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Zhang et al.

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(54) OPTICAL FULL-FIELD TRANSMITTER

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(51) **Int. Cl.**
H04B 10/50 (2013.01)
H04B 10/516 (2013.01)

(52) **U.S. Cl.**
CPC ***H04B 10/505*** (2013.01); ***H04B 10/504*** (2013.01); ***H04B 10/506*** (2013.01); ***H04B 10/5161*** (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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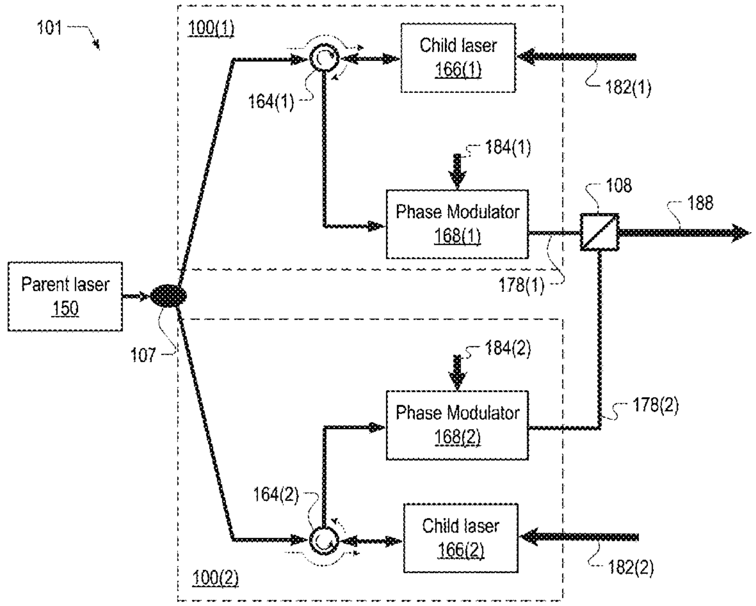
(57) **ABSTRACT**

An optical full-field transmitter (OFFT) includes a plurality of optical circulators and a polarization beam combiner. The plurality of optical circulators are fabricated on a silicon-on-insulator (SOI) substrate, where each of the optical circulators has (a) a first port that optically couples to a high-quality optical source, (b) a second port that optically couples to a child laser configured to receive amplitude modulation data, and (c) a third port optically coupled to a phase modulator that (i) is configured to receive a phase modulation data and (ii) includes an output port that outputs amplitude and phase modulated light. The polarization beam combiner receives the amplitude and phase modulated light from each of the optical circulators and outputs combined amplitude and phase modulated light.

4 Claims, 14 Drawing Sheets



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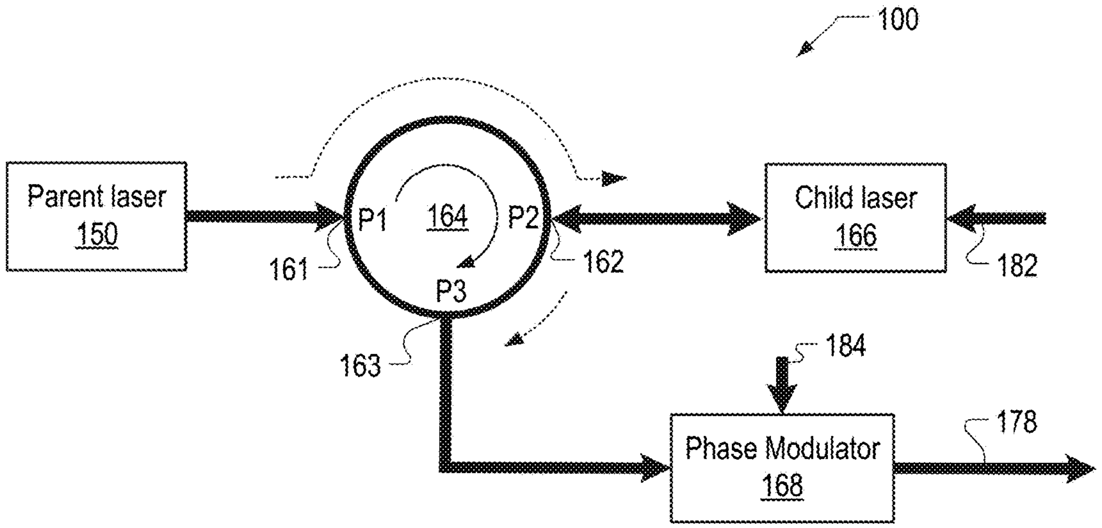
100
Parent laser
150
P1
164
P2
P3
161
162
163
Child laser
166
182
184
Phase Modulator
168
178

FIG. 1A

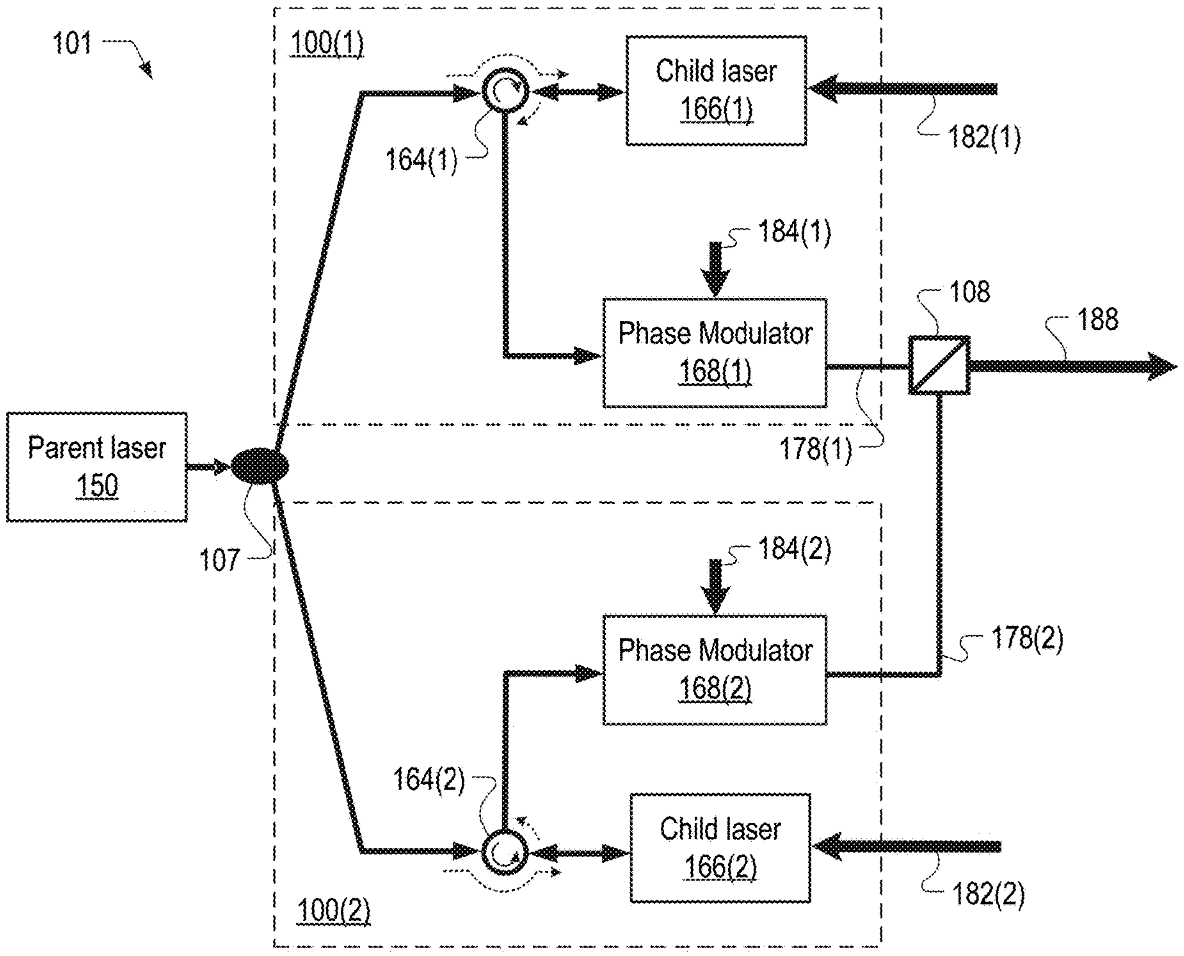
101
100(1)
Child laser
166(1)
182(1)
164(1)
184(1)
Phase Modulator
168(1)
108
188
178(1)
Parent laser
150
107
100(2)
184(2)
Phase Modulator
168(2)
178(2)
164(2)
Child laser
166(2)
182(2)

FIG. 1B

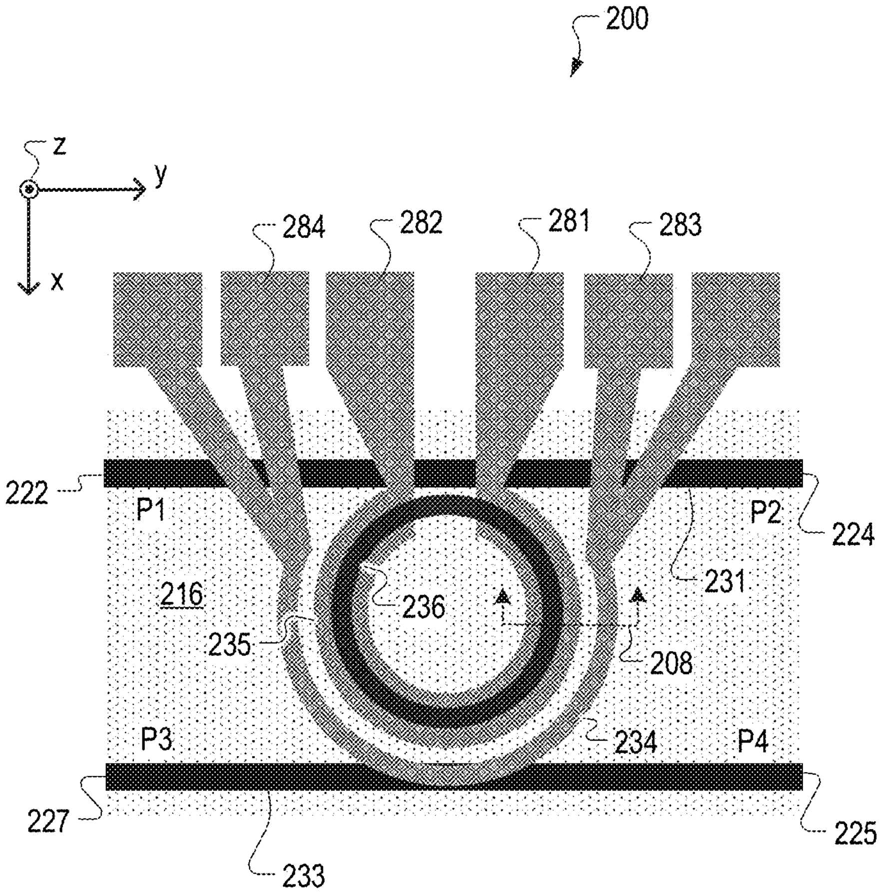
200
z
y
x
284
282
281
283
222
P1
P2
224
216
236
231
235
208
234
P3
P4
227
225
233

FIG. 2A

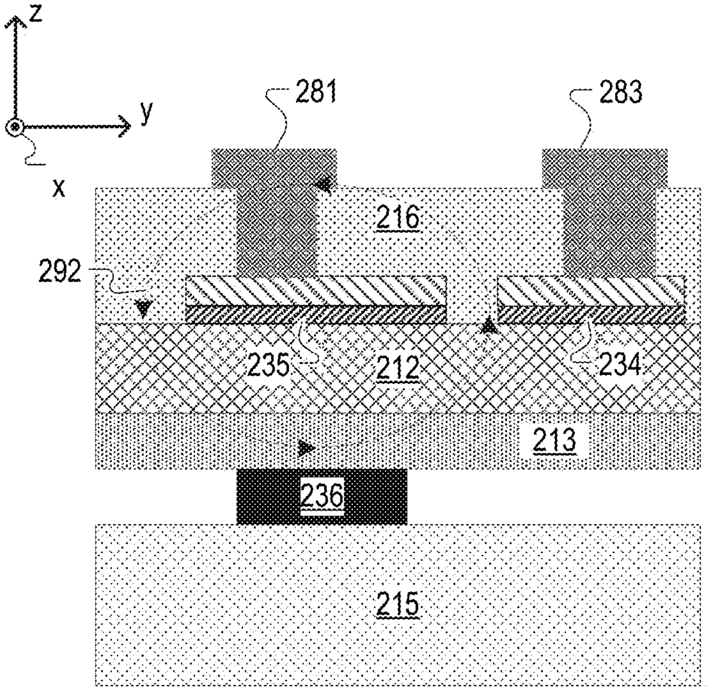
z
y
x
281
283
216
292
235
212
234
213
236
215

FIG. 2B

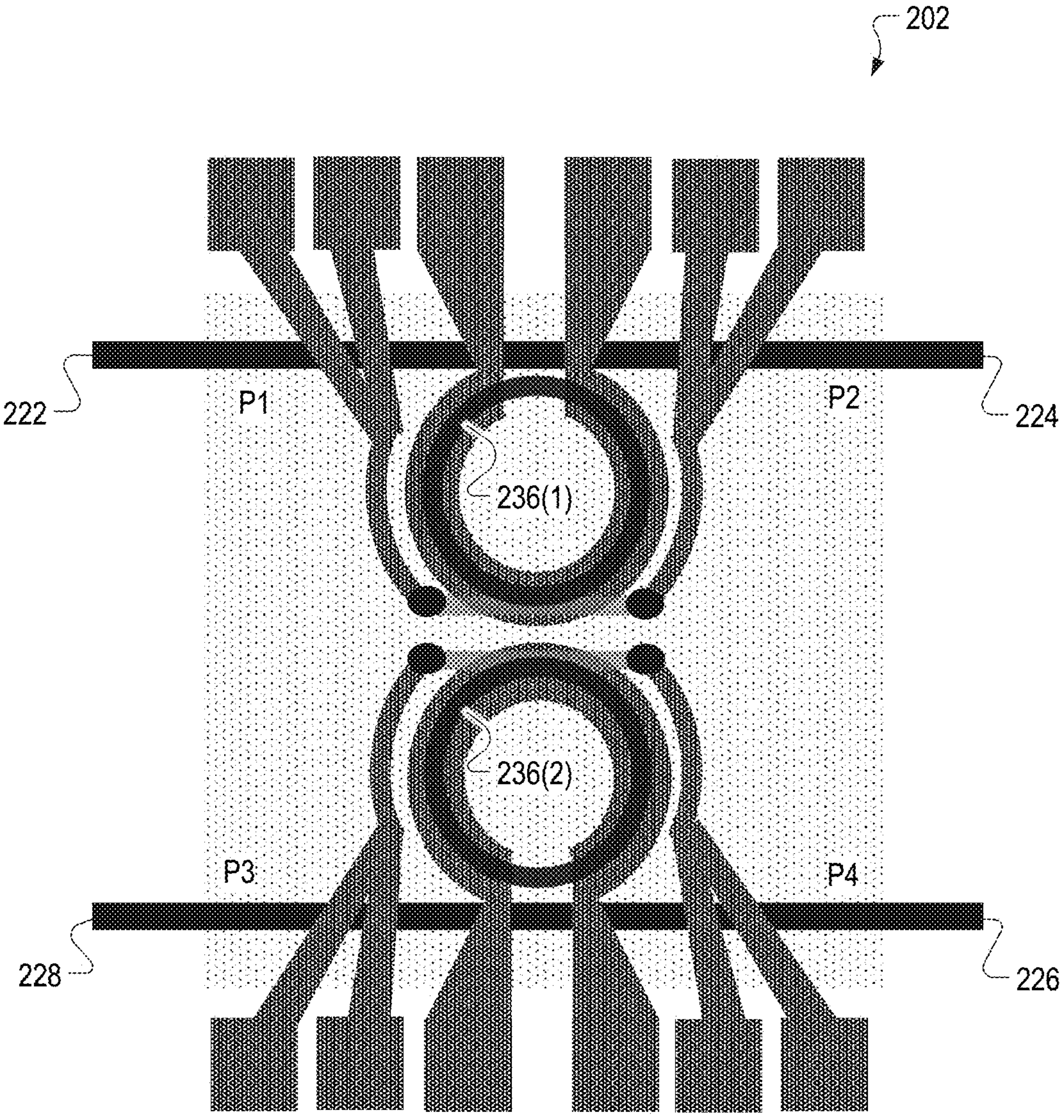

FIG. 2C

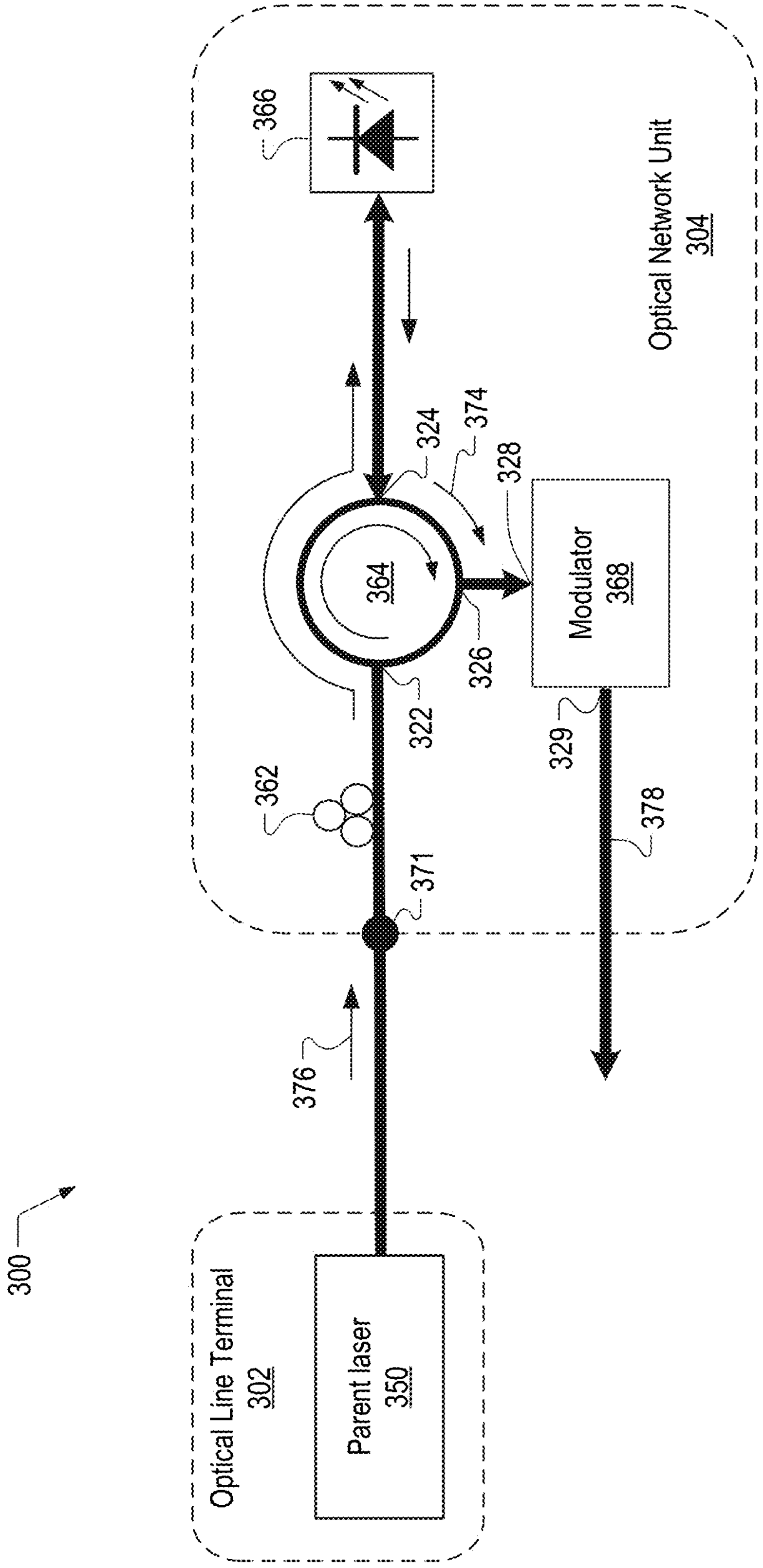
300
Optical Line Terminal
302
Parent laser
350
376
371
362
322
364
326
324
374
328
Modulator
368
329
378
366
Optical Network Unit
304

FIG. 3

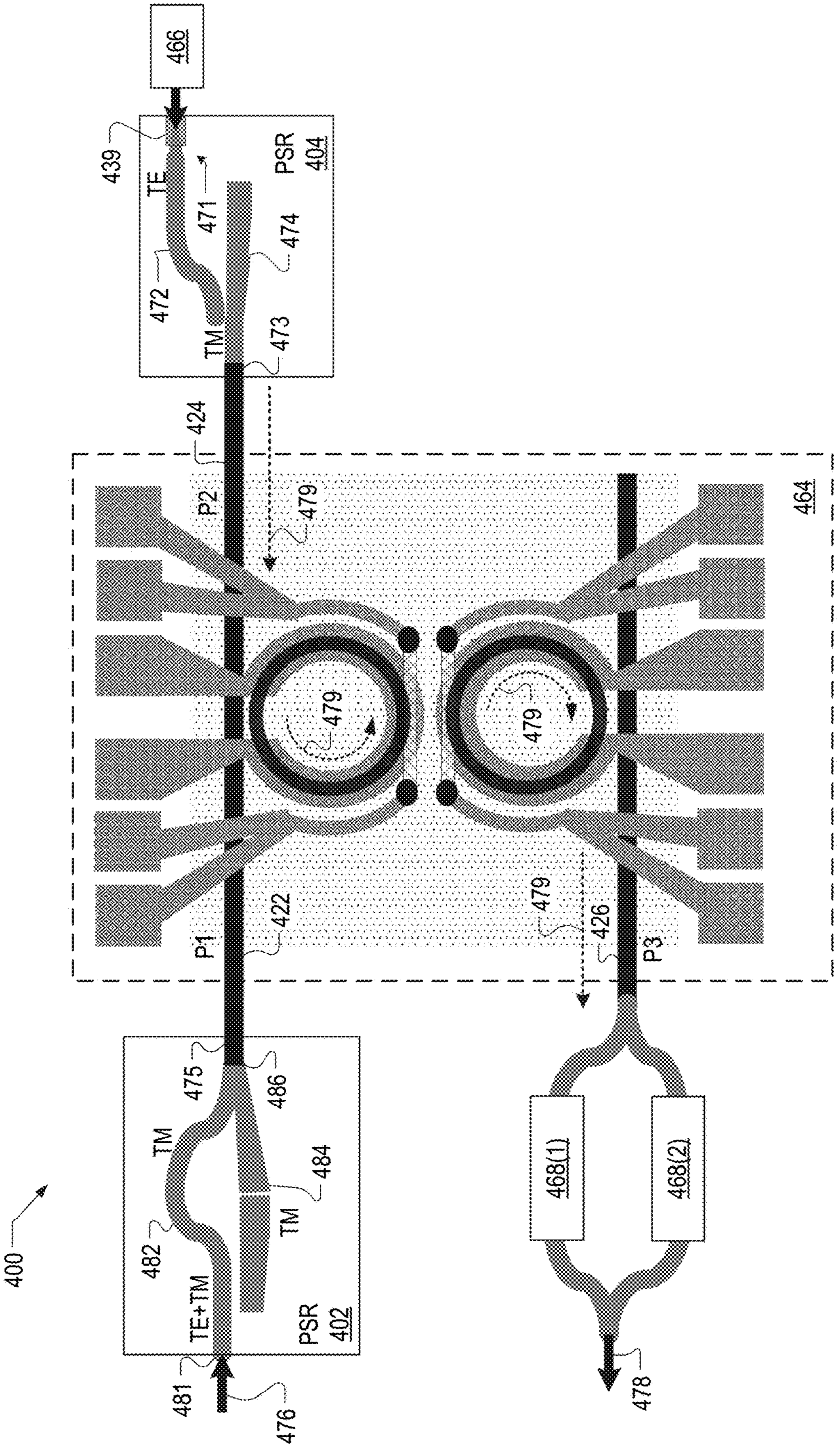
466
439
TE
471
PSR
404
472
474
TM
473
424
P2
479
464
479
479
479
422
426
P1
P3
475
486
TM
484
TM
482
TE+TM
PSR
402
481
476
400
468(1)
468(2)
478

FIG. 4

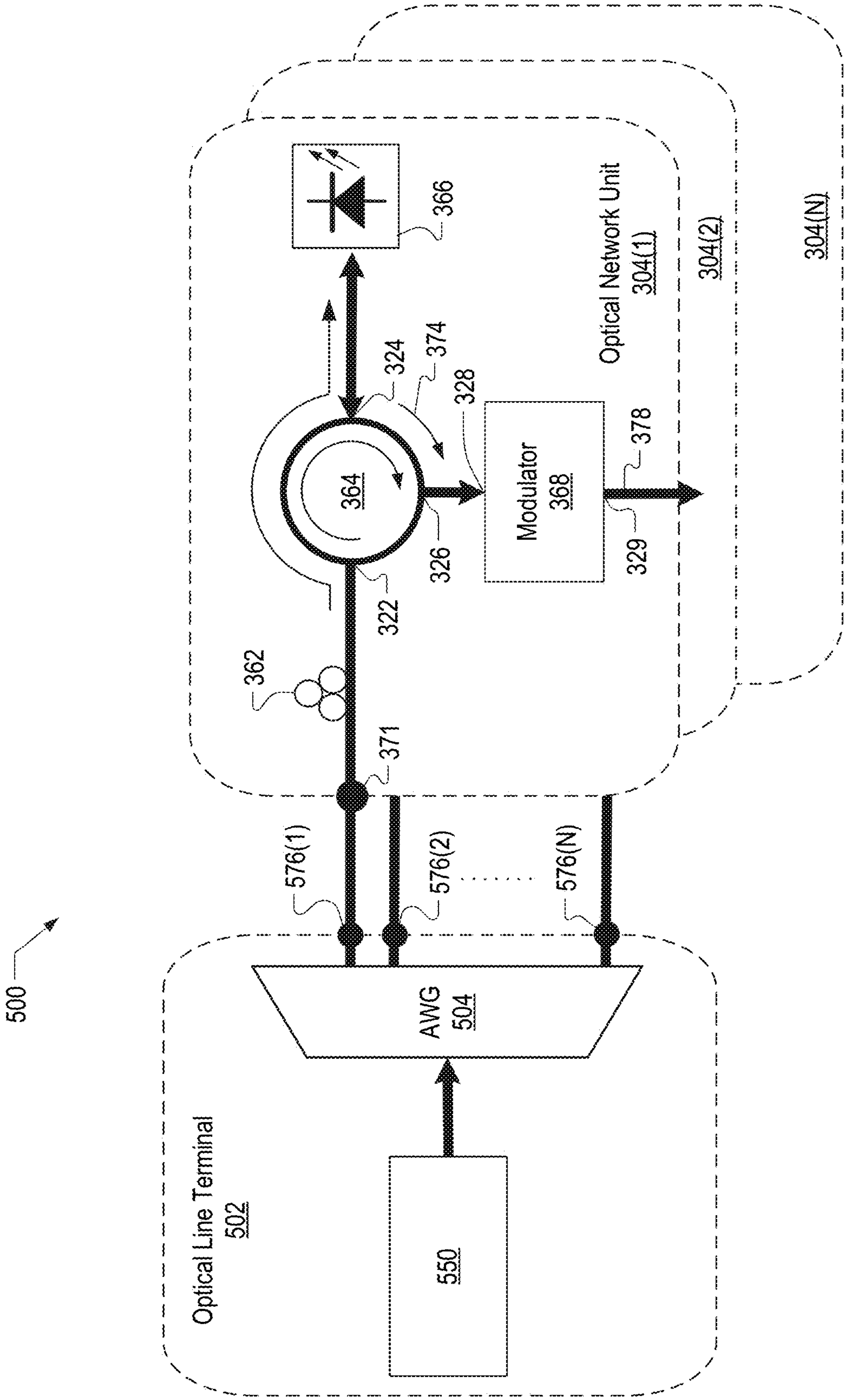
500
Optical Line Terminal
502
550
AWG
504
576(1)
576(2)
576(N)
371
362
322
364
326
324
374
328
Modulator
368
378
329
366
Optical Network Unit
304(1)
304(2)
304(N)

FIG. 5

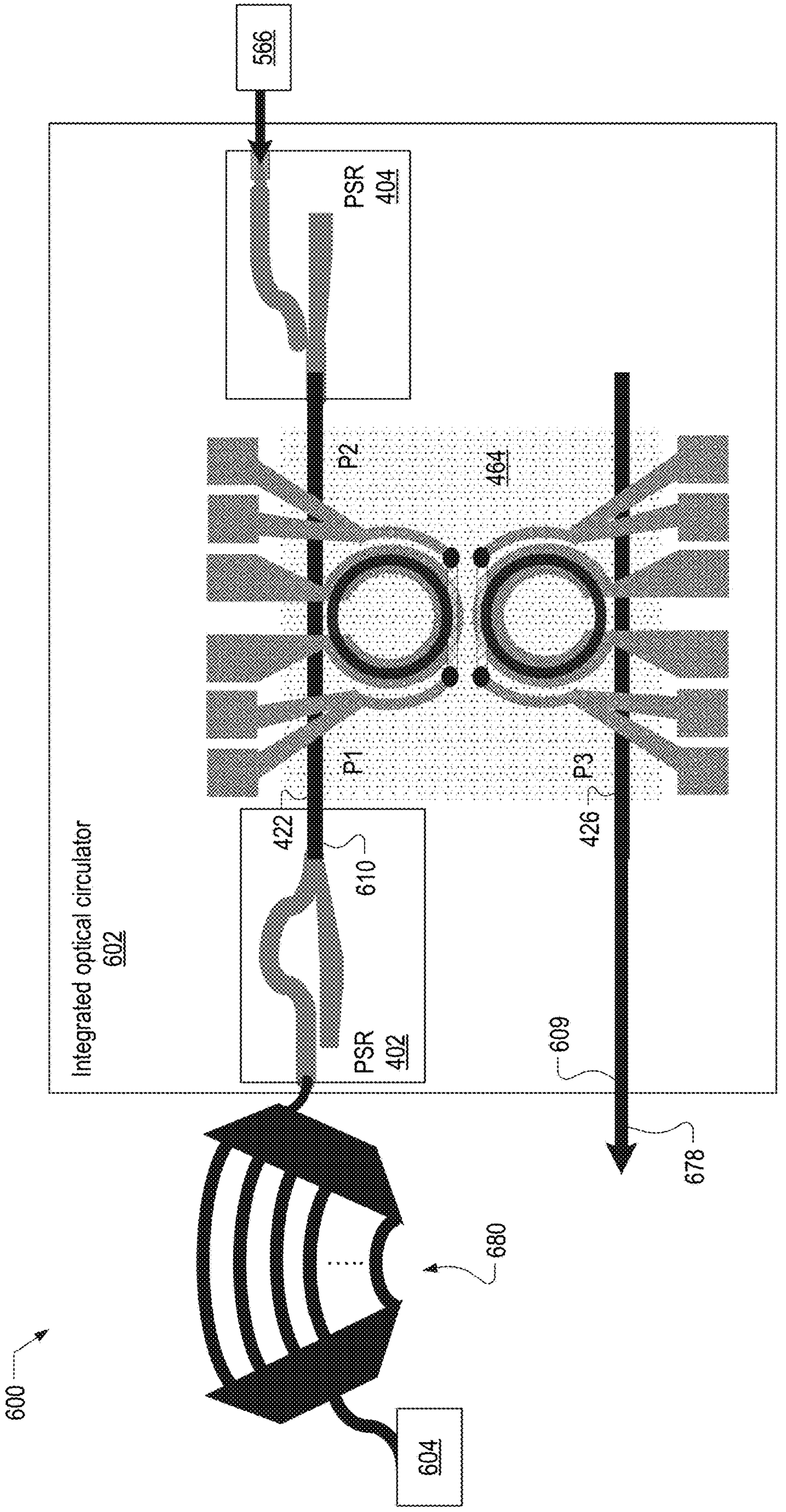
566
PSR
404
P2
464
P1
P3
422
610
426
Integrated optical circulator
602
PSR
402
609
678
680
600
604

FIG. 6

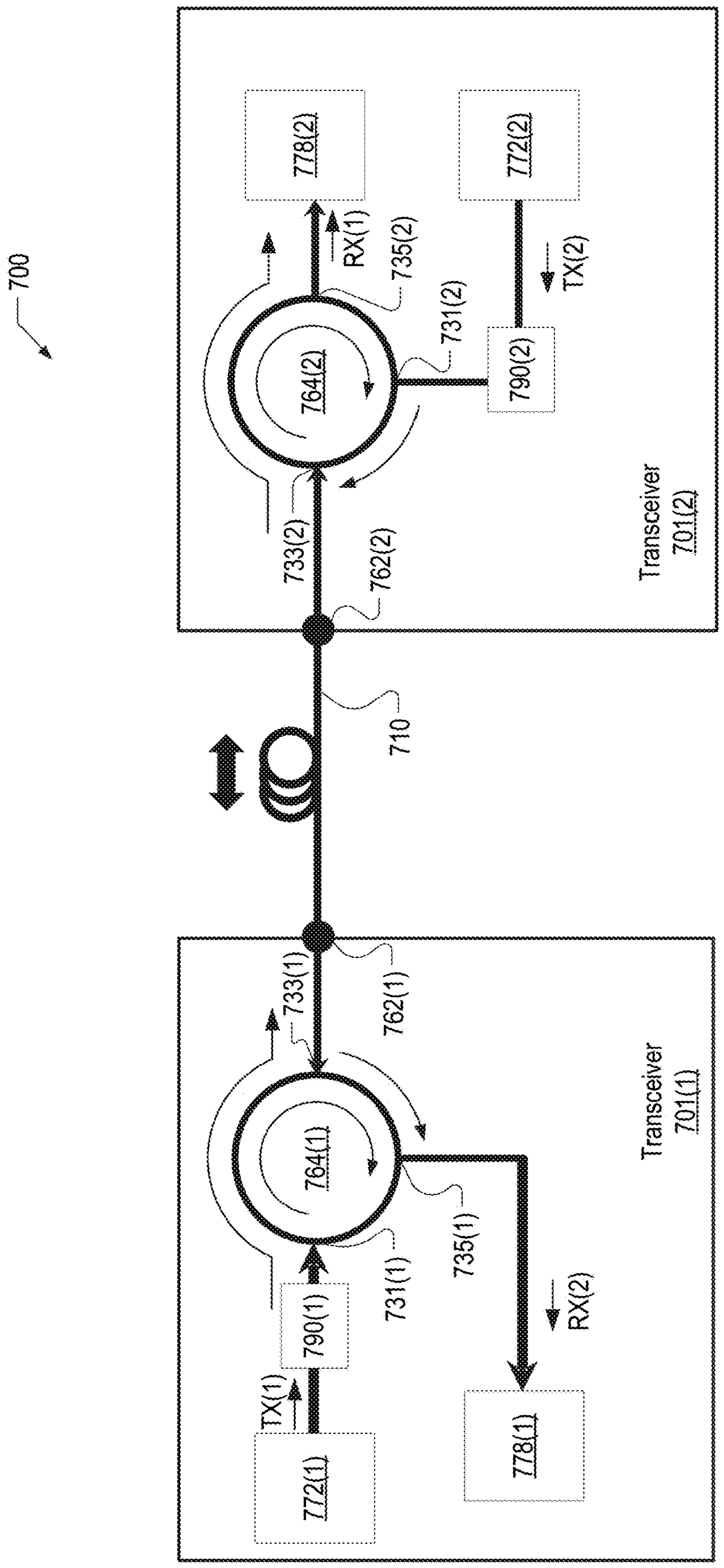
700
778(2)
772(2)
RX(1)
735(2)
TX(2)
731(2)
764(2)
790(2)
733(2)
762(2)
Transceiver
701(2)
710
733(1)
762(1)
764(1)
735(1)
731(1)
790(1)
TX(1)
RX(2)
772(1)
778(1)
Transceiver
701(1)

FIG. 7

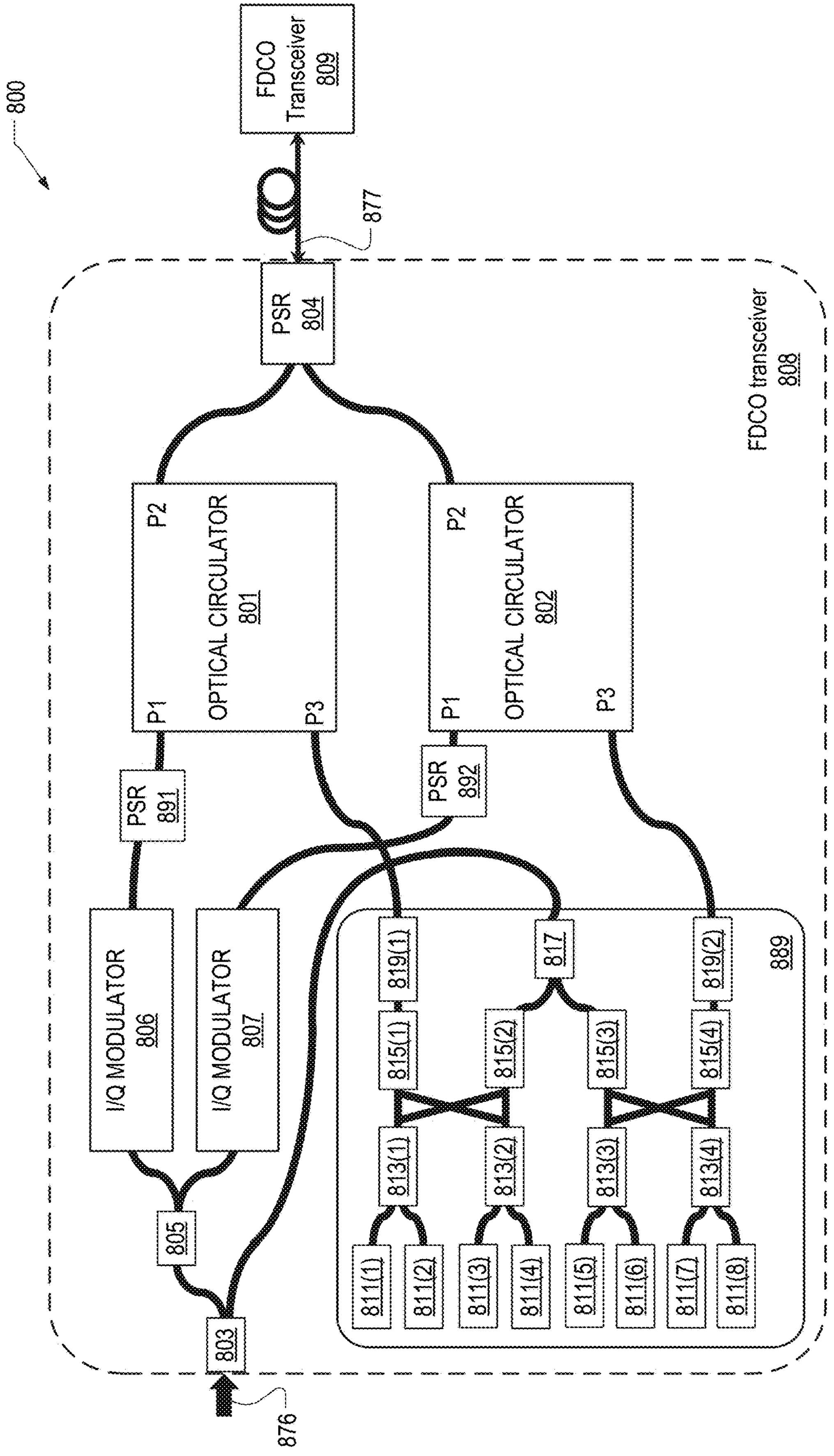
800
FDCO Transceiver 809
877
PSR 804
FDCO transceiver 808
P2
OPTICAL CIRCULATOR 801
P1
P3
P2
OPTICAL CIRCULATOR 802
P1
P3
PSR 891
PSR 892
I/Q MODULATOR 806
I/Q MODULATOR 807
805
803
876
889
819(1)
817
819(2)
815(1)
815(2)
815(3)
815(4)
813(1)
813(2)
813(3)
813(4)
811(1)
811(2)
811(3)
811(4)
811(5)
811(6)
811(7)
811(8)

FIG. 8

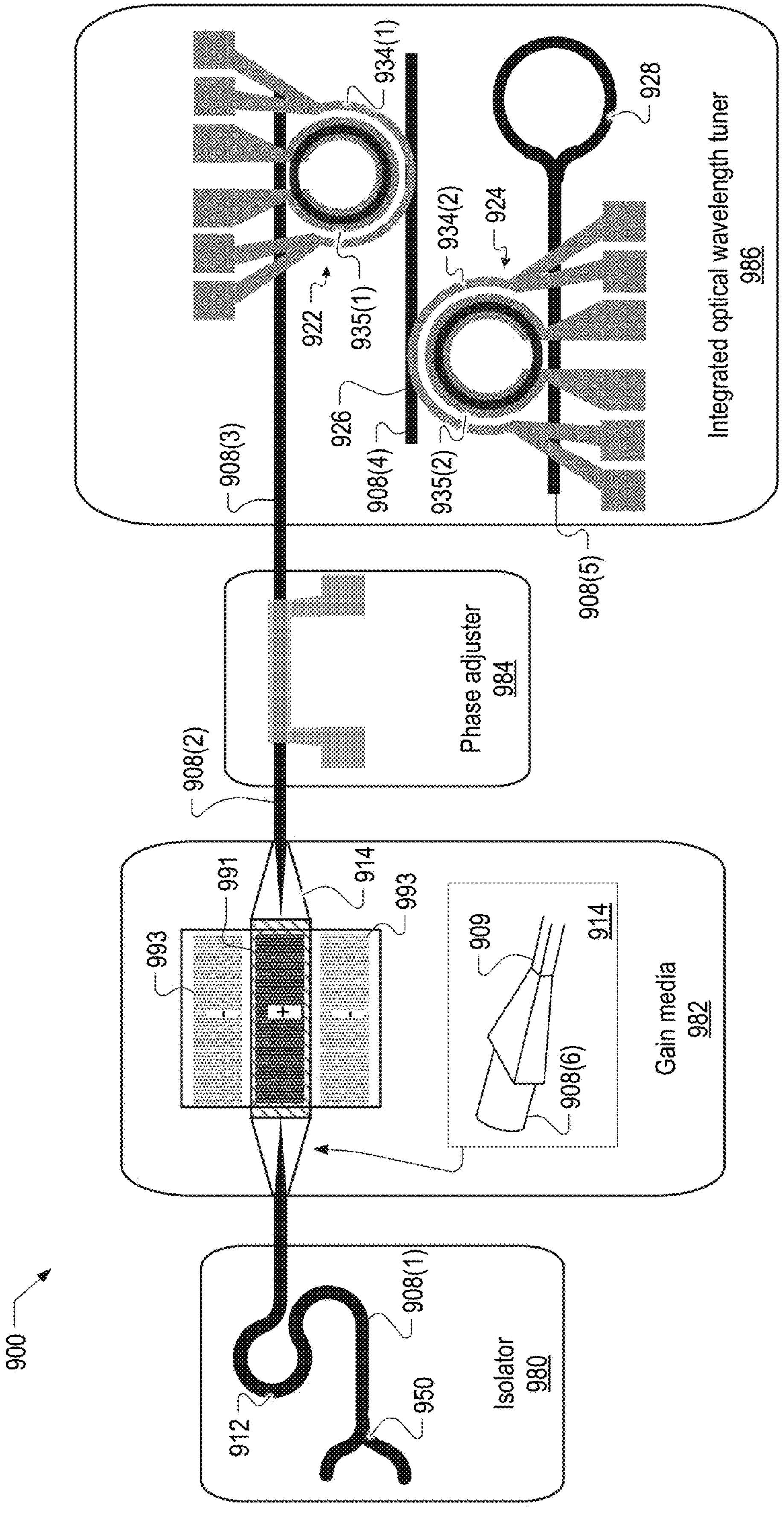
900
Isolator
980
912
908(1)
950
Gain media
982
993
991
+
-
914
909
908(6)
908(2)
Phase adjuster
984
908(3)
922
935(1)
934(1)
926
908(4)
935(2)
934(2)
924
928
908(5)
Integrated optical wavelength tuner
986

FIG. 9

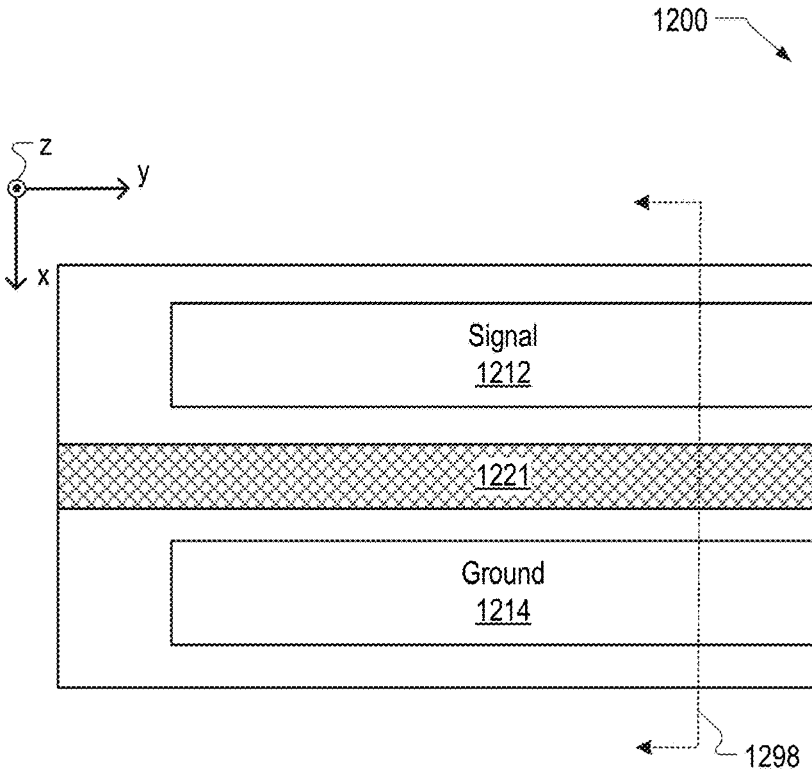

FIG. 10A

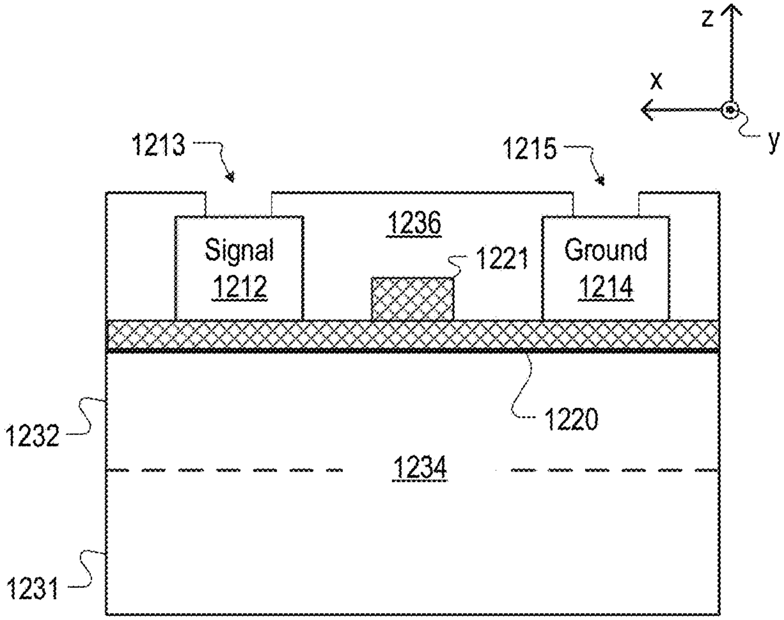

FIG. 10B

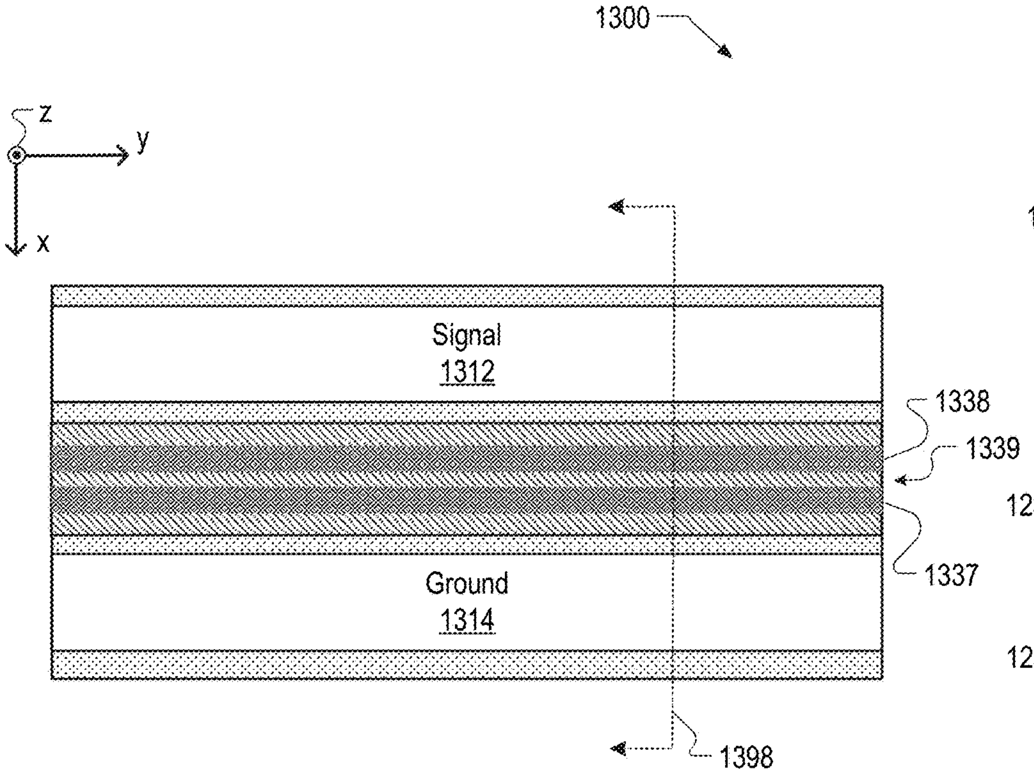

FIG. 11A

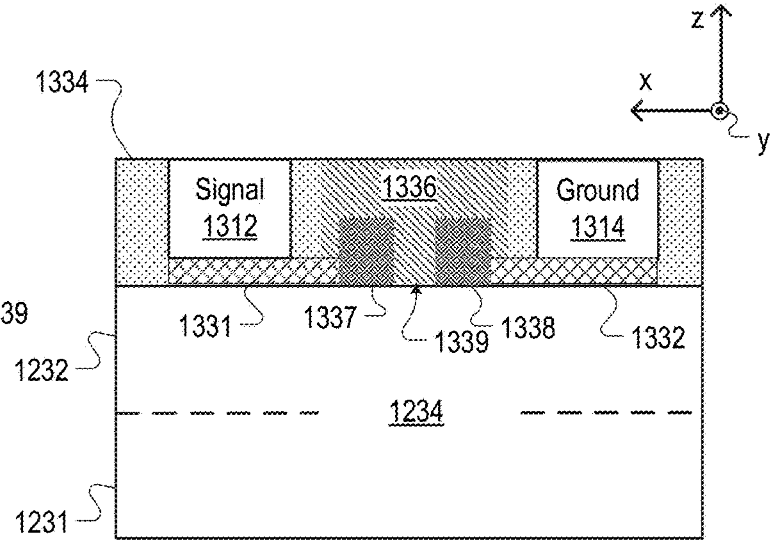

FIG. 11B

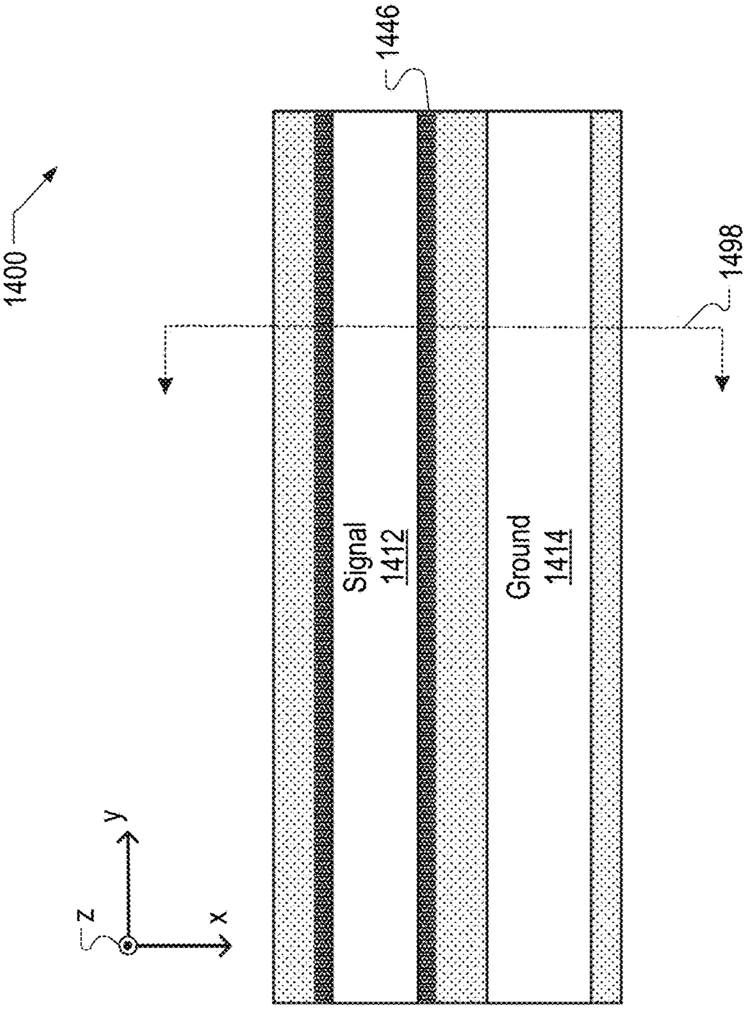

FIG. 12A

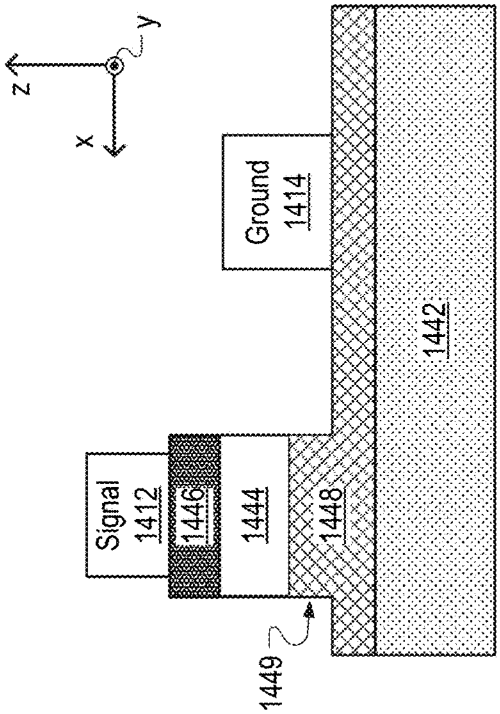

FIG. 12B

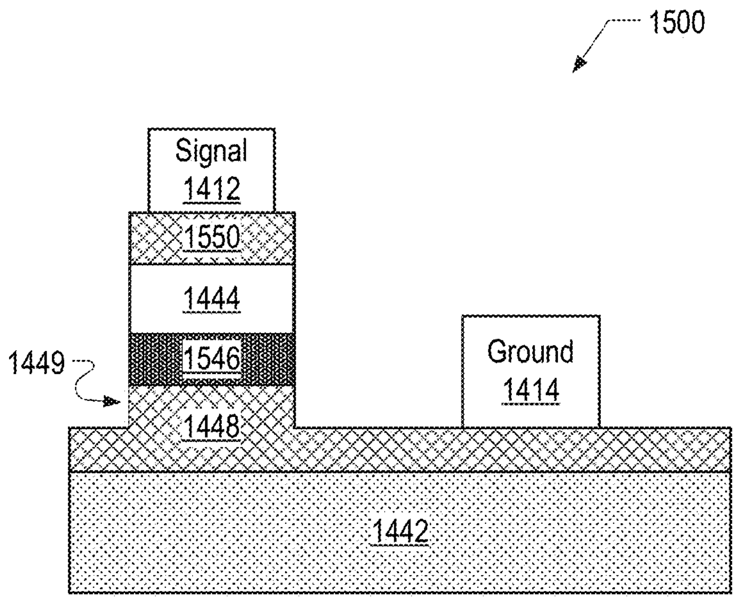

FIG. 13

OPTICAL FULL-FIELD TRANSMITTER

RELATED APPLICATION

This application claims priority to U.S. Provisional Patent Application No. 63/156,990, filed Mar. 5, 2021, and to U.S. Provisional Patent Application No. 63/158,777, filed Mar. 9, 2021, both of which are incorporated herein by reference in their entirety.

BACKGROUND

A significant increase in data intensive applications and services such as high-definition video-on-demand, cloud computing/storage, Internet of Things, and Big Data, has resulted in continuously increasing demand for bandwidth and growing levels of data traffic at both residential areas and businesses. By prediction, the ever-increasing demand will eventually reach multi-gigabit/s speed per user. Wired access networks based on passive optical network (PON) technologies are dominant in meeting such high-capacity demands made by subscribers. However, limited performance of the direct modulation/detection technology currently used in optical networks restricts the data rate per user. As PON evolves towards 100 Gb/s and higher data rates, coherent optical access network technology attracts much attention because of its superior performance and vast potential. Compared with traditional direct modulation/detection systems that suffer from limited modulation bandwidth, short transmission distance, and poor received sensitivity, coherent optical access network technology offers high receiver sensitivity, inherent frequency selectivity, and linear field detection that enables full compensation of linear channel impairments. Additionally, this technology has potential for exceptionally high data throughput over a long distance (>50 km).

SUMMARY

Coherent optical injection-locking (COIL) is a ‘laser-cloning’ technique that allows a low-cost Fabry-Perot (FP) laser output a high-performance narrow linewidth optical source by injecting a high-quality light into its cavity. This is a promising low-cost alternative to using expensive external cavity lasers (ECL) in a coherent system. Embodiments disclosed herein describe an optical full-field transmitter (OFFT) based on COIL. The use of COIL in OFFT designs not only reduces laser and modulator cost but also significantly reduces optical insertion loss and modulation loss by replacing parallel Mach-Zehnder modulator (MZM) with a combination of phase modulator and directly modulated COIL FP laser. In addition, embodiments disclosed herein illustrate photonics integration solutions that further reduce the cost of implementing COIL based OFFT and other types of transmitters in optical access networks while reducing device footprint and power consumption.

In a first embodiment, an optical full-field transmitter (OFFT) includes a plurality of optical circulators and a polarization beam combiner. The plurality of optical circulators are fabricated on a silicon-on-insulator (SOI) substrate, where each of the optical circulators has (a) a first port that optically couples to a high-quality optical source, (b) a second port that optically couples to a child laser configured to receive amplitude modulation data, and (c) a third port optically coupled to a phase modulator that (i) is configured to receive a phase modulation data and (ii) includes an output port that outputs amplitude and phase modulated

light. The polarization beam combiner receives the amplitude and phase modulated light from each of the optical circulators and outputs combined amplitude and phase modulated light.

In a second embodiment, an optical circulator includes a plurality of silicon waveguides, a plurality of silicon ring resonators, a magneto-optic film, a magneto-optic garnet layer, and a plurality of metal strips. The plurality of silicon waveguides is patterned on a SOI substrate, where each silicon waveguide of the plurality of waveguides is substantially linear and has first and second ends. The plurality of silicon ring resonators is also patterned on the SOI substrate. The magneto-optic film is bonded on top of the plurality of silicon waveguides and the plurality of silicon ring resonators. The magneto-optic garnet layer is on the magneto-optic film. The plurality of metal strips is patterned on the magneto-optic garnet layer.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1**A illustrates one optical full-field transmitter, in a single polarization configuration, in an embodiment.

FIG. **1**B illustrates another optical full-field transmitter, in a dual polarization configuration, in an embodiment.

FIGS. **2**A and **2**B illustrate an optical circulator, in a single ring resonator configuration, in an embodiment.

FIG. **2**C illustrates another optical circulator, in a double ring resonator configuration, in an embodiment.

FIG. **3** illustrates an optical injection locking system, in a point-to-point configuration, in an embodiment.

FIG. **4** illustrates an implementation of an optical circulator in an optical injection locking system, in an embodiment.

FIG. **5** illustrates another optical injection locking system, in a point-to-multipoint configuration, in an embodiment.

FIG. **6** illustrates another optical injection locking system, in a point-to-multipoint configuration, in an embodiment.

FIG. **7** illustrates a full-duplex coherent optical system, in a single polarization configuration, in an embodiment.

FIG. **8** illustrates another full-duplex coherent optical system, in a dual polarization configuration, in an embodiment.

FIG. **9** shows a schematic of an integrated external cavity laser, in an embodiment.

FIGS. **10**A and **10**B illustrate one phase modulator, with an integrated Lithium Niobate layer, in an embodiment.

FIGS. **11**A and **11**B illustrate another phase modulator, based on silicon-organic-hybrid technology, in an embodiment.

FIGS. **12**A and **12**B illustrate another phase modulator, with an integrated Indium Phosphide layer, in an embodiment.

FIG. **13** illustrates an alternate phase modulator to the phase modulator of FIGS. **12**A and **12**B.

DETAILED DESCRIPTION OF THE EMBODIMENTS

The term semiconductor substrate may refer to substrates formed of one or more semiconductors such as silicon, silicon-germanium, germanium, gallium arsenide, indium gallium arsenide, and other semiconductor materials known to those of skill in the art. The term semiconductor substrate may also refer to a substrate, formed of one or more semiconductors, subjected to previous process steps that form regions and/or junctions in the substrate. A semiconductor substrate may also include various features, such as doped and undoped semiconductors, epitaxial layers of silicon, and other semiconductor structures formed upon the substrate.

Throughout this specification, several terms of art are used. These terms are to take on their ordinary meaning in the art from which they come, unless specifically defined herein or the context of their use would clearly suggest otherwise. It should be noted that element names and symbols may be used interchangeably through this document (e.g., Si vs. silicon); however, both have identical meanings.

As described herein, critical functional components of an integrated optical full-field transmitter (OFFT) include a high-quality external cavity laser (ECL), one or more optical circulators, phase modulators, and child Fabry-Perot (FP) lasers. OFFTs may be fabricated on a single chip through a silicon hybrid integration process. FIG. **1**A illustrates one example OFFT **100**, in a single polarization configuration. OFFT **100** includes a parent laser **150**, a child laser **166**, an optical circulator **164**, and a phase modulator **168**. Parent laser **150** may be a high quality ECL for injection-locking child laser **166**. In embodiments, child laser **166** is a FP laser diode (FD-LD). Optical circulator **164** includes (i) a first port (P**1**) **161** optically coupled to parent laser **150**, (ii) a second port (P**2**) **162** optically coupled to child laser **166**, and (iii) a third port (P**3**) **163** optically coupled to phase modulator **168**. Optical circulator **164** routes beams from parent laser **150** to child laser **166** and from child laser **166** to phase modulator **168**. Child laser **166** may receive an amplitude modulation data **182** to control the amplitude modulation of the output light. Phase modulator **168** may receive a phase modulation data **184** to control the phase modulation of the received amplitude modulated light from child laser **166**. In one example of operation, high quality narrow linewidth light from parent laser **150** is injected into a cavity of child laser **166** causing child laser **166** to produce a high-power narrow linewidth light having substantially the same optical characteristics as optical characteristics of the high-quality narrow linewidth light from parent laser **150**. Amplitude modulation data **182** controls the amplitude modulation of the high-power narrow linewidth light from child laser **166**. The amplitude modulated light from child laser **166** is then received by phase modulator **168**, which controls the phase modulation of the received amplitude modulated light using the received phase modulation data **184**. The resulting amplitude and phase modulated light **178** is the output of OFFT **100**.

While OFFT **100** is configured for a single polarization system, it may also be used in a dual polarization configuration. FIG. **1**B illustrates another OFFT **101**, in a dual polarization configuration. OFFT **101** includes a plurality of optical circulators, which includes OFFTs **100**(**1**) and OFFT (**2**), and a polarization beam combiner (PBC) **108**. The plurality of optical circulators is fabricated on a silicon-on-insulator (SOI) substrate with each optical circulator **164** having (i) first port **161** optically coupled to parent laser **150**, (ii) second port **162** optically coupled to child laser **166**, where the child laser configured to receive an amplitude modulation data, and (iii) third port **163** optically coupled to phase modulator **168**, which is configured to receive a phase modulation data. Phase modulator **168** includes an output port for outputting an amplitude and phase modulated light **178** for each OFFT **100**. PBC **108** is configured to receive the amplitude and phase modulated light **178** from each optical circulator **164** and output a combined amplitude and phase modulated light **188**, which may be in a dual polarization state. OFFT **101** may also include a parent laser **150** for each OFFT **100**. However, OFFT **101** may also share parent laser **150** among the plurality of OFFTs including OFFTs **100**(**1**) and **100**(**2**). For example, OFFT **101** may include an optical splitter **107** that splits light from parent laser **150** to feed both OFFTs **100**(**1**) and **100**(**2**).

In the following sections, critical components of an OFFT, namely an optical circulator, an external cavity laser, and a phase modulator, are detailed for photonic integration. In particular, the optical circulator and its example applications in related optical and network devices are disclosed. The examples disclosed herein are not meant to be exhaustive but rather highlight some of the advantages of using an optical circulator in an integrated photonics solution.

Integrated Optical Circulator

An optical circulator, such as optical circulators **164** in FIGS. **1**A and **1**B, is a three-or four-port non-reciprocal optical device designed so that optical signals entering any ports exits from the next, as in a traffic roundabout for cars. Typically, discrete optical circulators break reciprocity by utilizing magneto-optically active materials. Such discrete devices are usually bulky (several centimeters long) and expensive, which increases the cost and footprint of the coherent system in access networks significantly.

Embodiments disclosed hereinbelow illustrate use of an optical circulator in an integrated photonics solution that may be utilized in coherent optical and network devices with significant reduction in terms of footprint and cost. Advantageously, these integrated designs also reduce the system complexity by eliminating the need for a large amount of input and output fibers and interconnects.

FIGS. **2**A and **2**B illustrate an optical circulator **200**, in a single ring resonator configuration. Optical circulator **200** may for example be used as optical circulators **164** of FIGS. **1**A and **1**B. FIGS. **2**A and **2**B denote axes x, y, and z, where the z-axis is orthogonal to a plane formed by orthogonal axes x and y. Herein, the x-y plane is formed by orthogonal axes x and y and is referred to as a horizontal plane. Also, herein, a width refers to an object's extent along the x axis, a depth refers to an object's extent along the y axis, a thickness (or thinness) refers to an object's extent along the z-axis, and vertical refers to a direction along the z-axis. Unless otherwise specified, heights of objects herein refer to the object's extent along axis z. Also, herein, "above" refers to a relative position along the z-axis in the positive direction and "below" refers to a relative position along the z-axis in the negative direction.

FIG. **2**A also denotes a section line **208**, which indicates the location of the orthogonal cross-sectional side view illustrated in FIG. **2**B, which is parallel to y-z plane. FIGS. **2**A and **2**B are best viewed together in the following description. Optical circulator **200** includes one or more silicon waveguides **231** and **233**, a silicon ring resonator **236**, a magneto-optic film **213**, a magneto-optic garnet layer **212**, and metal strips **234** and **235**. Silicon waveguide **231** and **233** may be patterned on a silicon-on-insulator (SOI) substrate **215**. Silicon ring resonator **236** may also be patterned on SOI substrate **215**. Magneto-optic film **213** may be bonded on top of silicon waveguides **231** and **233** and silicon ring resonator **236** in z-direction. Magneto-optic garnet layer **212** may be on top of magneto-optic film **213**. Metal strips **234** and **235** may be patterned on top of magneto-optic garnet layer **212**. Metal strips **234** and **235** form a concentric circular pattern above silicon ring resonator **236** with metal strip **235** forming a first circular pattern having a radius equal to a radius of silicon ring resonator **236** and metal strip **234** forming a second circular pattern having a radius larger than a radius of silicon ring resonator **236**.

Metal strip **235** has external electrical connections **281** and **282** at the ends. Metal strip **234** has external electrical connections **283** and **284** at the ends. In embodiments, metal strip **235** is made from one of Ti/Au, Ti/Pt, and Al. When powered, metal strip **235** generates a magnetic field **292** above silicon ring resonator **236** and produces heat. Metal strip **234**, which may be made from Ti/Pt, has a linear response to a temperature change and acts as a resistance temperature detector (RTD). Using the RTD property of metal strip **234**, the temperature and magnetic field generated by metal strip **235** may be controlled for a stable operation of optical circulator **200**.

By applying magnetic field **292**, for example by providing current through metal strip **235** in a positive x-direction in FIG. **2**B, with respect to the direction of optical field propagation, the symmetry of silicon ring resonator **236** is broken by the non-reciprocal phase shift (NRPS) effect. Once the symmetry is broken, the clockwise and the counterclockwise propagation constants for the optical field polarized in transverse magnetic (TM_0) mode may be differentiated significantly, resulting in a different resonant wavelength for the two propagating directions. As a result, the different frequency response of silicon ring resonator **236** filters out the backward light and provides circulating functions. An optical circulator, such as optical circulator **200**, with a single ring resonator design may have a channel isolation ratio of 9.15 dB at 1550 nm.

Optical circulator **200** includes optical ports P**1** **222** and P**2** **224**, which are two ends of a silicon waveguide **231**. Optical circulator **200** may also include at least one of optical ports P**3** **227** and P**4** **225**. Optical ports P**3** **227** and P**4** **225** may be the two ends of silicon waveguide **233**. Optical circulator **200** may be fabricated using a standard process for fabricating a complementary metal-oxide-semiconductor (CMOS). In embodiments, silicon waveguides **231** and **233** and silicon ring resonator **236**, which may be patterned on a silicon-on-insulator (SOI) substrate **215**, has a thickness of approximately 220 nm in z-direction. By utilizing direct wafer bonding approach, a magneto-optic film **213** may be grown on a magneto-optic garnet layer **212**. Magneto-optic film **213** may be Ce:YIG, and Magneto-optic garnet layer **212** may be a [Ca, Mg, Zr]-substituted gadolinium gallium garnet (SGGG) layer. Magneto-optic film **213** may then be bonded onto patterned SOI substrate **215**, followed by annealing. In embodiments, magneto-optic garnet layer **212** is thinned to a few micrometers using polishing. Metal strips **234** and **235** may then be patterned on the back side of magneto-optic garnet layer **212** through metal e-beam evaporation and liftoff process. Then a SiO2 layer **216** is deposited covering metal strips **234** and **235**.

FIG. **2**C illustrates another optical circulator **202**, in a double ring resonator configuration. Optical circulator **202** may be formed by optically coupling two optical circulators **200**. Optical circulator **202** includes two silicon ring resonators **236**(**1**) and **236**(**2**), ports P**1** **222** and P**2** **224** and may include at least one of ports P**3** **228** and P**4** **226**. Advantageously, by utilizing double ring resonator design, the optical isolation and the isolation bandwidth may be effectively enlarged. As a result, optical circulator with a double ring resonator design, such as optical circulator **202** may have a channel isolation ratio of 18.3 dB at 1550 nm.

Integration of Optical Circulator in OIL Systems

The first example application of the optical circulator is an optical injection locking (OIL) system. OIL is a technique that causes low-quality child lasers (e.g., child laser **166** in FIGS. **1**A and **1**B) to output a high-quality narrow bandwidth optical signal similar to high-performing lasers by injection locking light from a high-quality parent laser (e.g., parent laser **150** in FIGS. **1**A and **1**B) into resonators of the low-quality child lasers. The injection locked child laser behaves like a high-quality laser and may be a cost-effective solution in coherent optical systems. An OIL system may be implemented in a point-to-point (P2P) or a point-to-multipoint (P2MP) configuration. FIGS. **3** and **5** illustrate OIL systems, in a P2P configuration and P2MP configuration, respectively. FIG. **4** illustrates an implementation of an optical circulator in either configuration.

FIG. **3** illustrates an OIL system **300** in a P2P configuration. OIL system **300** includes an optical line terminal (OLT) **302** and an optical network unit (ONU) **304**. OLT **302** may be located at an optical hub or at a central office (CO). OLT **302** includes a parent laser **350**. In a coherent OIL (COIL) system, parent laser **350** may be a tunable ECL with C-band coverage to meet the requirement for the narrow frequency linewidth. ONU **304** includes an optical circulator **364**, an input port **371**, a child laser **366**, and a modulator **368**. Optical circulator **364** is an example of optical circulator **202** in FIG. **2**C. Input port **371** is optically coupled to a first port **322** of optical circulator **364** and is configured to receive light from an optical line terminal **302**. Child laser **366**, which may be a FP laser diode (LD), is optically coupled to a second port **324** of optical circulator **364**. Modulator **368** includes an input port **328** optically coupled to a third port **326** of optical circulator **364** and having a light output port **329**. ONU **304** may also include a polarization controller **362**, which controls the polarization of an injected light **376** for maximizing injection coupling efficiency. In one example of operation, optical circulator **364** routes injected light **376** into the cavity of child laser **366**. Optical circulator **364** then routes an output light **374** of child laser **366** into input port **328** of modulator **368** that may introduce modulation in output light **374** of child laser **366** and output a modulated light **378**. In an example application, since a COIL system locks a semiconductor laser such as child laser **366** to the frequency and phase of an externally injected optical signal such as injected light **376**, a low-cost multimode FP laser may be used as child laser **366** in a single mode operation by injecting a high-quality single-mode light from parent laser **350** into its cavity.

FIG. **4** illustrates an implementation of an optical circulator **464** in an OIL system **400**. Integrated optical circulator **464** and OIL system **400** are respective examples of optical circulator **202** and OIL system **300**. OIL system **400** may be implemented in ONU **304** using hybrid photonic integration. Optical circulator **464** may include a coupled ring resonator structure, an example of optical circulator **202** in FIG. **2**C, and is favored in OIL system **400** for the superior performance in channel isolation and bandwidth. In embodiments, optical circulator **464** includes ports P**1** **422**, P**2** **424**, and P**3** **426**, which are respective examples of ports P**1** **222**, P**2** **224**, and P**3** **228**.

OIL system **400** also includes a first polarization splitter rotator (PSR) **402** and a second PSR **404**. First PSR **402** controls the polarization of injected light **476** by converting injected light **476** into TM_0 mode and couples a converted light **475** to port P**1** **422** of optical circulator **464**. First PSR **402** may be fabricated on the SOI waveguide layer (e.g., the same layer as silicon waveguide **231** in FIG. **2**B). First PSR **402** includes an input port **481**, a narrow waveguide **484**, a tapered waveguide **482**, and an exit port **486**. Narrow waveguide **484** and tapered waveguide **482** may be formed of silicon. Injected light **476** is coupled to input port **481** of first PSR **402**. The design of first PSR **402** is based on a tapered directional coupler (DC), which couples in parallel a narrow waveguide **484** to a wide tapered waveguide **482**. The strong cross-polarization coupling between two waveguides results in (i) the transverse electric (TE_0) part of injected light **476** coupling to TM_0 mode in tapered waveguide **482** and exiting from an exit port **486**, and (ii) the TM_0 part of injected light **476** propagating along the narrow waveguide **484** and exiting from exit port **486**. The output lights from the two waveguides couple together as a TM_0 converted light **475** and enter port P**1** **422** of optical circulator **464**. As with optical circulators **200** and **202**, optical circulator **464** has a magneto-optic film (e.g., magneto-optic film **213** in FIG. **2**B) bonded on SOI waveguides and is optimized for TM_0 mode.

Second PSR **404** includes an input port **471**, an exit port **473**, a tapered waveguide **472**, and a narrow waveguide **474**. Waveguides **472** and **474** may be formed of silicon. A child laser **466**, which may be a FP-LD, is coupled to input port **471** through a spot size converter (SSC) **439**. Exit port **473** is coupled to port P**2** **424** of optical circulator **464**. Based on similar principle as above, TM_0 mode of optical circulator **464** may be converted to TE_0 mode to match the guided mode of child laser **466**. Optical circulator **464**, second PSR **404**, and child laser **466**, which is formed of indium phosphide, may be integrated together by butt coupling through tapered waveguide **472**. The injection-locked output of child laser **466** follows a path **479** and is routed to port P**3** **426**, followed by a coupling to one or more coherent in-phase/quadrature (I/Q) modulators **468** to generate injection locked light **478**. In fabrication, silicon photonics I/Q modulators may be directly integrated with optical circulator **464**. InP-based I/Q modulators may also be utilized by using hybrid integration.

While OIL systems **300** and **400** depict example use of optical circulators in a point-to-point (P2P) scenario, optical circulators may also be used in point-to-multipoint (P2MP) applications. FIG. **5** illustrates another OIL system **500**, in a point-to-multipoint configuration. OIL system **500** includes an optical circulator **364**. Optical circulator **364** may be implemented by using any of optical circulators **200**, **202**, **364**, and **464**.

OIL system **500** includes a plurality of optical network units **304** and an optical line terminal **502**. Optical line terminal **502** includes an optical frequency comb source **550**, a silicon arrayed wavelength grating (AWG) **504**, and a plurality of output ports **576**. Optical frequency comb source **550** may generate multiple frequency tones. AWG **504** is configured to separate the multiple frequency tones into a plurality of separated frequency tones. Plurality of output ports **576** has each output port **576**(**0**, where i is a positive integer not more than N, configured to send the separated frequency tone of the plurality of separated frequency tones to a corresponding optical network unit **304**(*i*).

In one example of operation, optical frequency comb source **550** generates multiple frequency tones. In embodiments, channel spacing between adjacent frequency tones are 25 GHz, 12.5 GHz, or 6.25 GHz. The generated frequency tones are then separated by AWG **504**. Each separated frequency tone is optically coupled to a corresponding optical network unit **304**(*i*) and is used to injection lock child laser **366**.

FIG. **6** illustrates another OIL system **600**, in a point-to-multipoint configuration. OIL system **600** may also be fabricated on a SOI substrate. OIL system **600** includes an integrated optical circulator **602**, which may include optical circulator **464** of FIG. **4**. Integrated optical circulator **602** also includes an output port **609**, PSRs **402** and **404**. Output port **609** is optically coupled to port P**3** **426** of optical circulator **464**. In embodiments, integrated optical circulator **602** is formed of silicon photonics. OIL system **600** also includes an optical frequency comb source **604**, a dual-AWG **680**, and a child laser **566**. One output of dual-AWG **680** is coupled to first PSR **402** of integrated optical circulator **602**. First PSR **402** converts the polarization mode of the guided light from dual-AWG **680** into a guided TM_0 light **610**, which enters optical circulator **464** at port P**1** **422** and subsequently injection locks child laser **566**. Second PSR **404** may be used to optimize the polarization of guided TM_0 light **610** to match the cavity mode of child laser **566**. Injection locked light **678**, which exits integrated optical circulator **602** via output port **609**, may be modulated by modulating child laser **566** or by coupling an external modulator at output port **609**. In fabrication, integrated optical circulator **602** may be butt coupled with child laser **566**, which may be an InP FP laser, through mode size converters used in hybrid photonic integration.

Integration of Optical Circulator in Full-Duplex Coherent Optics Systems

The second example application of the optical circulator is a full-duplex coherent optics (FDCO) technology, in which a single fiber is used to transmit both upstream and downstream signals. FDCO technology may be implemented in a FDCO transceiver in a single polarization or a dual polarization configuration. Both configurations, each using an optical circulator, are disclosed below. FIG. **7** illustrates a FDCO system **700**, in a single polarization configuration. FDCO system **700** may include two or more FDCO transceivers **701**. For brevity, only two FDCO transceivers are shown in FIG. **7**. FDCO transceivers **701**(**1**) and **701**(**2**) may be connected using a fiber **710**. FDCO transceiver **701** includes an optical circulator **764**. Optical circulator **764** includes a first port **731**, a second port **733**, and a third port **735**. First port **731** is configured to receive a transmitted light TX from a transmit source **772**. Second port **733** is optically coupled to an input/output (I/O) port **762** that may send and receive light through fiber **710**. Third port **735** is optically coupled to a coherent receiver **778**, configured to receive a received light RX. Coherent receiver **778** may include a photodetector that converts RX into an electrical signal. FDCO transceiver **701** may also include a polarization controller **790** disposed between transmit source **772** and first port **731** of optical circulator **764** and configured to control a polarization of transmitted light TX entering first port **731**.

In one example of operation of a bi-directional transmission, TX(**1**) from transmit source **772**(**1**) enters first port **731**(**1**) of optical circulator **764**(**1**) in transceiver **701**(**1**) and exits through second port **733**(**1**). TX(**1**) is received by transceiver **701**(**2**) and enters second port **733**(**2**) of optical circulator **764**(**2**), which then exits through third port **735**(**2**) and is received by coherent receiver **778**(**2**) as RX(**1**). In a reverse operation, TX(**2**) from transmit source **772**(**2**) in transceiver **701**(**2**) enters first port **731**(**2**) of optical circulator **764**(**2**) and exits through second port **733**(**2**). TX(**2**) is subsequently received by transceiver **701**(**1**) and enters second port **733**(**1**) of optical circulator **764**(**1**). TX(**2**) then exits through third port **735**(**1**) and is received by coherent receiver **778**(**1**) as RX(**2**). In general, one or more optical circulators may be used in each FDCO transceiver to reroute the optical path in different directions, thereby allowing a bi-directional transmission in a single fiber between any two FDCO transceivers in the system. Additionally, P2P FDCO systems, such as FDCO system **700**, may be used in P2MP FDCO systems by adding AWGs and coherent modulators, as described in examples of FIGS. **5** and **6**.

FIG. **8** illustrates another FDCO system **800**, in a dual polarization configuration. FDCO system **800** may include two or more FDCO transceivers, of which only two FDCO transceivers **808** and **809** are shown for brevity. FDCO transceiver **808** is shown in detail as an example of FDCO transceivers in a dual polarization configuration. FDCO transceiver **808** may be implemented in a complete photonic integration on a SOI platform. FDCO transceiver **808** includes two optical circulators **801** and **802**. Optical circulators **801** and **802** are examples of any optical circulator **200** or **202** in FIGS. **2**A, **2**B and **2**C. FDCO transceiver **808** also includes a fully integrated coherent receiver (ICR) **889**. In one example of operation, a discrete ECL light **876** is split by an optical power splitter **803** with one half propagating to receiver side comprising ICR **889** and the other half propagating to transmitter side. On the transmitter side, ECL light **876** is further split with an optical power splitter **805** and modulated by two I/Q modulators **806** and **807**. The polarization of the two modulated lights is then rotated with PSRs **891** and **892** such that the two modulated lights have different polarity, before each modulated light enters a first port P**1** of optical circulator **801** or **802**. The light emerging from a second port P**2** of optical circulators **801** and **802** are then combined by a PSR **804**, having a dual polarization, and transmitted to FDCO transceiver **809** using fiber **877**.

On the receiver side, ICR **889** may include variable optical attenuators (VOA) **819**, optical power splitters **813**, **815**, and **817**, and photodetectors **811**. Dual polarized received light from FDCO transceiver **809** is split into two single polarized light by PSR **804**, and each polarized light enters second port P**2** of optical circulators **801** or **802**. Single polarized lights after emerging from a third port P**3** of optical circulators **801** and **802** enter ICR **889**. In embodiments, in ICR **889**, the lights interfere with the local-oscillator (LO) in two 90° hybrids and propagate to eight photodetectors **811**, which subsequently converts the received light into electrical signals.

In photonic integration, photodetectors **811** may be formed of silicon-germanium alloy, which is infrared sensitive, and may be fully integrated on a SOI substrate. Modulators **806** and **807** and ICR **889**, which may be formed of different materials such as InP or silica planar lightwave circuit (PLC), may also be integrated using hybrid integration along with optical circulators (e.g., optical circulators **801** and **802**) by adding mode size converter designs on the waveguide coupling interfaces.

Integrated ECL

Another critical component in an OFFT is an ECL, such as parent laser **150** in FIGS. **1**A and **1**B, which is as a high-quality narrow-linewidth light source. Typically, a commercial ECL consists of multiple discrete components such as etalon filters, InP gain chips, end mirrors, optical isolators, and microlenses. Fabrication and packaging cost for such discrete devices may be very high. However, integrated ECL design disclosed herein improves upon the existing ECL by fabricating parts of chip-scale ECL on a hybrid silicon photonics platform that may be used in an OFFT.

FIG. **9** shows a schematic of an integrated ECL **900**. Integrated ECL **900** includes a plurality of silicon waveguides patterned on a surface of a SOI substrate, shown in thick dark lines in FIG. **9**. The plurality of silicon waveguides includes loop-mirrors **912** and **928**, and an output optical coupler **950**. Integrated ECL also includes an isolator **980**, an optical phase adjuster **984**, an integrated optical wavelength tuner **986**, and a gain media **982**. Gain media **982** includes an integrated III-V chip on the surface of the SOI substrate. Integrated optical wavelength tuner **986** includes silicon ring resonators **922** and **924**, an optical bus **926**, metal heaters **935**, and RTDs **934**. Silicon ring resonators **922** and **924** are examples of silicon ring resonator **236**. Metal heaters **935** are examples of metal strip **235**, and RTDs **934** are examples of metal strip **234**. Integrated optical wavelength tuner **986** utilizes a ring-bus-ring design, which provides stable lasing, reliable wavelength tuning, and high side-mode-suppression ratio. Wide wavelength tuning may be achieved by utilizing the Vernier effect in the silicon ring resonators. Similar to optical circulator **200** in FIGS. **2**A and **2**B, metal heaters **935** and RTDs **934** may be formed of Ti/Pt thin film and are patterned above silicon ring resonators **922** and **924** for thermal tuning and temperature sensing. Integrated optical wavelength tuner **986** may also include waveguide loop-mirror **928**, which functions as a back-reflector mirror for integrated ECL **900**.

In fabricating integrated ECL **900**, most of the parts of the chip-scale ECL, including loop-mirrors **912** and **928**, tapered patterns **914**, phase adjuster **984**, and integrated optical wavelength tuner **986** may be fabricated on a SOI substrate using standard CMOS processes. Passive silicon waveguides **908** are first patterned on the SOI substrate. The fabrication of active region in gain media **982** then follows through the heterogenous integration of III-V material on silicon. The III-V chip, typically of InGaAsP/InP multi-quantum well (MQW) structures, may be bonded on top of the SOI substrate using direct wafer bonding, or using organic material such as DVS-benzo cyclobutene (BCB). The InP MQW chip is then thinned down and etched by chemical selective etching and reactive ion etching (RIE). For low loss coupling between the active region in gain media **982** and passive silicon waveguides **908**, three-dimensional tapered patterns, such as tapered pattern **914** may be utilized in both vertical and lateral directions. Tapered pattern **914** shows a coupling where both InP active region **909** and silicon nano-wire waveguide **908**(**6**) are tapered for coupling. Eventually metal electrodes **991** and **993** are patterned on both P and N doped region of gain media **982**. For dual polarization OFFT design, a 3-dB coupler made of silicon waveguide may be integrated at output optical coupler **950**. When integrated ECL **900** is directly coupled to an integrated optical circulator (e.g., optical circulator **202** in FIG. **2**C), no coupling structures or spot size converter (SSC) design is required at output optical coupler **950**. However, for other application scenarios, additional SSCs may be required for fiber coupling.

Integrated Optical Phase Modulator

A phase modulator, such as phase modulators **168** in FIGS. **1**A and **1**B, is another critical part of the OFFT system. The OFFT system requires the phase modulator to have (i) low drive voltage, (ii) large bandwidth, (iii) low insertion loss, (iv) high extinction ratio, and (v) compatibility with large-scale manufacturing. To meet the requirements, materials such as Lithium Niobate (LN) may be used, which exhibit a linear change of its refractive index in response to an applied electric field. However, phase modulators based on LN tend to be large and are difficult to integrate. An alternative method is to utilize an LN thin film bonded on a SOI substrate and create LN waveguides by dry etching to achieve optical confinement, which results in improved electro-optic efficiencies and performance. Embodiments disclosed hereinbelow illustrate phase modulators that meet the requirements listed above and may be included in an OFFT, such as OFFTs **100** and **101** in FIGS. **1**A and **1**B, by photonic integration.

FIGS. **10**A and **10**B illustrate one phase modulator **1200**, with an integrated LN layer. Phase modulator **1200** may for example be used as phase modulators **168** of FIGS. **1**A and **1**B. FIG. **10**A shows a top view of phase modulator **1200**, which is parallel to x-y plane and denotes a section line **1298**, which indicates the location of the orthogonal cross-sectional side view illustrated in FIG. **10**B, which is parallel to x-z plane. FIGS. **10**A and **10**B are best viewed together in the following description. Phase modulator **1200** includes a LN thin film **1220** bonded on a surface of a SOI substrate **1234**, a pair of metal electrodes **1212** and **1214** deposited on a top surface of LN thin film **1220**. LN thin film **1220** has a protrusion **1221** between the pair of metal electrodes **1212** and **1214**. Protrusion **1221** has a height that does not exceed a height of the pair of metal electrodes **1212** and **1214**. Phase modulator **1200** also includes an insulating layer **1236** that covers the LN thin film **1220** and an area between the protrusion **1221** and the pair of metal electrodes **1212** and **1214**, such that the pair of metal electrodes **1212** and **1214** are accessible for an external electrical contact.

SOI substrate **1234** may include a SiO_2 layer **1232** on a Si layer **1231**. Protrusion **1221** may be formed by first patterning through standard photolithography, followed by Art-based ion-milling process to etch halfway through the thickness of LN thin film **1220**. Metal electrodes **1212** and **1214**, which may be formed of Ti/Au or Al, are then produced through a metal deposition/evaporation and liftoff process. Insulating layer **1236**, which may be a SiO_2 layer, is deposited by plasma-enhanced chemical vapor deposition (PECVD) and followed by etching of contact windows **1213** and **1215**. With the high index contrast of 0.7 between protrusion **1221** and insulating layer **1236**, phase modulator **1200** may achieve low-driving voltage, high bandwidth, and a relatively small footprint in millimeter scale. Advantageously, when integrated with other devices, the coupling between LN waveguide, such as protrusion **1221**, and silicon waveguide used in a silicon photonics-based devices (e.g., optical circulator **200** of FIGS. **2**A and **2**B) may result in a low loss coupling by adding a SSC at the coupling.

FIGS. **11**A and **11**B illustrate another phase modulator **1300**, based on silicon-organic-hybrid technology. FIG. **11**A shows a top view of phase modulator **1300**, which is parallel to x-y plane and denotes a section line **1398**, which indicates the location of the orthogonal cross-sectional side view illustrated in FIG. **11**B, which is parallel to x-z plane. FIGS. **11**A and **11**B are best viewed together in the following description. Phase modulator **1300** may for example be used as phase modulators **168** of FIGS. **1**A and **1**B. Phase modulator **1300** includes two n-doped silicon optical rails **1337** and **1338**, an electro-optic polymer layer **1336**, two n-doped silicon slabs **1331** and **1332**, a SiO_2 layer **1334**, and a pair of metal electrodes **1312** and **1314**. N-doped silicon optical rails **1337** and **1338** are bonded on a surface of a SOI substrate **1234** and includes two separate substantially parallel waveguides. SOI substrate **1234** may be a SiO_2 layer **1232** on a Si layer **1231**. Electro-optic polymer layer **1336** covers a top surface of and in-between the two n-doped silicon optical rails **1337** and **1338**. N-doped silicon slabs **1331** and **1332** are patterned on the surface of SOI substrate **1234** and are electrically coupled to n-doped silicon optical rails **1337** and **1338**, respectively. Metal electrodes **1312** and **1314** are electrically coupled to n-doped silicon slabs **1331** and **1332**, respectively. N-doped silicon optical rails **1337** and **1338** are waveguides separated by a slot **1339**. In embodiments, the width of slot **1339** is in the range of 100 nm to 200 nm.

Electro-optic polymer layer **1336** may be either spin-coated or dispensed. In embodiments, electro-optic polymer layer **1336** is formed from one of organic electro-optic materials DLD-164, SEO100, and SE0250. The refractive index of electro-optic polymer layer **1336** is directly modulated by an electric field applied between the two n-doped silicon optical rails **1337** and **1338**. Modulating electric field is generated by applying a drive voltage to metal electrodes **1312** and **1314**, which are connected to silicon optical rails **1337** and **1338** via n-doped silicon slabs **1331** and **1332**. Phase modulator **1300** uses silicon-organic-hybrid (SOH) technology to achieve low driving voltage and high bandwidth. By combining the conventional SOI waveguides with highly efficient organic electro-optic material, SOH Mach Zehnder Modulator (MZM) with a π-voltage of 1.6 V may generate a channel with 16 quadrature amplitude modulations (QAM) at 100 GHz. Advantageously, phase modulator **1300** may be fabricated on a standard SOI platform and may therefore share the same substrate with other silicon photonics-based devices (e.g., optical circulator **200** of FIGS. **2**A and **2**B). With the change in optical confinement in the slot waveguide, a coupler such as SSC may be required when coupling to an integrated optical circulator to ensure low loss optical coupling.

FIGS. **12**A and **12**B illustrate another phase modulator **1400**, with an integrated InP layer. FIG. **12**A shows a top view of phase modulator **1400**, which is parallel to x-y plane and denotes a section line **1498**, which indicates the location of the orthogonal cross-sectional side view illustrated in FIG. **12**B, which is parallel to x-z plane. FIGS. **12**A and **12**B are best viewed together in the following description. Phase modulator **1400** also may for example be used as phase modulators **168** of FIGS. **1**A and **1**B. Phase modulator **1400** includes an n-doped InP layer **1448**, a waveguide **1444**, a p-doped InP layer **1446**, and a pair of metal electrodes **1412** and **1414**. N-doped InP layer **1448** is bonded on a surface of a SOI substrate **1442** and has a protrusion rail **1449**. Waveguide **1444** is an undoped MQW layer is deposited on protrusion rail **1449**. P-doped InP layer **1446** is deposited on waveguide **1444**. Pair of metal electrodes **1412** and **1414** has one metal electrode **1412** electrically coupled to p-doped InP layer **1446**, and another metal electrode **1414** electrically coupled to the n-doped InP layer **1448**.

Phase modulator **1400** is based on another organic electro-optic material, InP, for the high modulation bandwidth, low drive voltage and compact size. The material InP MZM may exhibit a 3-dB electro-optic bandwidth of over 67 GHz, a it-voltage of 1.5V, and an on-chip loss of 2 dB. SOI substrate **1442** may be a Si—InP layer. The layering of p-doped InP layer **1446**, the undoped MQW layer as waveguide **1444**, and protrusion rail **1449** in n-doped InP layer **1448** forms a p-i-n configuration. Waveguide **1444**, which is used as a waveguide, may be formed of InGaAlAs and InAlAs.

In an alternate example of phase modulator **1400**, the modulation bandwidth may be improved further by replacing p-doped InP layer **1446** with an n-doped InP layer. FIG. **13** illustrates an alternate phase modulator **1500** to phase modulator **1400** of FIGS. **12**A and **12**B. Phase modulator **1500** is based on phase modulator **1400** and may for example be used as phase modulators **168** of FIGS. **1**A and **1**B. Phase modulator **1500** includes n-doped InP layer **1448**, a p-doped InP layer **1546**, waveguide **1444**, an n-doped InP cladding layer **1550**, and pair of metal electrodes **1412** and **1414**. N-doped indium phosphide (InP) layer **1448** is bonded on a surface of SOI substrate **1442** and has a protrusion rail **1449**. P-doped InP layer **1546** is deposited on protrusion rail

1449. Waveguide **1444** is an undoped MQW layer deposited on p-doped InP layer **1546**. N-doped InP cladding layer **1550** is deposited on the waveguide **1444**. Pair of metal electrodes **1412** and **1414** has one metal electrode **1412** electrically coupled to n-doped InP cladding layer **1550**, and another metal electrode **1414** electrically coupled to n-doped InP layer **1448**. The layering arrangement for phase modulator **1500** follows an n-i-p-n heterostructure, where p-doped InP layer **1546** acts as a current flow blocker to enable voltage applying across waveguide **1444**. Similar to previous examples of phase modulators, low loss coupling to an integrated optical circulator (e.g., optical circulator **200** of FIGS. **2**A and **2**B) may be achieved by using a coupler such as SSC at the coupling.

Changes may be made in the above methods and systems without departing from the scope hereof. It should thus be noted that the matter contained in the above description or shown in the accompanying drawings should be interpreted as illustrative and not in a limiting sense. The following claims are intended to cover all generic and specific features described herein, as well as all statements of the scope of the present method and system, which, as a matter of language, might be said to fall therebetween.

What is claimed is:

1. An optical full-field transmitter (OFFT), comprising:

a plurality of optical circulators fabricated on a silicon-on-insulator (SOI) substrate, each of the optical circulators having:

(a) a first port that optically couples to a high-quality optical source;

(b) a second port that optically couples to a child laser configured to receive amplitude modulation data; and

(c) a third port that optically couples to a phase modulator (i) configured to receive a phase modulation data and (ii) including an output port that outputs amplitude and phase modulated light; and

a polarization beam combiner that receives the amplitude and phase modulated light from each of the optical circulators and that outputs combined amplitude and phase modulated light.

2. The OFFT of claim **1**, wherein the child laser comprises a Fabry-Perot laser diode integrated on the SOI substrate.

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

a plurality of parent lasers integrated on the SOI substrate, each of the parent lasers generating the high-quality optical source, optically coupled to one first port of one optical circulator.

4. The OFFT of claim **1**, further comprising:

a parent laser integrated on the SOI substrate for generating the high-quality optical source; and

an optical power splitter having an input port that receives an output light from the parent laser and a plurality of output ports, each of the output ports optically coupling to one first port of one optical circulator.

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