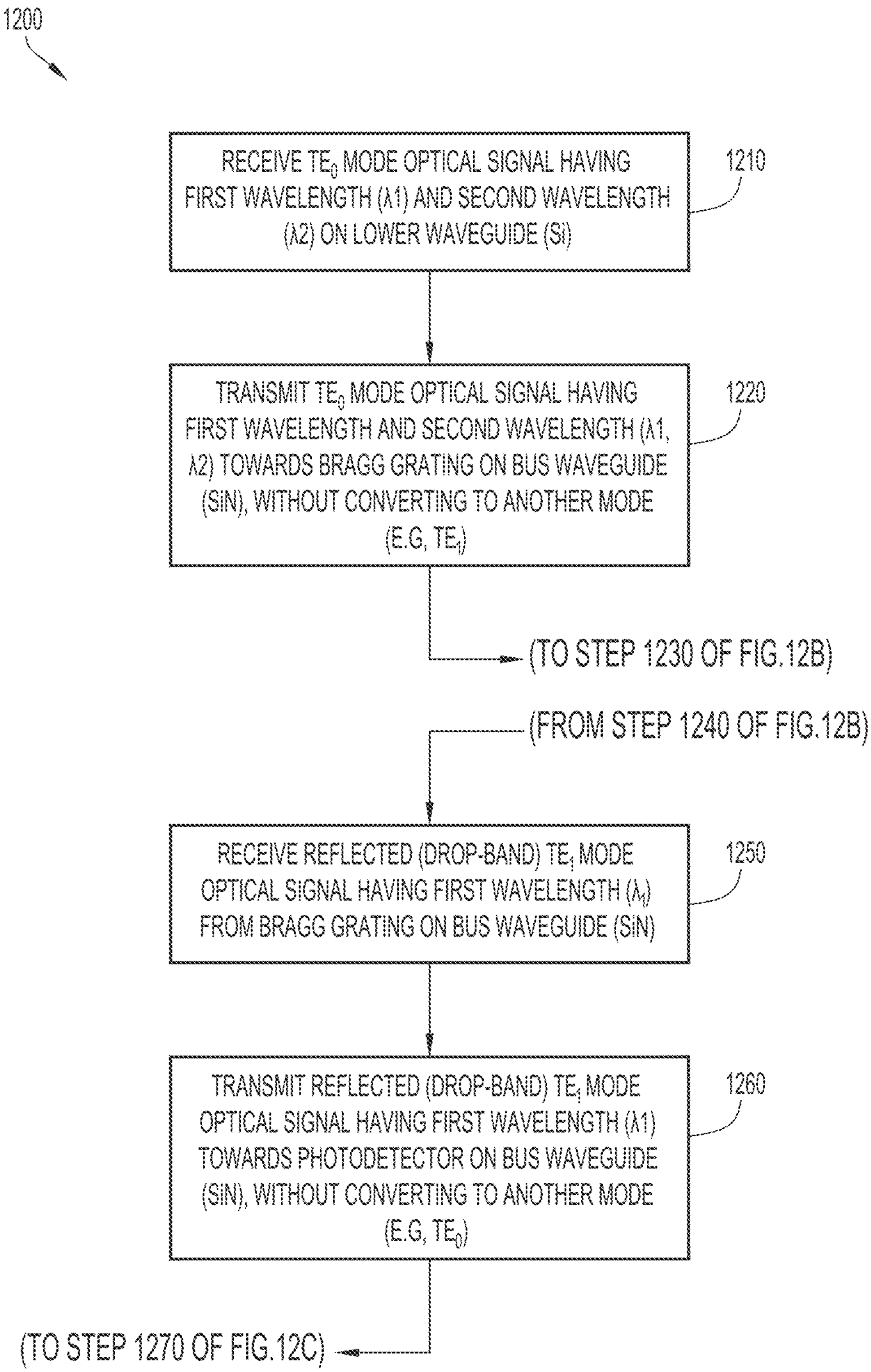

1200
RECEIVE TE$_0$ MODE OPTICAL SIGNAL HAVING FIRST WAVELENGTH (λ1) AND SECOND WAVELENGTH (λ2) ON LOWER WAVEGUIDE (Si)
1210
TRANSMIT TE$_0$ MODE OPTICAL SIGNAL HAVING FIRST WAVELENGTH AND SECOND WAVELENGTH (λ1, λ2) TOWARDS BRAGG GRATING ON BUS WAVEGUIDE (SiN), WITHOUT CONVERTING TO ANOTHER MODE (E.G, TE$_1$)
1220
(TO STEP 1230 OF FIG.12B)
(FROM STEP 1240 OF FIG.12B)
RECEIVE REFLECTED (DROP-BAND) TE$_1$ MODE OPTICAL SIGNAL HAVING FIRST WAVELENGTH (λ_1) FROM BRAGG GRATING ON BUS WAVEGUIDE (SiN)
1250
TRANSMIT REFLECTED (DROP-BAND) TE$_1$ MODE OPTICAL SIGNAL HAVING FIRST WAVELENGTH (λ1) TOWARDS PHOTODETECTOR ON BUS WAVEGUIDE (SiN), WITHOUT CONVERTING TO ANOTHER MODE (E.G, TE$_0$)
1260
(TO STEP 1270 OF FIG.12C)

FIG.12A

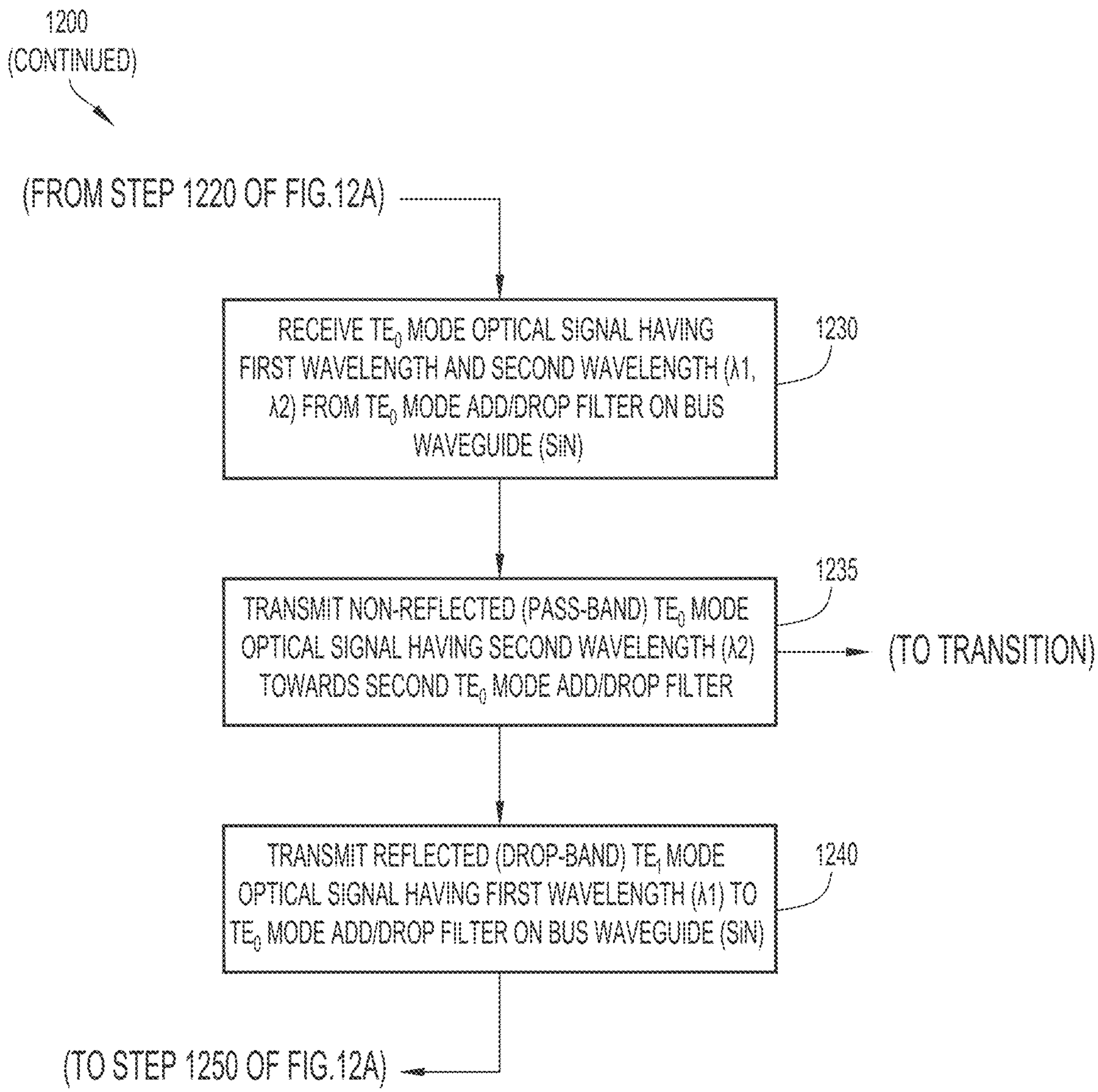

1200
(CONTINUED)
(FROM STEP 1220 OF FIG.12A)
RECEIVE TE_0 MODE OPTICAL SIGNAL HAVING FIRST WAVELENGTH AND SECOND WAVELENGTH (λ1, λ2) FROM TE_0 MODE ADD/DROP FILTER ON BUS WAVEGUIDE (SiN)
1230
TRANSMIT NON-REFLECTED (PASS-BAND) TE_0 MODE OPTICAL SIGNAL HAVING SECOND WAVELENGTH (λ2) TOWARDS SECOND TE_0 MODE ADD/DROP FILTER
1235
(TO TRANSITION)
TRANSMIT REFLECTED (DROP-BAND) TE_1 MODE OPTICAL SIGNAL HAVING FIRST WAVELENGTH (λ1) TO TE_0 MODE ADD/DROP FILTER ON BUS WAVEGUIDE (SiN)
1240
(TO STEP 1250 OF FIG.12A)

FIG.12B

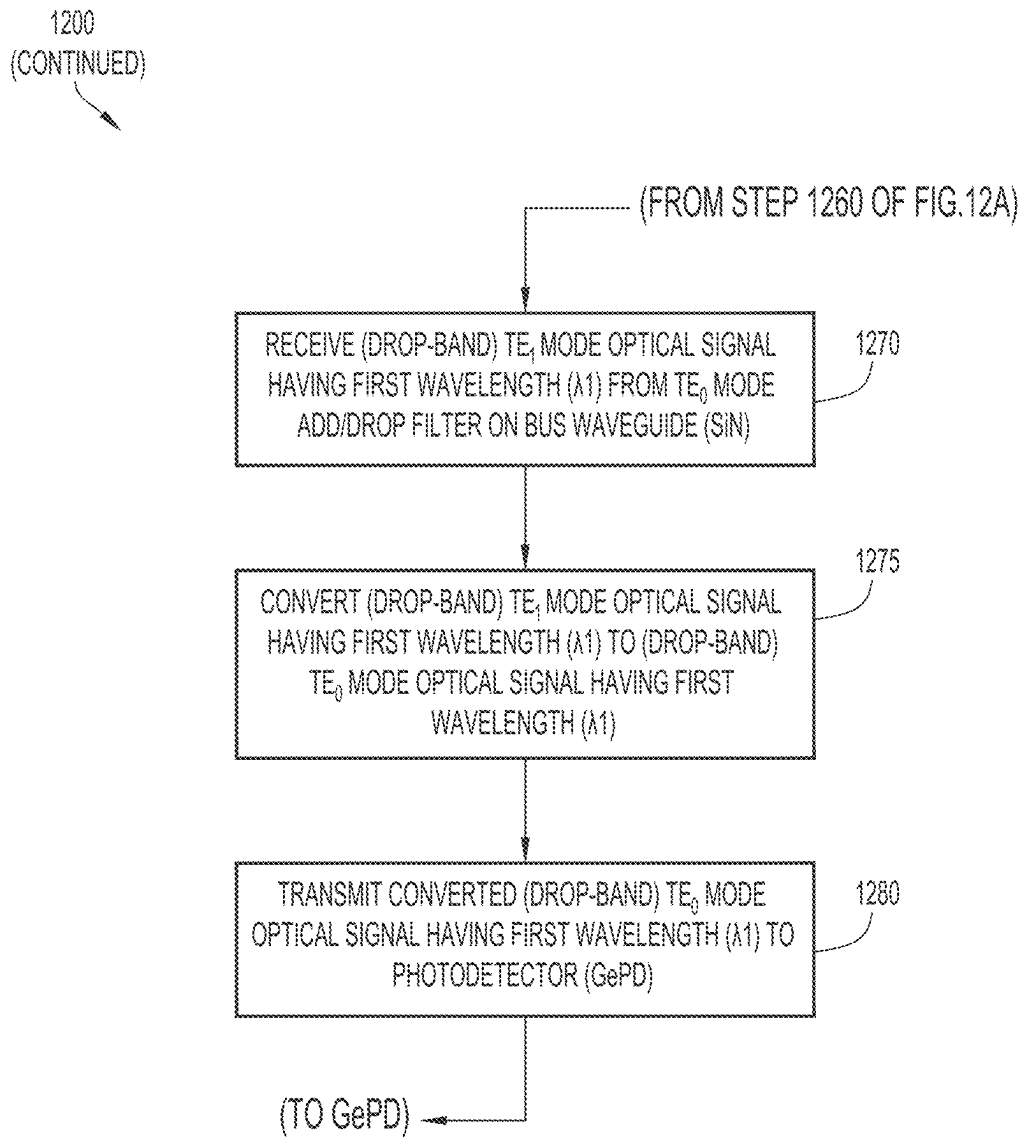

1200
(CONTINUED)
(FROM STEP 1260 OF FIG.12A)
RECEIVE (DROP-BAND) TE1 MODE OPTICAL SIGNAL HAVING FIRST WAVELENGTH (λ1) FROM TE0 MODE ADD/DROP FILTER ON BUS WAVEGUIDE (SIN)
1270
CONVERT (DROP-BAND) TE1 MODE OPTICAL SIGNAL HAVING FIRST WAVELENGTH (λ1) TO (DROP-BAND) TE0 MODE OPTICAL SIGNAL HAVING FIRST WAVELENGTH (λ1)
1275
TRANSMIT CONVERTED (DROP-BAND) TE0 MODE OPTICAL SIGNAL HAVING FIRST WAVELENGTH (λ1) TO PHOTODETECTOR (GePD)
1280
(TO GePD)

FIG.12C

WAVELENGTH DIVISION MULTIPLEXING ARCHITECTURE BASED ON INTEGRATED BRAGG AND ADIABATIC TE0 MODE ADD/DROP FILTER

TECHNICAL FIELD

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_0 mode add/drop filter, and a $TE_1 \rightarrow TE_0$ mode converter.

BACKGROUND

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.

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.

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.

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.

A typical modemux converts TE_1 to TE_0 of an isolated waveguide. However, converting TE_1 to TE_0 to avoid cross-talk can be challenging.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a plan view of a modemux, according to an example embodiment.

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.

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.

FIG. **4**A is a graph showing TE_1 transmission of the modemux, according to an example embodiment.

FIG. **4**B is a graph showing TE_0-TE_1 cross-talk of the modemux, according to an example embodiment.

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.

FIGS. **6**A and **6**B are functional block diagrams of a modemux, according to an example embodiment.

FIG. **7** is a flowchart showing a series of operations for processing light with a modemux, according to an example embodiment.

FIG. **8** is a block diagram of a use case device including a TE_0 mode add/drop filter (modemux), a (backward-reflecting) Bragg grating, and a $TE_1 \rightarrow TE_0$ mode converter to provide a Bragg-based demultiplexer, according to an example embodiment.

FIGS. **9**A, **9**B, and **9**C are block diagrams of different implementations for the $TE_1 \rightarrow TE_0$ mode converter of FIG. **8**, according to an example embodiment.

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.

FIG. **11** is a block diagram of another use case device including a TE_0 mode add/drop filter (modemux), a forward Bragg, and a $TE_1 \rightarrow TE_0$ mode converter to provide a Bragg-based demultiplexer, according to an example embodiment.

FIGS. **12A-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

Overview

Presented herein is a method that includes receiving, at a TE_0 mode add/drop filter, a TE_0 mode optical signal having a first wavelength (λ_1) and a second wavelength (λ_2) on a lower waveguide, and transmitting, from the TE_0 mode add/drop filter, the TE_0 mode optical signal having the first wavelength and the second wavelength (λ_1, λ_2) towards a Bragg grating on a bus waveguide disposed above the lower waveguide, without converting the TE_0 mode optical signal having the first wavelength and the second wavelength (λ_1, λ_2) to another mode (e.g., TE_1). The method further includes receiving, at the TE_0 mode add/drop filter, a reflected (drop-band) TE_1 mode optical signal having the first wavelength (λ_1) from the Bragg grating on the bus waveguide, and transmitting, from the TE_0 mode add/drop filter, the reflected (drop-band) TE_1 mode optical signal (λ_1) towards a photodetector on the bus waveguide, without converting the reflected (drop-band) TE_1 mode optical signal (λ_1) to another mode (e.g., TE_0).

According to an aspect, the method further includes mode multiplexing, by the TE_0 mode add/drop filter, the TE_0 mode optical signal having the first wavelength and the second wavelength (λ_1, λ_2) with the reflected (drop-band) TE_1 mode optical signal having the first wavelength (λ_1). According to an aspect, the method includes receiving, by a $TE_1 \rightarrow TE_0$ mode converter, the (drop-band) TE_1 mode optical signal having the first wavelength (λ_1) from the TE_0 add/drop filter on the bus waveguide, converting, by the $TE_1 \rightarrow TE_0$ mode converter, the (drop-band) TE_1 mode optical signal having the first wavelength (λ_1) to a (drop-band) TE_0 mode optical signal having the first wavelength (λ_1), and transmitting, from the $TE_1 \rightarrow TE_0$ mode converter, the converted (drop-band) TE_0 mode optical signal at the first wavelength (λ_1) to the photodetector. According to an aspect, the method further includes transmitting, from the Bragg grating, a non-reflected (pass-band) TE_0 mode optical signal having the second wavelength (λ_2) towards a second TE_0 mode add/drop filter.

According to another aspect, another method is provided. The method includes passing an optical signal through a plurality of TE_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_0 mode add/drop filter in the plurality of TE_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_0 mode add/drop filter in the plurality of TE_0 mode add/drop filters is an adiabatic TE_0 mode add/drop filter.

According to yet another aspect, presented herein is an apparatus including a TE_0 mode add/drop filter, and a Bragg grating connected with the TE_0 mode add/drop filter. The TE_0 mode add/drop filter is configured to receive a TE_0 mode optical signal having a first wavelength (λ_1) and a second wavelength (λ_2) on a lower waveguide, and transmit the TE_0 mode optical signal having the first wavelength and the second wavelength (λ_1, λ_2) towards the Bragg grating on a bus waveguide disposed above the lower waveguide, without converting the TE_0 mode optical signal having the first wavelength and the second wavelength (λ_1, λ_2) to another mode (TE_1). The TE_0 mode add/drop filter is further configured to receive a reflected (drop-band) TE_1 mode optical signal having the first wavelength (λ_1) from the Bragg grating on the bus waveguide, and transmit the reflected (drop-band) TE_1 mode optical signal having the first wavelength (λ_1) towards the photodetector on the bus waveguide, without converting the reflected (drop-band) TE_1 mode optical signal having the first wavelength (λ_1) to another mode (TE_0).

According to an aspect, the TE_0 mode add/drop filter of the apparatus is an adiabatic TE_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_0 mode add/drop filter further establishes a pseudo-symmetry about a longitudinal axis of the bus waveguide (SiN) to prevent TE_1-TM_0 mode hybridization of optical signals that traverse the bus waveguide (SiN). According to an aspect, the TE_0 mode add/drop filter is configured to mode multiplex the TE_0 mode optical signal having the first wavelength and the second wavelength (λ_1, λ_2) with the reflected (drop-band) TE_1 mode optical signal having the first wavelength (λ_1).

According to an aspect, the apparatus further includes further a $TE_1 \rightarrow TE_0$ mode converter configured to receive the (drop-band) TE_1 mode optical signal having the first wavelength (λ_1) from the TE_0 mode add/drop filter, convert the (drop-band) TE_1 mode optical signal having the first wavelength (λ_1) to a (drop-band) TE_0 mode optical signal having the first wavelength (λ_1), and transmit the converted (drop-band) TE_0 mode optical signal having the first wavelength (λ_1) to the photodetector. According to an aspect, the Bragg grating is configured to transmit a non-reflected (pass-band) TE_0 mode optical signal having the second wavelength (λ_2) towards a second TE_0 add/drop filter.

Example Embodiments

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_0, TE_1, and TM_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_1-TM_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.

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_0 index to avoid mode hybridization.

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).

More specifically, the present disclosure provides a multimode waveguide with an adiabatic TE_0 mode add/drop filter in the form of a modemux that takes optical power in the TE_0 mode of a high index waveguide, and adiabatically transfers it into the TE_0 mode of a lower index, multimode waveguide. The modemux is designed to have low TE_0-TE_1 cross-talk by ensuring that when the TE_0 muxing takes place, either: (1) symmetry is used to negate scattering between even and odd modes, or (2) the effective indices of TE_0 (in Si) and TE_1 (in SiN) are substantially different (i.e., result in negligible phase-matching between the two modes).

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.

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_1 generation and component characterization. A significant challenge in obtaining a viable modemux using this scheme is overcoming unwanted TE_1-TM_0 mode hybridization. Notably, this challenge can be overcome using the modemux described herein.

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_1 as TE_1 (instead of converting TE_1 to TE_0 like a standard modemux does), and multiplexes TE_0 onto a TE_1-carrying waveguide.

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.

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_0 and TE_1 modes.

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.

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.

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**.

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.

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).

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).

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 ($TE_0 \rightarrow TE_1$) as shown in FIG. **4**B, and insertion loss (excluding propagation loss) is less than 0.03 dB as shown in FIG. **4**A.

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.

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_1-TM_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).

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_1-TM_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.

FIG. **3**A shows simulated optical power of a TE_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**).

FIG. **3**B shows simulated optical power of a TE_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**).

FIG. **3**C shows simulated optical power of a TE_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_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.

As can be seen from FIGS. **3**A, **3**B and **3**C, TE_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_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_1 mode light is not converted to TE_0 mode light as it passes through the modemux **100** described herein, unlike a standard modemux. Instead, the TE_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_1 and TE_0 modes.

FIG. **4**A shows simulated TE_1 transmission for (bend in) first region **102** of the modemux **100**, and FIG. **4**B shows simulated TE_0-TE_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_0 insertion loss and very low TE_1 insertion loss (e.g., about ~0.025 dB) as shown in FIG. **4**A. There is also low TE_0-TE_1 cross-talk (e.g., less than −45 dB) as shown in FIG. **4**B.

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.

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_0 index, avoiding TE_1-TM_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_1-TM_0 mode hybridization.

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_1-TM_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 $TE_0 \rightarrow TE_1$ cross-talk (e.g., less than −40 dB). Insertion loss is also very low.

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).

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).

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_0 and TE_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 ($TE_1 \rightarrow TE_0$) 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_1 insertion loss (scattering into TM_0 and TM_1 modes) compared to a device that is configured according to the first example embodiment of FIGS. **1** and **2**A-**2**C.

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_0 to TE_1. However, the modemux **100** of the present disclosure does not convert TE_0 to TE_1, as shown in FIG. **6**A. Also, if TE_0 is launched into the nitride port (e.g., bus waveguide **120** (SiN 1)) of the modemux **100**, the TE_0 will radiate out from modemux **100**, as shown in FIG. **6**B. This is not true for a standard mux in which TE_0 would not radiate out, but is instead converted to TE_1).

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), $LiNbO_3$ or InP. Bus waveguide **120**, lower waveguide **130** and upper waveguide **140** may have identical or different thicknesses (in the y-axis direction).

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.

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_1 mode optical signal on a bus waveguide (SiN). At step **720**, the photonic component receives a TE_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_1 mode optical signal and the TE_0 mode optical signal, without converting the TE_0 mode optical signal or the TE_1 mode optical signal to another mode. At step **740**, the photonic component outputs the mode multiplexed TE_0 mode optical signal and TE_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_1-TM_0 mode hybridization of an optical signal that traverses the bus waveguide (SiN).

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.

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_1-TM_0 mode hybridization of an optical signal that traverses the bus waveguide (SiN).

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_1-TM_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_1-TM_0 mode hybridization.

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_0 mode optical signal with a first TE_1 mode optical signal, without converting the first TE_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_0 mode optical signal with the first TE_1 mode optical signal, without converting the first TE_1 mode optical signal into a second TE_0 mode optical signal.

Example Use Case Device (Bragg-Based Demultiplexer)

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**.

TE_{HO} represents a "higher order TE-mode" (TE_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_1, which is typically used in many instances. The example embodiments described herein and illustrated in the drawings generally use $TE_{HO}=TE_1$. 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.

An example architecture for a Bragg-based WDM may use some form of modemux and a Bragg grating. The Bragg converts TE_0 to TE_{HO} (e.g., TE_1), and the modemux multiplexes inputs from two single-mode (TE_0) waveguides onto two modes (TE_0 and TE_{HO}) of one multimode output waveguide. TE_0 from input A is passed through to TE_0 on the output, and TE_0 from input B is converted to TE_{HO} on the output ($TE_{0,A}$<→$TE_{0,B}$ and $TE_{0,B}$<→TE_{HO}). An existing architecture may rely on a modemux that performs the $TE_{0,A}$<→TE_0 and the $TE_{0,B}$<→TE_{HO} in a single component, in which multiplexing and mode conversion are done as a single step.

A first typical Bragg-based demultiplexing architecture consists of a Bragg grating that converts TE_0<→TE_1 excited through a directional coupler style multiplexer. The directional coupler style multiplexer (or "coupler mux") couples TE_0 from one port to TE_1 on output (conversion), and passes TE_0 from the other port as TE_0 on output (pass). The multiplexing principle behind this typical architecture is that the multiplexing directional coupler relies on phase-matching the TE_0 mode of a single waveguide to the TE_1 of a multimode waveguide. However, this style of coupler mux is essentially unusable for integrated WDM receiver requirements because phase matching of TE_0 of a single-mode waveguide to TE_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_0 in the single-mode waveguide to TE_0 in the multimode waveguide, causing large cross-talk.

A second typical Bragg-based demultiplexing architecture consists of a Bragg grating that converts TE_0<→TE_1 excited through an adiabatic modemux. The "modemux" couples TE_0 from one port to TE_1 on output (conversion), and passes TE_0 from the other port as TE_0 on output (pass). The multiplexing principle behind this typical architecture is that the modemux relies on a single component to convert TE_0 to TE_1 of a multimode waveguide, while transmitting TE_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_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_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_0 mode signal into an output TE_1 mode signal, without causing any scattering into an output TE_0 mode signal. However, this is a difficult task when the first input TE_0 mode signal and a second input TE_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_0 mode signal and the output TE_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.

Thus, some typical architectures may use a regular modemux (e.g., a standard, traditional, or conventional modemux), in which TE_0 is multiplexed into a multimode waveguide at the same time that TE_0 is converted into TE_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_0'→TE_1 and 'TE_1'→TE_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.

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_0 from A to TE_0 on a multimode waveguide, while also transmitting a B input that is TE_{HO} to TE_{HO} on the same multimode waveguide (via the "adiabatic TE_0 mode add/drop filter" **100** functionality), and (2) separately convert a TE_0-like input to the input B TE_{HO} mode (via the "TE1→TE0 mode converter" **850** functionality).

FIG. **8** is a block diagram of a use case device for an adiabatic TE_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_0 mode add/drop filter **100** (modemux **100** as described above), along with a $TE_1 \rightarrow TE_0$ mode converter **850** component as further described below. The TE_0 add/drop filter (modemux) **100** has a unique design, in that it does not convert a TE_0 mode optical signal to a TE_1 mode optical signal and/or does not convert a TE_1 mode optical signal to a TE_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_1 in a multi-mode SiN waveguide into an optical signal (e.g., TE_0 mode light or ~99% TE_0-like mode light) that can be detected by the photodetector **870** (GePD), for example.

More specifically, referring to FIG. **8**, the TE_0 add/drop filter **100** includes a lower waveguide **130** (e.g., a single-mode Si waveguide) that is configured to receive a TE_0 mode optical signal having two or more wavelengths (e.g., $\lambda_1, \lambda_2, \ldots, \lambda_N$), 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_0 mode optical signal (all wavelengths λ_1-λ_N) to the Bragg **810**, without converting the TE_0 mode optical signal to another mode (e.g., TE_1).

The Bragg **810** is configured to receive the TE_0 mode optical signal (all as) from the TE_0 add/drop filter **100** on the multimode (SiN) bus waveguide **120**, and reflect a first portion of the TE_0 mode optical signal having a particular wavelength (e.g., λ_P, which is one of $\lambda_1, \lambda_2, \ldots, \lambda_N$) back to the TE_0 add/drop filter **100** on the bus waveguide **120**. The operation of reflecting the first portion of the TE_0 mode optical signal (λ_P) converts this optical signal to a (drop-band) TE_1 mode optical signal having that particular wavelength (λ_P). The TE_0 add/drop filter **100** is further configured to receive the reflected (drop-band) TE_1 mode optical signal at the particular wavelength (λ_P) from the Bragg **810** on the bus waveguide **120**, and (modemux and) transmit the reflected (drop-band) TE_1 mode optical signal (λ_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_1 mode optical signal (λ_P) to another mode (e.g., TE_0).

The $TE_1 \rightarrow TE_0$ mode converter **850** is configured to receive the (drop-band) TE_1 mode optical signal at the particular wavelength (λ_P) from the TE_0 add/drop filter **100** on the bus waveguide **120**, and convert the (drop-band) TE_1 mode optical signal having the particular wavelength (λ_P) to a (drop-band) TE_0 mode optical signal having the particular wavelength (λ_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_0 mode optical signal at the particular wavelength (λ_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_0 mode optical signal at the particular wavelength (λ_P) that is received from the mode converter **850**.

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_0 mode optical signal to the inter-layer transition **814** on the multimode (SiN) waveguide **812**, where the (pass-band) TE_0 mode optical signal corresponds to a second portion of the TE_0 mode optical signal having one or more wavelengths (e.g., $\lambda_1, \lambda_2, \ldots, \lambda_N$) other than the particular wavelength (λ_P) that is not reflected by (and passes through) the Bragg **810**.

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 ($TE_1 \rightarrow TE_0$ or $TE_0 \rightarrow TE_1$) 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.

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_{eff} of TE_0 never matches (or nearly matches) n_{eff} of TE_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_0 and TE_1, so cross-talk is extremely low.

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_0 and TE_1 in one component (adiabatic TE_0 mode add/drop filter **100**), and converts TE_1 to TE_0-like mode(s) in another component (TE_1-TE_0 mode converter **850**, as shown in FIG. **8**). Thus, the device of FIG. **8** converts $TE_0 \leftrightarrow TE_1$ independently of muxing onto the multimode waveguide. Notably, TE_0 is muxed onto the multimode waveguide once TE_1 is fully present. In this device, cross-talk is irrelevant at the $TE_1 \rightarrow TE_0$ 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_0 mode add/drop filter **100** block (modemux component) of FIG. **8** is designed to have very low cross-talk (for $TE_0 \rightarrow TE_1$ and $T_1 \rightarrow TE_0$ 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.

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 $TE_1 \rightarrow TE_0$ mode converter **850** is utilized in addition to the TE_0 add/drop filter (modemux) **100**, as shown in FIG. **8**.

Next, three example implementations (options A, B, and C) for the "$TE_1 \rightarrow TE_0$ mode converter" **850** of FIG. **8**, which converts TE_1 in multimode SiN waveguide into TE_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→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→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_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_1" port) in this example.

As described above, the integrated Bragg-based WDM architecture of FIG. **8** utilizes the novel multiplexing (or modemuxing) functionality embodied by adiabatic TE_0 mode add/drop filter (modemux) **100**, in which the modemux **100** does not attempt to convert an input TE_0 mode optical signal of an individual (or "single-mode") waveguide into an output TE_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_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_1 mode optical signal as a TE_1 mode optical signal, while adiabatically transferring the TE_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**.

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.

More specifically, referring to FIG. **10**, the first apparatus **800**(**1**) includes a first adiabatic TE_0 mode add/drop filter (modemux) **100**(**1**), a first Bragg **810**(**1**), and a first $TE_1 \rightarrow TE_0$ mode converter **850**(**1**). The first TE_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_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 λs"), 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_0 mode optical signal (all λs) to the first Bragg **810**(**1**) without converting the TE_0 mode optical signal to another mode (e.g., TE_1).

The first Bragg **810**(**1**) is configured to receive the TE_0 mode optical signal (all λs) from the first TE_0 add/drop filter **100**(**1**) on the first bus waveguide **120**(**1**), and reflect a first portion of the TE_0 mode optical signal having a first wavelength (λ_1) back to the first TE_0 add/drop filter **100**(**1**) on the first bus waveguide **120**(**1**). The operation of reflecting the first portion of the TE_0 mode optical signal (λ_1) converts this optical signal to a first (drop-band) TE_1 mode optical signal having the first wavelength (λ_1). The first TE_0 add/drop filter **100**(**1**) is further configured to receive the reflected first (drop-band) TE_1 mode optical signal at the first wavelength (λ_1) from the first Bragg **810**(**1**) on the first bus waveguide **120**(**1**), and (modemux and) transmit the reflected first (drop-band) TE_1 mode optical signal (λ_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_1 mode optical signal (λ_1) to another mode (e.g., TE_0).

The first $TE_1 \rightarrow TE_0$ mode converter **850**(**1**) is configured to receive the first (drop-band) TE_1 mode optical signal at the first wavelength (λ_1) from the first TE_0 add/drop filter **100**(**1**) on the first bus waveguide **120**(**1**), and convert the first (drop-band) TE_1 mode optical signal having the first wavelength (λ_1) to a first (drop-band) TE_0 mode optical signal having the first wavelength (λ_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_0 mode optical signal (λ_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_0 mode optical signal at the first wavelength (λ_1) that is received from the first mode converter **850**(**1**).

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_0 mode optical signal to the first transition **814**(**1**) on the waveguide **812**(**1**), where the first (pass-band) TE_0 mode optical signal corresponds to a second portion of the TE_0 mode optical signal having one or more wavelengths (e.g., three wavelengths denoted as λ_2, λ_3, λ_4) other than the first wavelength (λ_1) that is not reflected by (and passes through) the first Bragg **810**(**1**).

The first transition **814**(**1**) is configured to receive the first (pass-band) TE_0 mode optical signal having the other wavelengths (λ_2, λ_3, λ_4) on the waveguide **812**(**1**), and transmit the first (pass-band) TE_0 mode optical signal (λ_2, λ_3, λ_4) towards a second adiabatic TE_0 mode add/drop filter **100**(**2**) of the second apparatus **800**(**2**). The first transition **814**(**1**) is connected to the second TE_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_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_1) in the first stage, while allowing a (pass-band) optical signal having other wavelengths (λ_2, λ_3, λ_4) to pass through (to the second stage) for further processing, and effectively limiting cross-talk.

Likewise, the second apparatus **800**(**2**) includes the second adiabatic TE_0 mode add/drop filter (modemux) **100**(**2**), a second Bragg **810**(**2**), and a second $TE_1 \rightarrow TE_0$ mode converter **850**(**2**). The second TE_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_0 mode optical signal having the other wavelengths (e.g., λ_2, λ_3, λ_4) other than the first wavelength (λ_1) from the first Bragg **810**(**1**) via the first transition **814**(**1**) and the waveguides **816**(**1**), **818**(**1**). The second TE_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_0 mode optical signal at the other wavelengths (λ_2, λ_3, λ_4) to the second Bragg **810**(**2**), without converting the first (pass-band) TE_0 mode optical signal (λ_2, λ_3, λ_4) to another mode (e.g., TE_1). The second Bragg **810**(**2**) receives the first (pass-band) TE_0 mode optical signal (λ_2, λ_3, λ_4) from the second TE_0 add/drop filter **100**(**2**) on the second bus waveguide **120**(**2**), and reflects a first portion of the first (pass-band) TE_0 mode optical signal having a second wavelength (λ_2) back to the second TE_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_1 mode optical signal having the second wavelength (λ_2). The second TE_0 add/drop filter **100**(**2**) receives the reflected second (drop-band) TE_1 mode optical signal having the second wavelength (λ_2) from the second Bragg **810**(**2**) on the second bus waveguide **120**(**2**), and transmits the reflected second (drop-band) TE_1 mode optical signal (λ_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_1 mode optical signal (λ_2) to another mode (e.g., TE_0).

The second $TE_1 \rightarrow TE_0$ mode converter **850**(**2**) receives the second (drop-band) TE_1 mode optical signal at the second wavelength (**0**.**2**) from the second TE_0 add/drop filter **100**(**2**) on the second bus waveguide **120**(**2**), converts the second (drop-band) TE_1 mode optical signal having the second wavelength (λ_2) to a second (drop-band) TE_0 mode optical signal having the second wavelength (λ_2), and transmits the converted second (drop-band) TE_0 mode optical signal (λ_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_0 mode optical signal at the second wavelength (λ_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_0 mode optical signal to the second transition **814**(**2**) on the waveguide **812**(**2**), where the second (pass-band) TE_0 mode optical signal corresponds to a second portion of the first (pass-band) TE_0 mode optical signal having other wavelengths (e.g., λ_3, λ_4) other than the second wavelength (λ_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_0 mode optical signal at the other wavelengths (λ_3, λ_4) on the waveguide **812**(**2**), and transmits the second (pass-band) TE_0 mode optical signal (λ_3, λ_4) towards a third adiabatic TE_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_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_2) in the second stage, while allowing a (pass-band) optical signal having other wavelengths (λ_3, λ_4) to pass through (to the third stage) for further processing, and effectively limiting cross-talk.

Likewise, the third apparatus **800**(**3**) includes the third adiabatic TE_0 mode add/drop filter (modemux) **100**(**3**), a third Bragg **810**(**3**), and a third $TE_1 \rightarrow TE_0$ mode converter **850**(**3**). The third TE_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_0 mode optical signal having the other wavelengths (e.g., λ_3, λ_4) other than the second wavelength (λ_2) from the second Bragg **810**(**2**) via the second transition **814**(**2**) and the waveguides **816**(**2**), **818**(**2**). The third TE_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_0 mode optical signal at the other wavelengths (λ_3, λ_4) to the third Bragg **810**(**3**), without converting the second (pass-band) TE_0 mode optical signal (λ_3, λ_4) to another mode (e.g., TE_1). The third Bragg **810**(**3**) receives the second (pass-band) TE_0 mode optical signal (λ_3, λ_4) from the third TE_0 add/drop filter **100**(**3**) on the third bus waveguide **120**(**3**), and reflects a first portion of the second (pass-band) TE_0 mode optical signal having a third wavelength (λ_3) back to the third TE_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_1 mode optical signal having the third wavelength (λ_3). The third TE_0 add/drop filter **100**(**3**) receives the reflected third (drop-band) TE_1 mode optical signal at the third wavelength (λ_3) from the third Bragg **810**(**3**) on the third bus waveguide **120**(**3**), and (modemuxes and) transmits the reflected third (drop-band) TE_1 mode optical signal (λ_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_1 mode optical signal (λ_3) to another mode (e.g., TE_0).

The third $TE_1 \rightarrow TE_0$ mode converter **850**(**3**) receives the third (drop-band) TE_1 mode optical signal at the third wavelength (λ_3) from the third TE_0 add/drop filter **100**(**3**) on the third bus waveguide **120**(**3**), converts the third (drop-band) TE_1 mode optical signal having the third wavelength (λ_3) to a third (drop-band) TE_0 mode optical signal having the third wavelength (λ_3), and transmits the converted third (drop-band) TE_0 mode optical signal (λ_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_0 mode optical signal at the third wavelength (λ_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_0 mode optical signal to the third transition **814**(**3**) on the waveguide **812**(**3**), where the third (pass-band) TE_0 mode optical signal corresponds to a second portion of the second (pass-band) TE_0 mode optical signal having other wavelengths (e.g., λ_4) other than the third wavelength (λ_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_0 mode optical signal (λ_4) on the waveguide **812**(**3**), and transmits the third (pass-band)

TE_0 mode optical signal (λ_4) (which, in this example corresponds to a fourth (drop-band) TE_0 mode optical signal having the fourth wavelength (λ_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_0 mode optical signal having the fourth wavelength (λ_4) (i.e., receives and detects the fourth (drop-band) TE_0 mode optical signal having the fourth wavelength (λ_4)). Thus, the third apparatus **800**(**3**) reflects and detects a (drop-band) optical signal having a third wavelength (λ_3) in the third stage, while allowing a (pass-band) optical signal having the other wavelengths (λ_4) to pass through for further processing (to the fourth photodetector **870**(**4**) that detects the fourth (drop-band) TE_0 optical signal having the fourth wavelength (λ_4)), and effectively limiting cross-talk.

Although three stages including three apparatuses **800** (Bragg-based demultiplexers, with three adiabatic TE_0 mode add/drop filters (modemuxes) **100**, three Braggs **810**, and three $TE_1 \rightarrow TE_0$ 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.

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_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→nitride interlayer transition (or "Si→SiN transition") is not needed, since it is already built into the TE_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_0 mode add/drop filters" **100**(**1**), **100**(**2**), **100**(**3**) of FIG. **10**) is expected to have cross-talk ($TE_0 \leftrightarrow TE_1$) of <−45 dB, an insertion loss (excluding propagation loss)<0.03 dB, and a total length of about ~100 um.

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_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 "$TE_1 \rightarrow TE_0$ 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 "$TE_1 \rightarrow TE_0$ 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.

FIG. **11** is a block diagram of another use case device for an adiabatic TE_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_0 mode add/drop filter (modemux) **100**, and a mode converter **1150** (i.e., $TE_1 \rightarrow TE_0$). 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_0 (received via waveguide **1112**) to forward-propagating TE_1, and consequently, the adiabatic components (e.g., TE_0 add/drop filter **100** and $TE_1 \rightarrow TE_0$ 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.

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.

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_0 mode add/drop filter (modemux) **100** and Bragg grating **810**, as well as a $TE_1 \rightarrow TE_0$ mode converter **850** that operates independently of the TE_0 mode add/drop filter **100**, according to an example embodiment. FIG. **12**A shows operations from the perspective of the TE_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 $TE_1 \rightarrow TE_0$ mode converter **850**.

As shown in FIG. **12**A, at step **1210**, a TE_0 mode add/drop filter (e.g., the TE_0 mode add/drop filter **100** of FIG. **8**) receives a TE_0 mode optical signal on a lower waveguide (e.g., a single-mode (Si) waveguide **130**), where the TE_0 mode optical signal has at least a first wavelength (λ_1) and a second wavelength (λ_2) (i.e., light modulating at different frequencies (e.g., $\lambda_1, \lambda_2, \ldots, \lambda_N$)). At step **1220**, the TE_0 add/drop filter transmits the TE_0 mode optical signal having the first wavelength and the second wavelength (λ_1, λ_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_0 add/drop filter modemuxes and transmits without converting the TE_0 mode optical signal having the first wavelength and the second wavelength (λ_1, λ_2) to another mode (e.g., TE_1).

As shown in FIG. **12**B, at step **1230**, the Bragg grating receives the TE_0 mode optical signal having the first wavelength and the second wavelength (λ_1, λ_2) from the TE_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_0 mode add/drop filter on the bus waveguide (SiN). The reflected (drop-band) TE_1 mode optical signal corresponds to a first portion of the TE_0 mode optical signal having the first wavelength (λ_1) that is reflected by the Bragg grating back to the TE_0 mode add/

drop filter, where the operation of reflecting converts the first portion of the TE_0 mode optical signal having the first wavelength (λ_1) to the reflected (drop-band) TE_1 mode optical signal having the first wavelength (λ_1).

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_0 mode optical signal having the second wavelength (λ_2) towards a second TE_0 mode add/drop filter. The non-reflected (pass-band) TE_0 mode optical signal having the second wavelength (λ_2) corresponds to a second portion of the TE_0 mode optical signal having one or more other wavelengths (e.g., $\lambda_2, \ldots, \lambda_N$) other than the first wavelength (λ_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_0 mode optical signal having the second wavelength (λ_2) to the second TE_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_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_2)).

Referring again to FIG. **12**A, at step **1250**, the TE_0 mode add/drop filter receives the reflected (drop-band) TE_1 mode optical signal having the first wavelength (λ_1) from the Bragg grating on the bus waveguide (SiN). At step **1260**, the TE_0 mode add/drop filter transmits the reflected (drop-band) TE_1 mode optical signal having the first wavelength (λ_1) towards a photodetector (e.g., the photodetector (GePD) **870** of FIG. **8**) on the bus waveguide (SiN). In step **1260**, the TE_0 mode add/drop filter modemuxes and transmits without converting the (drop-band) TE_1 mode optical signal (λ_1) to another mode (e.g., TE_0).

As shown in FIG. **12**C, at step **1270**, a $TE_1 \rightarrow TE_0$ mode converter (e.g., $TE_1 \rightarrow TE_0$ mode converter **850** of FIG. **8**) receives the (drop-band) TE_1 mode optical signal having the first wavelength (λ_1) from the TE_0 add/drop filter on the bus waveguide (SiN). At step **1275**, the $TE_1 \rightarrow TE_0$ mode converter converts the (drop-band) TE_1 mode optical signal having the first wavelength (λ_1) to a (drop-band) TE_0 mode optical signal having the first wavelength (λ_1). At step **1280**, the $TE_1 \rightarrow TE_0$ mode converter transmits the converted (drop-band) TE_0 mode optical signal having the first wavelength (λ_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_0 mode optical signal having the first wavelength (λ_1) that is received from the $TE_1 \rightarrow TE_0$ mode converter.

In the example of FIG. **12**A, the TE_0 mode add/drop filter (modemux) component is configured to mode multiplex TE_1 mode optical signals and TE_0 mode optical signals, without converting either the TE_0 mode optical signal or the TE_1 mode optical signal to a different mode, respectively. The conversion operation is performed separately by the $TE_1 \rightarrow TE_0$ mode converter component, as shown in the example of FIG. **12**C. The structure and operation of the TE_0 mode add/drop filter are designed to prevent/avoid TE_1-TM_0 mode hybridization of an optical signal that traverses the bus waveguide (multimode SiN waveguide), for example.

Variations and Implementations

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.

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.

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.

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.

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.

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.

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.

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.

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.

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)).

In some aspects, the techniques described herein relate to a method including: receiving, at a TE_0 mode add/drop filter, a TE_0 mode optical signal having a first wavelength and a second wavelength; transmitting, from the TE_0 mode add/drop filter, the TE_0 mode optical signal having the first wavelength and the second wavelength towards a Bragg grating, without converting the TE_0 mode optical signal having the first wavelength and the second wavelength to another mode; receiving, at the TE_0 mode add/drop filter, a reflected TE_1 mode optical signal having the first wavelength from the Bragg grating; and transmitting, from the TE_0 mode add/drop filter, the reflected TE_1 mode optical signal having the first wavelength towards a photodetector, without converting the reflected TE_1 mode optical signal having the first wavelength to another mode.

In some aspects, the TE_0 mode add/drop filter is an adiabatic TE_0 mode add/drop filter.

In some aspects, the method further includes: receiving the TE_0 mode optical signal having the first wavelength and the second wavelength on a lower waveguide; and transmitting the TE_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.

In some aspects, the method further includes: receiving the reflected TE_1 mode optical signal having the first wavelength from the Bragg grating on the bus waveguide; and transmitting the reflected TE_1 mode optical signal having the first wavelength towards the photodetector on the bus waveguide.

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.

In some aspects, the method further includes: establishing a pseudo-symmetry about a longitudinal axis of the bus waveguide to prevent TE_1-TM_0 mode hybridization of optical signals that traverse the bus waveguide.

In some aspects, the method further includes: mode multiplexing, by the TE_0 mode add/drop filter, the TE_0 mode optical signal having the first wavelength and the second wavelength with the reflected TE_1 mode optical signal having the first wavelength.

In some aspects, the method further includes: receiving, at a $TE_1 \rightarrow TE_0$ mode converter, the reflected TE_1 mode optical signal having the first wavelength from the TE_0 mode add/drop filter; converting, by the $TE_1 \rightarrow TE_0$ mode converter, the reflected TE_1 mode optical signal having the first wavelength to a converted TE_0 mode optical signal having the first wavelength; and transmitting, from the $TE_1 \rightarrow TE_0$ mode converter, the converted TE_0 mode optical signal having the first wavelength to the photodetector.

In some aspects, the method further includes: transmitting, from the Bragg grating, a non-reflected (pass-band) TE_0 mode optical signal having the second wavelength towards a second TE_0 mode add/drop filter.

In some aspects, the techniques described herein relate to a method including: passing an optical signal through a plurality of TE_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_0 mode add/drop filter in the plurality of TE_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_0 mode add/drop filter in the plurality of TE_0 mode add/drop filters is an adiabatic TE_0 mode add/drop filter.

In some aspects, the techniques described herein relate to an apparatus including: a TE_0 mode add/drop filter; and a Bragg grating connected with the TE_0 mode add/drop filter; wherein the TE_0 mode add/drop filter is configured to: receive a TE_0 mode optical signal having a first wavelength and a second wavelength; transmit the TE_0 mode optical signal having the first wavelength and the second wavelength towards the Bragg grating, without converting the TE_0 mode optical signal having the first wavelength and the second wavelength to another mode; receive a reflected TE_1 mode optical signal having the first wavelength from the Bragg grating; and transmit the reflected TE_1 mode optical signal having the first wavelength towards a photodetector, without converting the reflected TE_1 mode optical signal having the first wavelength to another mode.

In some aspects, the TE_0 mode add/drop filter is an adiabatic TE_0 mode add/drop filter.

In some aspects, the TE_0 mode add/drop filter is configured to: receive the TE_0 mode optical signal having the first wavelength and the second wavelength on a lower waveguide; and transmit the TE_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.

In some aspects, the TE_0 mode add/drop filter is configured to: receive the reflected TE_1 mode optical signal having the first wavelength from the Bragg grating on the bus waveguide; and transmit the reflected TE_1 mode optical signal having the first wavelength towards the photodetector on the bus waveguide.

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.

In some aspects, the techniques described herein relate to an apparatus, wherein the TE_0 mode add/drop filter further establishes a pseudo-symmetry about a longitudinal axis of the bus waveguide to prevent TE_1-TM_0 mode hybridization of optical signals that traverse the bus waveguide.

In some aspects, the techniques described herein relate to an apparatus, wherein the TE_0 mode add/drop filter is configured to mode multiplex the TE_0 mode optical signal having the first wavelength and the second wavelength with the reflected TE_1 mode optical signal having the first wavelength.

In some aspects, the techniques described herein relate to an apparatus, further including: a $TE_1 \rightarrow TE_0$ mode converter configured to: receive the reflected TE_1 mode optical signal having the first wavelength from the TE_0 mode add/drop filter; convert the reflected TE_1 mode optical signal having the first wavelength to a converted TE_0 mode optical signal having the first wavelength; and transmit the converted TE_0 mode optical signal having the first wavelength to the photodetector.

In some aspects, the techniques described herein relate to an apparatus, wherein the Bragg grating is configured to transmit a non-reflected TE_0 mode optical signal having the second wavelength towards a second TE_0 add/drop filter.

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.

What is claimed is:

1. A method comprising:

receiving, at a TE_0 mode add/drop filter, a TE_0 mode optical signal having a first wavelength and a second wavelength;

transmitting, from the TE_0 mode add/drop filter, the TE_0 mode optical signal having the first wavelength and the second wavelength towards a Bragg grating, without converting the TE_0 mode optical signal having the first wavelength and the second wavelength to another mode;

receiving, at the TE_0 mode add/drop filter, a reflected TE_1 mode optical signal having the first wavelength from the Bragg grating; and

transmitting, from the TE_0 mode add/drop filter, the reflected TE_1 mode optical signal having the first wavelength towards a photodetector, without converting the reflected TE_1 mode optical signal having the first wavelength to another mode,

wherein the TE_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_0 mode add/drop filter is an adiabatic TE_0 mode add/drop filter.

3. The method of claim **1**, further comprising:

receiving the TE_0 mode optical signal having the first wavelength and the second wavelength on the lower waveguide; and

transmitting the TE_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_1 mode optical signal having the first wavelength from the Bragg grating on the bus waveguide; and

transmitting the reflected TE_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_1-TM_0 mode hybridization of optical signals that traverse the bus waveguide.

7. The method of claim 1, further comprising:

mode multiplexing, by the TE_0 mode add/drop filter, the TE_0 mode optical signal having the first wavelength and the second wavelength with the reflected TE_1 mode optical signal having the first wavelength.

8. The method of claim 1, further comprising:

receiving, at a $TE_1 \rightarrow TE_0$ mode converter, the reflected TE_1 mode optical signal having the first wavelength from the TE_0 mode add/drop filter;

converting, by the $TE_1 \rightarrow TE_0$ mode converter, the reflected TE_1 mode optical signal having the first wavelength to a converted TE_0 mode optical signal having the first wavelength; and

transmitting, from the $TE_1 \rightarrow TE_0$ mode converter, the converted TE_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_0 mode optical signal having the second wavelength towards a second TE_0 mode add/drop filter.

10. An apparatus comprising:

a TE_0 mode add/drop filter; and

a Bragg grating connected with the TE_0 mode add/drop filter;

wherein the TE_0 mode add/drop filter is configured to:

receive a TE_0 mode optical signal having a first wavelength and a second wavelength;

transmit the TE_0 mode optical signal having the first wavelength and the second wavelength towards the Bragg grating, without converting the TE_0 mode optical signal having the first wavelength and the second wavelength to another mode;

receive a reflected TE_1 mode optical signal having the first wavelength from the Bragg grating; and

transmit the reflected TE_1 mode optical signal having the first wavelength towards a photodetector, without converting the reflected TE_1 mode optical signal having the first wavelength to another mode,

wherein the TE_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_0 mode add/drop filter is an adiabatic TE_0 mode add/drop filter.

12. The apparatus of claim 10, wherein the TE_0 mode add/drop filter is configured to:

receive the TE_0 mode optical signal having the first wavelength and the second wavelength on the lower waveguide; and

transmit the TE_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_0 mode add/drop filter is configured to:

receive the reflected TE_1 mode optical signal having the first wavelength from the Bragg grating on the bus waveguide; and

transmit the reflected TE_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_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_1-TM_0 mode hybridization of optical signals that traverse the bus waveguide.

16. The apparatus of claim 10, wherein the TE_0 mode add/drop filter is configured to mode multiplex the TE_0 mode optical signal having the first wavelength and the second wavelength with the reflected TE_1 mode optical signal having the first wavelength.

17. The apparatus of claim 12, further comprising:

a $TE_1 \rightarrow TE_0$ mode converter configured to:

receive the reflected TE_1 mode optical signal having the first wavelength from the TE_0 mode add/drop filter;

convert the reflected TE_1 mode optical signal having the first wavelength to a converted TE_0 mode optical signal having the first wavelength; and

transmit the converted TE_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_0 mode optical signal having a first wavelength and a second wavelength;

transmitting the TE_0 mode optical signal having the first wavelength and the second wavelength towards a Bragg grating, without converting the TE_0 mode optical signal having the first wavelength and the second wavelength to another mode;

receiving a reflected TE_1 mode optical signal having the first wavelength from the Bragg grating; and

transmitting the reflected TE_1 mode optical signal having the first wavelength towards a photodetector, without converting the reflected TE_1 mode optical signal having the first wavelength to another mode,

wherein receiving the TE_0 mode optical signal having a first wavelength and a second wavelength comprises receiving the TE_0 mode optical signal having a first wavelength and a second wavelength at a TE_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_0 mode optical signal, transmitting the TE_0 mode optical signal, receiving reflected TE_1 mode optical signal, and transmitting the reflected TE_1 mode optical signal are performed by the TE_0 mode add/drop filter.

* * * * *