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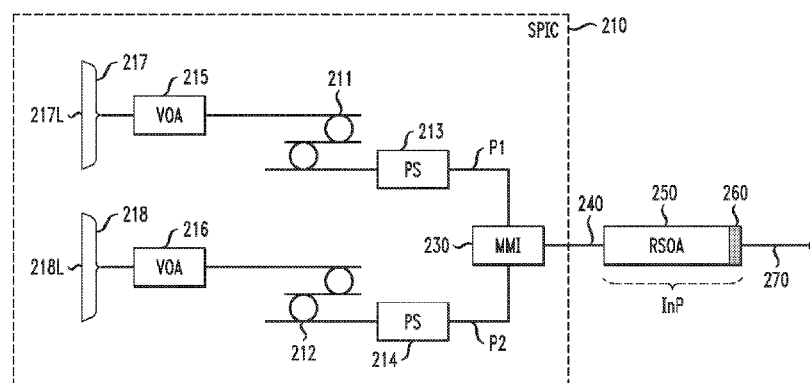
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FIG. 2

200



(57) Abstract: An apparatus is disclosed comprising a silicon photonic integrated circuit optically coupled to a reflective semiconductor optical amplifier and having a first ring resonator pair coupled to a first phase shifter and a first mirror optically forming a first optical path and a second ring resonator pair coupled to a second phase shifter and a second mirror forming a second optical path. The first optical path and the second optical path are each optically coupled to the reflective semiconductor optical amplifier thereby forming a first laser cavity and a second laser cavity respectively. A tunable laser and a transmitter are also disclosed.

Silicon-Photonic Tunable Laser

This patent application claims the benefit of U.S. provisional patent application no. 62/287146, filed on January 26, 2016 the content of which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

[0001] The present disclosure is directed, in general, to silicon-photonic lasers and devices using such lasers.

BACKGROUND

[0002] This section introduces aspects that may help facilitate a better understanding of the present disclosure. Accordingly, the statements of this section are to be read in this light and are not to be understood as admissions about what is in the prior art or what is not in the prior art.

[0003] The data traffic in metropolitan-area networks has been witnessing substantial increase due, in part, to the use of content delivery networks as well as the interconnections between large data centers that may be in separate geographical locations. Such evolution is likely to create bursty and distributed traffic profiles which may in turn require connections with flexible bandwidth-on-demand. To meet these requirements, some solutions are based on the use of elastic optical network as well as optical packet switching for the next-generation of ultrafast, energy- and resource-efficient data transport systems with fast reconfigurable connections. However, this network segment is typically sensitive to cost and thus may need to rely on the development of low-cost photonic integrated circuits such as a fast-tunable coherent transponder and a fast optical wavelength blocker to enable reuse of the fiber traffic capacity.

SUMMARY

[0004] Some embodiments feature an apparatus comprising:

- a silicon photonic integrated circuit having a first ring resonator pair, a first phase shifter and a first mirror optically coupled to each other to form a first optical path; and a second ring resonator pair, a second phase shifter and a second mirror optically coupled to each other to form a second optical path; and
- a reflective semiconductor optical amplifier optically coupled to the silicon photonic integrated circuit and having a third mirror;

wherein the first optical path is configured to be selectively optically coupled to the reflective semiconductor optical amplifier to thereby form a first laser cavity, and the second optical path is configured to be selectively optically coupled to the reflective semiconductor optical amplifier to thereby form a second laser cavity.

[0005] According to some specific embodiments, said selective optical coupling of each one of the first optical path and the second optical path with the reflective semiconductor optical amplifier is made by using a respective variable optical attenuator provided in each one of the respective first optical path and the second optical path.

[0006] According to some specific embodiments, said selective optical coupling of each one of the first optical path and the second optical path with the reflective semiconductor optical amplifier is made by using an Nx1 optical coupler provided between each one of the first optical path and the second optical path and the reflective semiconductor optical amplifier and a respective optical switch provided in each one of the respective first optical path and the second optical path.

[0007] According to some specific embodiments, said selective optical coupling of each one of the first optical path and the second optical path with the reflective semiconductor optical amplifier is made by using an optical switch provided between each one of the first optical path and the second optical path and the reflective semiconductor optical amplifier and configured to switch from a first switching state where the first optical path is formed to a second switching state where the second optical path is formed.

[0008] According to some specific embodiments, said selective optical coupling of each one of the first optical path and the second optical path with the reflective semiconductor optical amplifier is made by using an Nx1 optical coupler provided between each one of the first optical path and the second optical path and the reflective semiconductor optical amplifier and a respective optical switch provided in each one of the respective first optical path and the second optical path.

[0009] According to some specific embodiments, said first mirror and second mirror are partially reflective and said third mirror is fully reflective.

[0010] According to some specific embodiments, said first mirror and second mirror are fully reflective and said third mirror is partially reflective.

[0011] According to some specific embodiments, the ring resonators of the first ring resonator pair have respective free spectral ranges which are different from each other.

[0012] According to some specific embodiments, the ring resonators of the second ring resonator pair have respective free spectral ranges which are different from each other.

[0013] According to some specific embodiments, the apparatus is configured to selectively lase using the first laser cavity or the second laser cavity.

[0014] According to some specific embodiments, the first ring resonator pair is configured to produce a Vernier effect based on the difference between respective free spectral ranges of the

rings in the first ring resonator pair, said Vernier effect capable of enabling tunability of a wavelength of a first optical signal generated by the apparatus.

[0015] According to some specific embodiments, the second ring resonator pair is configured to produce a Vernier effect based on the difference between respective free spectral ranges of the rings in the second ring resonator pair, said Vernier effect capable of enabling tunability of a wavelength of a second optical signal generated by the apparatus.

[0016] According to some specific embodiments, the silicon photonic integrated circuit and the reflective semiconductor optical amplifier are coupled to each other by butt-coupling, vertical grating coupling, molecular bonding or using coupling lenses.

[0017] According to some specific embodiments, apparatus is configured to switch off the first variable optical attenuator and to switch on the second variable optical attenuator and to pre-tune the ring resonators of the second ring resonator pair to a target wavelength.

[0018] According to some specific embodiments, the apparatus is configured to emit a target wavelength by switching off the second variable optical attenuator and switching on the first variable optical attenuator.

[0019] According to some specific embodiments, the first mirror, the second mirror or the third mirror are a Sagnac loop mirror or a Bragg grating mirror.

[0020] According to some specific embodiments, each one of the phase shifter or the second phase shifter is configured to control a position of a mode of an optical signal within the respective first or the second cavity.

[0021] Some embodiments feature a tunable laser comprising:

- a silicon photonic integrated circuit having a first ring resonator pair, a first phase shifter and a first mirror optically coupled to each other to form a first optical path; and a second ring

resonator pair, a second phase shifter and a second mirror optically coupled to each other to form a second optical path; and

- a reflective semiconductor optical amplifier optically coupled to the silicon photonic integrated circuit and having a third mirror;

wherein the first optical path is configured to be selectively optically coupled to the reflective semiconductor optical amplifier to thereby form a first laser cavity, and the second optical path is configured to be selectively optically coupled to the reflective semiconductor optical amplifier to thereby form a second laser cavity.

[0022] Some embodiments feature an optical transmitter comprising:

- a silicon photonic integrated circuit having a first ring resonator pair, a first phase shifter and a first mirror optically coupled to each other to form a first optical path; and a second ring resonator pair, a second phase shifter and a second mirror optically coupled to each other to form a second optical path;
- a reflective semiconductor optical amplifier optically coupled to the silicon photonic integrated circuit and having a third mirror; and
- a first optical modulator and a second optical modulator;

wherein the first optical path is configured to be selectively optically coupled to the reflective semiconductor optical amplifier to thereby form a first laser cavity, and the second optical path is configured to be selectively optically coupled to the reflective semiconductor optical amplifier to thereby form a second laser cavity; and

wherein the first optical modulator is provided at an output of the first laser cavity and is configured to modulate a laser signal generated by the first laser cavity and the second optical modulator is

provided at an output of the second laser cavity and is configured to modulate a laser signal generated by the second laser cavity.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] The embodiments of the disclosure are best understood from the following detailed description, when read with the accompanying figures. Various features may not be drawn to scale and may be arbitrarily increased or reduced in size for clarity of discussion. Reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0024] FIG. 1 is a schematic representation of an example of a wavelength selective laser comprising an array waveguide grating according to known solutions.

[0025] FIG. 2 is a schematic representation of an example of a wavelength selective apparatus, e.g. a laser, according to some embodiments.

[0026] FIG. 3 is a schematic representation of an example of a wavelength selective apparatus, e.g. a laser, according to some embodiments.

[0027] FIG. 4 is a schematic representation of an example of a wavelength selective apparatus, e.g. a laser, according to some embodiments.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0028] As mentioned above, it is desirable to provide a solution toward enabling energy and resource efficient connections for the next-generation of ultrafast data transport systems. It is also desirable that such solutions are cost effective and provide fast tunability as well as capability of being manufactured by integration. Silicon photonics is considered to be a promising option to provide large-scale integration of photonic components with high-volume manufacturing

compatibility. Recently, fully integrated coherent receivers and fast optical wavelength blockers using silicon photonic technology based on an integration platform have been proposed. However, the development of fast-wavelength tunable lasers, for example as a local oscillator compatible with the aforementioned material, is still a challenge.

[0029] It is therefore desirable to provide a fast-wavelength-tunable hybrid silicon-based laser apparatus.

[0030] One solution toward the above goal may include the use of arrayed waveguide gratings (AWG) in the laser structure. A laser manufactured based on AWG (herein also referred to as AWG-laser) may be used as a fast wavelength tunable laser by switching ON and OFF each of the channels propagating through the AWG. The AWG-laser comprises an AWG filter incorporated in the laser cavity which is made using an InP platform.

[0031] FIG. 1 represents a schematic view of an AWG-laser 100 according to a known approach. The AWG laser 100 comprises an AWG element which includes an array of waveguides 110, a first free space region 120 coupled to a respective end of each one of the waveguides of the array 110 and a second free space region 130 coupled to another respective end of each one of the waveguides of the array 110. An input waveguide 140 is optically coupled to an input port 121 of the first free space region 120 and a plurality of output waveguides 150 are each coupled to respective output ports 132 of the second free space region 130. This configuration of the AWG is well-known in the related art.

[0032] The AWG-laser 100 further includes a first semiconductor optical amplifier (SOA) 160 optically coupled to the input waveguide 140 and an array of second semiconductor optical amplifiers (SOAs), collectively shown by reference numeral 170, such that each SOA from the array

of SOAs 170 is optically coupled to an end of a respective one of the output waveguides from the plurality of the output waveguides 150.

[0033] The AWG-laser 100 further includes an array of mirrors, collectively shown by reference numeral 180. Each mirror from the array of mirrors 180 is coupled, at a respective facet thereof, to a respective output 171 of an SOA from the array of SOAs 170. The AWG-laser 100 further includes a partially reflective mirror 190.

[0034] In operation, an optical signal is injected into the input waveguide 140 before being input into the first free space region 120 through the input port 121.

[0035] The optical signal further propagates through the first free space region 120 and enters, through respective output ports 122, into the plurality of waveguides 110. As the waveguides in the plurality of waveguides 110 have different lengths, different amounts of phase shifts are introduced on each portion of the optical signal as it propagates therethrough. The portion of the optical signal in each waveguide of the plurality of waveguides 110 is then input into the second free space region 130, through input ports 131 thereof. The propagation of the various light-beams through the second free space region 130 causes interferences between them at the output ports 132 thereof. As a consequence, each output waveguide from the array of the output waveguide 150 receives an optical signal of a specific wavelength.

[0036] The optical signals in each respective output waveguide from the array of the output waveguides 150 is then input into a respective SOA from the array of SOAs 170, impinges on a respective facet of a mirror from the array of mirrors 180 and is subsequently reflected back into the same SOA from the array of SOAs 170 from which it received the optical signal.

[0037] Upon reflection from the facets 171 each reflected optical signal propagates in the opposite direction from the respective SOA of the array of SOAs 170 to the first SOA 160 traversing

the output waveguides 150, the second free space region 130, the array of waveguides 110, the first free space region 120 (where it is multiplexed), the input waveguide 140 and the first SOA 160.

[0038] As shown in FIG.1, the first SOA is optically coupled to a facet 191 of the partially reflective mirror 190. Upon impinging on the facet 191 of the partially reflective mirror 190, the multiplexed optical signal is reflected back in the opposite direction where it undergoes the same process as discussed above related to the propagation of the optical signal from the first SOA 160 to the array of SOAs 170.

[0039] It is to be noted that in each direction of propagation the optical signal is amplified, in multiplexed form as it traverse the first SOA, and is also amplified, in demultiplexed form as each one of the demultiplexed portions of the optical signal traverses through each one of the respective SOAs from the array of SOAs 170.

[0040] The combined arrangement of the AWG, the first SOA, the array of SOAs, the partially reflective mirror and array of mirrors, as described above constitutes a laser cavity which can amplify light at each back and forth propagation until the optical signal reaches the lasing threshold and the AWG-laser 100 starts to lase through output fiber F.

[0041] In order to provide tunability in the AWG-laser 100, each SOA from the array of SOAs 170 is turned ON in order to emit one wavelength and is turned OFF in order to inhibit the emission of the corresponding wavelength.

[0042] The AWG-laser of FIG. 1 is therefore capable of providing a multi-frequency laser as it is capable of emitting several wavelengths at the same time. However an integration of this laser structure in an InP platform should typically exhibit a large footprint (18 cm x 9 mm). Such large size introduces certain drawbacks, including but not limited to high cost (as InP material is typically

more expensive than silicon material) and the modal selectivity as long Fabry-Perot cavities typically induce closer longitudinal modes.

[0043] Other known solutions toward providing an integrated fast-tunable laser include, hybrid III-V/Si multiwavelength lasers based on wafer bonding techniques or ring-based lasers. The concept in such solutions is similar to the one presented above with reference to FIG. 1 with the exception that the gain sections of the lasers are in III-V material and the AWG, the mirrors and the couplers are in silicon.

[0044] However, in all the above approaches, one SOA per channel is required for proper operation of the device. This requirement imposes an important drawback as it may hinder the reliability of the device and limit the number of channels due to the current limited yield in SOA fabrication. Furthermore, compatibility with CMOS manufacturing technology is reduced.

[0045] Manufacturing tunable lasers by hybridization through butt coupling between an SOA and a silicon photonic integrated circuit (PIC) has proven to be a successful approach with state-of-the-art performances of hybrid tunable lasers. This fabrication technique commonly involves the alignment of two devices, in this case at least one SOA with a silicon PIC. However, in case where a plurality of SOAs need to be aligned, such as the array of SOAs in the examples provided above, the alignment task may become quite complex.

[0046] Still another drawback associated with the above configurations is that the AWG-lasers are typically not continuously tunable because typically each lasing wavelength is defined by the transfer function of the AWG and such transfer function includes discrete channels thus the lasing wavelength is generated on a discrete grid.

[0047] In contrast hybrid ring-based tunable lasers have typically shown capability for continuous tunability; however rings used in such structures typically need to be thermally tuned which may lead to slower switching time (of the order of tens of microseconds).

[0048] In order to overcome the above drawbacks of the known solutions, a wavelength-tunable hybrid silicon-based apparatus, e.g. a laser, is herein proposed, based on the use of a plurality of parallel and tunable Vernier ring resonator laser cavities.

[0049] FIG. 2 is a schematic representation of an example of a tunable apparatus, e.g. a laser, according to some embodiments. In this example, apparatus 200 is based on a dual structure comprising two laser cavities as will be described below; however, the disclosure is not so limited and other number of cavities may likewise be provided.

[0050] On a silicon photonic integrated circuit (SPIC) platform 210, a first optical path P1 may comprise a first pair of ring resonators 211, a first phase shifter 213, a first variable optical attenuator (VOA) 215 and a first 100% reflection mirror 217. These elements are optically coupled to each other on the first optical path P1 using a first waveguide 219 and the order of their location in the optical path may be different than what is shown in FIG. 2.

[0051] The first 100% reflection mirror 217 is located at an end of the first optical path P1, as shown in FIG. 2, so as to provide reflection of the optical signal back into the first optical path P1. The first 100% reflection mirror 217 may be for example a Sagnac loop mirror comprising a 1x2 MMI (not specifically shown in FIG. 2) and a waveguide loop 217L, as known in the related art.

[0052] Likewise, on the same SPIC platform 210, a second optical path P2 may comprise a second pair of ring resonators 212, a second phase shifter 214, a second variable optical attenuator (VOA) 216 and a second 100% reflection mirror 218. These elements are optically coupled to each other on second optical path P2 using a second waveguide 220. The second 100% reflection mirror

218 is located at an end of the second optical path P2, as shown in FIG. 1, so as to provide reflection of the optical signal back into the second optical path P2. The second 100% reflection mirror 218 may also be a Sagnac loop mirror 218 comprising a 1x2 MMI (not specifically shown in FIG. 1) and a waveguide loop 218L.

[0053] Optical path P1 and optical path P2 are then optically coupled to each other by a combiner 230, which may be for example a 2x1 MMI (for only two optical paths and Nx1 for N optical paths).

[0054] The two optical paths may comprise substantially similar, or even identical, elements (with the exception of the first and the second ring resonator pairs 211 and 212 having different resonant frequencies). Therefore, the following description will only refer to optical path P1, noting that in this example the optical path P2 preferably has substantially similar or identical characteristics (with the exception mentioned above). Examples of paths with different characteristics are provided with reference to FIGS. 3-4. A combination of such different paths may also be possible.

[0055] Referring to optical path P1, the ring resonator pair 211 comprises two ring resonators having slightly different free spectral ranges. For example, the free spectral range (FSR) of one ring resonator from the first pair of ring resonators may be 400 GHz and the FSR of the other one of the first pair may be 440 GHz.

[0056] The difference between the respective FSRs of the ring resonators of the first pair 211 causes the so-called Vernier effect when an optical signal is propagating through the ring resonator pair 211. The Vernier effect is a well-known phenomenon. Briefly, the Vernier effect is produced due to the difference in the FSRs of the ring resonators of the first pair 211 which in turn causes the transmittance spectra of the two ring resonators in the pair 211 overlap with each other,

therefore enabling a wider combined spectrum with an improved tunability range as compared to the tunability ranges available in individual ring resonators.

[0057] The apparatus 200 further comprises a reflective semiconductor optical amplifier (RSOA) 250 comprising a partially reflective mirror 260. The RSOA 250 may be of any known type and may be provided on a III-V material, preferably an InP, platform. The RSOA is aligned to the SPIC platform 210 by an optical path 240. Such alignment may be made using known techniques such as butt-coupling, using lenses, vertical grating couplers, evanescent coupling (using molecular bonding) and other techniques as known by those skilled in the related art. Preferably a buried-ridge structure RSOA with a passive waveguide may be used as it has certain fabrication advantages and provides efficient current injection and good thermal dissipation.

[0058] The operation of the apparatus, with reference to the first optical path P1, is now described. Assuming that an optical signal is injected into the optical path P1 in a direction, e.g. from the first 100% reflection mirror 217 to the partially reflective mirror 260 and further assuming that the first VOA 215 is turned OFF (i.e. no or negligible attenuation is present), the optical signal would propagate through the first ring resonator pair 211 thereby producing a Vernier effect. Next the optical signal output from the first ring resonator pair 211 is input into the first phase shifter 213. The phase shifter is used to control the position of the Fabry-Perot mode of the cavity during lasing. Then the FP mode could aligned with the ring resonator transmission in a very accurate way. The phase shifted optical signal is then input, through optical path 240, into the RSOA 250 where it undergoes a first amplification. The amplified optical signal further propagates within the RSOA 250, impinges on the partially reflective mirror 260 and is reflected back in the opposite direction.

[0059] In the opposite direction, namely from the partially reflective mirror 260 towards the first 100% reflection mirror 217, the reflected optical signal undergoes a further amplification within

the RSOA 250 and from the latter is directed back into the first phase shifter 213. The optical signal is further input into the first ring resonator pair 211 and subsequently into the first VOA 215 which is turned off and therefore introduces no or negligible attenuation on the optical signal. The optical signal is then input into the first 100% reflection mirror 217. In the example of FIG. 2 the latter mirror is illustrated as a Sagnac loop mirror where the light is split by a 1x2 MMI (not specifically shown) into the two branches, each portion of the split light travelling in one of the two branches in directions opposite to one another. The two branches form a closed loop 217L as shown in FIG. 2.

[0060] After travelling through the loop 217L of the 100% reflection mirror 217, the two portions of the split light combine with each other and are output from the 100% reflection mirror and input back into the first optical path P1 through the same (although in this direction 2x1) MMI. As the optical signal is input back into the first optical path P1 in the direction toward the partially reflective mirror 260, the same processes as already described above, in the forward and reverse directions., will occur. Note that in each direction of propagation, the optical signal is further amplified as it passes through the RSOA 250 multiple times in forward and reverse directions. As a result of such amplification, the light intensity increases in every propagation cycle and when such intensity increases above a specific threshold, lasing occurs.

[0061] As can be appreciated from the above, the reflective semiconductor optical amplifier 250, the first phase shifter 213, the first ring resonator pair 211, the first variable optical attenuator 215 and the first 100% reflection mirror 217, optically coupled to each other through the optical paths P1 and 240 form a first laser cavity.

[0062] As mentioned above, the structure and the principles of operation of the second optical path P2 is similar or identical to that of the first optical path P1. Therefore, based on similar description as that provided with reference to the first optical path P1, it may be concluded that the

reflective semiconductor optical amplifier 250, the second phase shifter 214, the second ring resonator pair 212, the second variable optical attenuator 216 and the second 100% reflection mirror 218, optically coupled to each other through optical paths P2 and 240 form a second laser cavity.

[0063] Each of the ring resonator pairs 211 and 212 may be designed such that each pair's respective resonant frequency is different from the other ring resonator pair. In this manner, a first wavelength may propagate in the first optical path P1 and a second wavelength, different from the first wavelength, may propagate in the second optical path P2.

[0064] With the above arrangement, the apparatus 200, as described herein, is capable of providing single mode operation with wavelength tunability by switching the VOAs ON and OFF to decouple or to couple the optical path, to which a particular VOA corresponds, from or to the RSOA. In particular, one VOA, for example the first VOA 215, may be turned OFF, thereby allowing the passage of an optical signal with a specific wavelength (with no or negligible attenuation). At the same time the other VOA, e.g. the second VOA 216, may be turned ON, thereby substantially blocking the passage of an optical signal (with a different wavelength). By propagating back and forth through the first optical path P1, the optical signal is progressively amplified and once the lasing threshold is reached, it is emitted from the RSOA 250 as a laser beam 270. Furthermore, due to the presence of the Vernier effect in the ring resonator pair 211, said pair generates a spectrum within which the wavelength of the optical signal propagating through such ring resonator pair 211 can be tuned. A similar process, *mutatis mutandis*, maybe applied with respect to optical path 2 in conjunction with the RSOA 250.

[0065] The VOAs 215 and 216 may be of any known type. High-speed p-i-n junction VOAs may be used to enable switching between cavities based on carrier injection. Therefore switching times between the two wavelengths in the range of tens of nanoseconds may be achieved. Such

VOAs may operate upon the injection a control current, resulting in the generation of free carriers that absorb, and thereby, attenuate the light. Such carrier injection process, and thus the switching speed of the VOA is substantially faster than the switching speed of the known solutions, e.g. by thermo-optically exciting the ring resonators. As non-limiting example, a small signal electro-optic bandwidth of VOA up to 300 MHz is believed to be achievable. Such electro-optic bandwidth characterizes the time needed for the device to respond to an electrical excitement.

[0066] The ring resonators may each be operated by thermo-optic effect to obtain tuning of the wavelength of the optical signal. For example, electrically excited metal heaters may be used on the ring resonators to allow thermal tuning of the ring resonator peak wavelengths. As this process maybe slow, i.e. tens of microseconds, the pre-tuning technique as described below may preferably be used to improve speed.

[0067] Assuming that the first VOA 215 is switched OFF and the second VOA 216 is switched ON so that the apparatus 200 emits at a first wavelength propagating through the first optical path P1, the ring resonators of the second pair 212 of the second optical path P2 are pre-tuned to a second desired wavelength during a small (preferably minimum) time duration. When it is desired to emit wavelength from the second optical path P2, the second VOA 216 is turned OFF and the first VOA 215 is turned ON. As the ring resonators of the second pair 212 were already pre-tuned, the laser can switch to the state of emitting the second wavelength without needing additional tuning time for the ring resonators of the second pair 212.

[0068] In the embodiment of FIG. 2, it was assumed that the mirrors 217 and 218 provided respectively on the optical paths P1 and P2 were fully reflective while the mirror 260 comprised in the RSOA 250 was partially reflective. This arrangement would allow lasing from the output 270 of the RSOA 250.

[0069] However, it is also possible to configure the apparatus 200 such that mirror 260 comprised in the RSOA 250 is fully (100%) reflective and the mirrors 217 and 218 provided on the optical paths P1 and P2 are partially reflective. In this arrangement, lasing would selectively occur at respective outputs (not shown) provided at the partially reflective mirrors 217 and 218.

[0070] The use of VOAs corresponds to one example of an embodiment for providing a coupling configuration between the optical paths and the RSOA to form a laser cavity. Further embodiments of such coupling configuration may also be considered in the context of the present disclosure. Some non-limiting examples of such further embodiments are provided below with reference to FIGS. 3-4.

[0071] Referring to FIG. 3, the wavelength selective apparatus 300, e.g. a laser, is illustrated having a silicon photonic integrated circuit (SPIC) platform 310 which comprises N optical paths P1-PN. A first optical path P1 may comprise a first pair of ring resonators 311-1, a first phase shifter 313-1, a first optical switch 315-1 and a first 100% reflection mirror 317-1. These elements are optically coupled to each other on the first optical path P1 using a first waveguide 319-1 and the order of their location in the optical path P1 is not limited to what is shown in FIG. 3.

[0072] The first 100% reflection mirror 317-1 is located at an end of the first optical path P1, as shown in FIG. 3, so as to provide reflection of the optical signal back into the first optical path P1. The first pair of ring resonators 311-1, first 100% reflection mirror 317-1 and the first phase shifter 319-1 may be similar to the ones described with reference to FIG. 2.

[0073] The plurality of optical paths P1-PN may preferably have identical or similar structures and functionalities. Each one of the optical paths P1-Pn is coupled to a respective port 370-1 to 370-N of an Nx1 optical coupler 370. A further port 371 of the Nx1 optical coupler 370 is coupled to the optical path 340.

[0074] The apparatus 300 further comprises a reflective semiconductor optical amplifier (RSOA) 350 comprising a partially reflective mirror 360. The RSOA 350 may be of the type described with reference to FIG. 2. The RSOA 350 is aligned to the SPIC platform 310 by the optical path 340. Such alignment may be made in similar manners as described with reference to FIG. 2.

[0075] The operation of the apparatus 300 is substantially similar to the operation of the apparatus 200 described with reference to the apparatus of FIG. 2, with the difference that instead of using VOAs for closing (forming) or opening (inhibiting) laser cavities, the apparatus 300 of FIG. 3 uses a plurality of optical switches 315-1 to 315-N each located on a respective optical path P1-PN. In this manner, in order to form a laser cavity using optical path P1, the first optical switch 315-1 is closed to thereby form a laser cavity between the optical path P1 and the RSOA 350 and allow propagation of an optical signal back and forth in the laser cavity between the partially reflective mirror 317-1 and the reflective mirror 360 and subsequently lase once the lasing threshold is reached.

[0076] While optical switch 317-1 is closed (i.e. the laser cavity formed), the other optical switches 317-2 to 317-N may be kept open to inhibit formation of laser cavities in their respective optical paths.

[0077] In this manner, a laser capable of generating different optical wavelengths is provided such that lasing in each desired wavelength may be selectively obtained.

[0078] In the embodiment of FIG. 3, it was assumed that the mirrors 317-1 to 317-N provided on the optical paths P1-PN were fully reflective while the mirror 360 comprised in the RSOA 350 was partially reflective. This arrangement would allow lasing from the output 380 of the RSOA 350.

[0079] However, it is also possible to configure the apparatus 300 such that mirror 360 comprised in the RSOA 350 is fully (100%) reflective and the mirrors 317-1 to 317-N provided on

the optical paths P1-PN are partially reflective. In this arrangement, lasing would selectively occur at outputs 390-1 to 390-N of the partially reflective mirrors 317-1 to 317-N.

[0080] Referring to FIG. 4, the wavelength selective apparatus 400, e.g. a laser, is illustrated having a silicon photonic integrated circuit (SPIC) platform 410 which comprises N optical paths P1-PN. A first optical path P1 may comprise a first pair of ring resonators 411-1, a first phase shifter 413-1 and a first 100% reflection mirror 417-1. These elements are optically coupled to each other on the first optical path P1 using a first waveguide 319-1 and the order of their location in the optical path P1 is not limited to what is shown in FIG. 4.

[0081] The first 100% reflection mirror 417-1 is located at an end of the first optical path P1, as shown in FIG. 4, so as to provide reflection of the optical signal back into the first optical path P1. The first pair of ring resonators 411-1, first 100% reflection mirror 417-1 and the first phase shifter 419-1 may be similar to the ones described with reference to FIGS. 2 or 3.

[0082] The plurality of optical paths P1-PN may preferably have identical or similar structures and functionalities.

[0083] The apparatus 400 further comprises an optical switch. Optical switch 470 is configured to switch between optical paths P1-PN by establishing optical connection with respective ports 420-1 to 420-N of the optical paths P1-Pn.

[0084] The apparatus 300 further comprises a reflective semiconductor optical amplifier (RSOA) 450 comprising a partially reflective mirror 460. The RSOA 450 may be of the type described with reference to FIGS. 2 or 3. The RSOA 450 is aligned to the SPIC platform 410 by the optical path 440. Such alignment may be made in similar manners as described with reference to FIGS. 2 or #.

[0085] The operation of the apparatus 400 is substantially similar to the operation of the apparatus 200 described with reference to the apparatus of FIG. 2 (or apparatus 300 described with reference to the apparatus of FIG. 3), with the difference that instead of using VOAs in the embodiment of FIG. 2 or using optical switches on each optical path as in the embodiment of FIG. 3, for closing (forming) or opening (inhibiting) laser cavities, the apparatus 400 of FIG. 4 uses an optical switches 470 located between the plurality of optical paths P1-PN and the RSOA 450. In this manner, in order to form a laser cavity using optical path P1, the optical switch 470 establishes optical connection between the port 420-1 of the optical path P1 and the RSOA 450 to thereby allow propagation of an optical signal back and forth in the laser cavity between the partially reflective mirror 417-1 and the reflective mirror 460 and subsequently lase once the lasing threshold is reached.

[0086] While optical switch 420 is connected to optical path P1 (i.e. forms the laser cavity in path P1), the other optical paths P2-PN may be kept open to inhibit formation of laser cavities in their respective optical paths.

[0087] In this manner, a laser capable of generating different optical wavelengths is provided such that lasing in each desired wavelength may be selectively obtained.

[0088] In the embodiment of FIG. 4, it was assumed that the mirrors 417-1 to 417-N provided on the optical paths P1-PN were fully reflective while the mirror 460 comprised in the RSOA 450 was partially reflective. This arrangement would allow lasing from the output 480 of the RSOA 450.

[0089] However, it is also possible to configure the apparatus 400 such that mirror 460 comprised in the RSOA 450 is fully reflective and the mirrors 417-1 to 417-N provided on the optical paths P1-PN are partially reflective. In this arrangement, lasing would selectively occur at outputs 490-1 to 490-N of the partially reflective mirrors 417-1 to 417-N.

[0090] The optical switches as described with reference to FIGs. 3 and 4 may be for example made using pn junction switches included, for example, in a Mach-Zehnder configuration with the associated advantage of switching speeds of less than 1 ns.

[0091] The solution proposed herein, therefore, allows fast optical switching on a continuous range over wavelength and not on one predetermined grid as is the case with known AWG-lasers.

[0092] Furthermore, in the architecture herein proposed, only one SOA is needed. Therefore, compared to the known AWG-lasers requiring an array of SOAs, the present solution provides substantial advantages in terms of alignment of the SPIC and the InP platforms. Reducing edge reflectivity and using a spot-size converter (mode matching) in such alignment may result in efficient coupling between the RSOA and the InP platforms.

[0093] Another advantage of this design is that the III-V chip and the silicon chip may be fabricated separately and hybridized once the individual chips are prepared. Therefore, current commercial foundry can be used and the compatibility with CMOS technology can be maintained.

[0094] Instead of the III-V material other gain medium material may also be used. One option may be using doped and strained Germanium material as known by those skilled in the related art.

[0095] Based on certain experiments, using the solution proposed herein may provide an improvement by a factor of 1000 in the switching time as compared to the known ring-based solutions. With less than 20 mA of combined injected current in both heaters, operation based on a single mode wavelength having a range over 35 nm, from 1554 nm to 1589 nm (corresponding to the RSOA optical-gain bandwidth with a wavelength peak at 1570 nm) and side-mode suppression ratio (SMSR) of over 30 dB may be achieved.

[0096] Still a further advantage of the apparatus herein proposed is the improvement that can be achieved regarding the size of the overall device. Indeed, the size of the final chip may be about 1.1 mm x 2.8 mm including the probing pads. Reducing the edge reflectivity and using spot-size converter (mode matching) results in efficient coupling between the RSOA and the silicon cavity.

[0097] The apparatus proposed herein may be used in order to build a fast wavelength-tunable transmitter which would further known OOK modulators or advanced modulators in order to generate QPSK signals for instance. Furthermore, the apparatus may be used to build local oscillators with a coherent receiver in order to provide a fast reconfigurable receiver. A laser apparatus as proposed herein may be an important building block in providing an optical packet switched network as it may form part of a transmitter and a receiver.

[0098] Accordingly, a fast-wavelength-tunable hybrid silicon-based laser apparatus is herein proposed based on the use of two parallel widely tunable Vernier ring resonator laser cavities capable of being integrated into a single silicon chip. Fast in-cavity carrier-injection variable optical attenuators enable the wavelength selection between the two cavities.

[0099] In one example where the free spectral range (FSR) of one ring resonator is 400 GHz and the FSR of the other ring resonator is 440 GHz, the proposed solution provides single mode operation and wavelength tunability over more than 35 nm with fast switching time in the tens of nanosecond range. Other ring resonator configurations may also be used to provide other tuning ranges. For example, for FSR pairs of 215/207 GHz the tuning range may be about 44.5 nm and for FSR pairs of 625/560 GHz the tuning range may be about 43.12 nm. In general terms, the tuning range may be obtained based on the following formula:

$$\text{Tuning range (TR)} = \lambda^2/c * (\text{FSR1} * \text{FSR2} / (\text{FSR1} - \text{FSR2}));$$

where λ is the central wavelength and c is the speed of light

[00100] While this disclosure includes references to illustrative embodiments, this specification is not intended to be construed in a limiting sense. Various modifications of the described embodiments, as well as other embodiments within the scope of the disclosure, which are apparent to persons skilled in the art to which the disclosure pertains are deemed to lie within the principle and scope of the disclosure, e.g., as expressed in the following claims.

[00101] Some embodiments may be implemented as circuit-based processes, including possible implementation on a single integrated circuit.

[00102] Unless explicitly stated otherwise, each numerical value and range should be interpreted as being approximate as if the word “about” or “approximately” preceded the value or range.

[00103] It will be further understood that various changes in the details, materials, and arrangements of the parts which have been described and illustrated in order to explain the nature of this disclosure may be made by those skilled in the art without departing from the scope of the disclosure, e.g., as expressed in the following claims.

[00104] Reference herein to “one embodiment” or “an embodiment” means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the disclosure. The appearances of the phrase “in one embodiment” in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments necessarily mutually exclusive of other embodiments. The same applies to the term “implementation.”

[00105] The described embodiments are to be considered in all respects as only illustrative and not restrictive. In particular, the scope of the disclosure is indicated by the appended

claims rather than by the description and figures herein. All changes that fall within the meaning and range of equivalency of the claims are to be embraced within their scope.

[00106] It should be appreciated by those of ordinary skill in the art that any block diagrams herein represent conceptual views of illustrative circuitry embodying the disclosed principles.

WHAT IS CLAIMED IS:

1. An apparatus comprising:
 - a silicon photonic integrated circuit having a first ring resonator pair, a first phase shifter and a first mirror optically coupled to each other to form a first optical path; and a second ring resonator pair, a second phase shifter and a second mirror optically coupled to each other to form a second optical path; and
 - a reflective semiconductor optical amplifier optically coupled to the silicon photonic integrated circuit and having a third mirror;

wherein the first optical path is configured to be selectively optically coupled to the reflective semiconductor optical amplifier to thereby form a first laser cavity, and the second optical path is configured to be selectively optically coupled to the reflective semiconductor optical amplifier to thereby form a second laser cavity.

2. The apparatus of claim 1, wherein said selective optical coupling of each one of the first optical path and the second optical path with the reflective semiconductor optical amplifier is made by using a respective variable optical attenuator provided in each one of the respective first optical path and the second optical path.

3. The apparatus of claim 1, wherein said selective optical coupling of each one of the first optical path and the second optical path with the reflective semiconductor optical amplifier is made by using an Nx1 optical coupler provided between each one of the first optical path and the second optical path and the reflective semiconductor optical amplifier and a respective optical switch provided in each one of the respective first optical path and the second optical path.

4. The apparatus of claim 1, wherein said selective optical coupling of each one of the first optical path and the second optical path with the reflective semiconductor optical amplifier is made by using an optical switch provided between each one of the first optical path and the second optical path and the reflective semiconductor optical amplifier and configured to switch from a first switching state where the first optical path is formed to a second switching state where the second optical path is formed.
5. The apparatus of claim 1, wherein said selective optical coupling of each one of the first optical path and the second optical path with the reflective semiconductor optical amplifier is made by using an Nx1 optical coupler provided between each one of the first optical path and the second optical path and the reflective semiconductor optical amplifier and a respective optical switch provided in each one of the respective first optical path and the second optical path.
6. The apparatus of claim 1, wherein said first mirror and second mirror are partially reflective and said third mirror is fully reflective.
7. The apparatus of claim 1, wherein said first mirror and second mirror are fully reflective and said third mirror is partially reflective.
8. The apparatus of claim 1, wherein the ring resonators of the first ring resonator pair have respective free spectral ranges which are different from each other.
9. The apparatus of claim 1, wherein the ring resonators of the second ring resonator pair have respective free spectral ranges which are different from each other.
10. The apparatus of claim 1, wherein the apparatus is configured to selectively lase using the first laser cavity or the second laser cavity.
11. The apparatus of claim 8, wherein the first ring resonator pair is configured to produce a Vernier effect based on the difference between respective free spectral ranges of the rings in the first

ring resonator pair, said Vernier effect capable of enabling tunability of a wavelength of a first optical signal generated by the apparatus.

12. The apparatus of claim 9, wherein the second ring resonator pair is configured to produce a Vernier effect based on the difference between respective free spectral ranges of the rings in the second ring resonator pair, said Vernier effect capable of enabling tunability of a wavelength of a second optical signal generated by the apparatus.

13. The apparatus of claim 1, wherein the silicon photonic integrated circuit and the reflective semiconductor optical amplifier are coupled to each other by butt-coupling, vertical grating coupling, molecular bonding or using coupling lenses.

14. The apparatus of claim 2, wherein the apparatus is configured to switch off the first variable optical attenuator and to switch on the second variable optical attenuator and to pre-tune the ring resonators of the second ring resonator pair to a target wavelength.

15. The apparatus of claim 2, wherein the apparatus is configured to emit a target wavelength by switching off the second variable optical attenuator and switching on the first variable optical attenuator.

16. The apparatus of claim 1, wherein the first mirror, the second mirror or the third mirror are a Sagnac loop mirror or a Bragg grating mirror.

17. The apparatus of claim 1, wherein each one of the first phase shifter or the second phase shifter is configured to control a position of a mode of an optical signal within the respective first or the second cavity.

18. A tunable laser comprising:

- a silicon photonic integrated circuit having a first ring resonator pair, a first phase shifter and a first mirror optically coupled to each other to form a first optical path; and a second ring

resonator pair, a second phase shifter and a second mirror optically coupled to each other to form a second optical path; and

- a reflective semiconductor optical amplifier optically coupled to the silicon photonic integrated circuit and having a third mirror;

wherein the first optical path is configured to be selectively optically coupled to the reflective semiconductor optical amplifier to thereby form a first laser cavity, and the second optical path is configured to be selectively optically coupled to the reflective semiconductor optical amplifier to thereby form a second laser cavity.

19. An optical transmitter comprising:

- a silicon photonic integrated circuit having a first ring resonator pair, a first phase shifter and a first mirror optically coupled to each other to form a first optical path; and a second ring resonator pair, a second phase shifter and a second mirror optically coupled to each other to form a second optical path;
- a reflective semiconductor optical amplifier optically coupled to the silicon photonic integrated circuit and having a third mirror; and
- a first optical modulator and a second optical modulator;

wherein the first optical path is configured to be selectively optically coupled to the reflective semiconductor optical amplifier to thereby form a first laser cavity, and the second optical path is configured to be selectively optically coupled to the reflective semiconductor optical amplifier to thereby form a second laser cavity; and

wherein the first optical modulator is provided at an output of the first laser cavity and is configured to modulate a laser signal generated by the first laser cavity and the second optical modulator is

provided at an output of the second laser cavity and is configured to modulate a laser signal generated by the second laser cavity.

FIG. 1

100

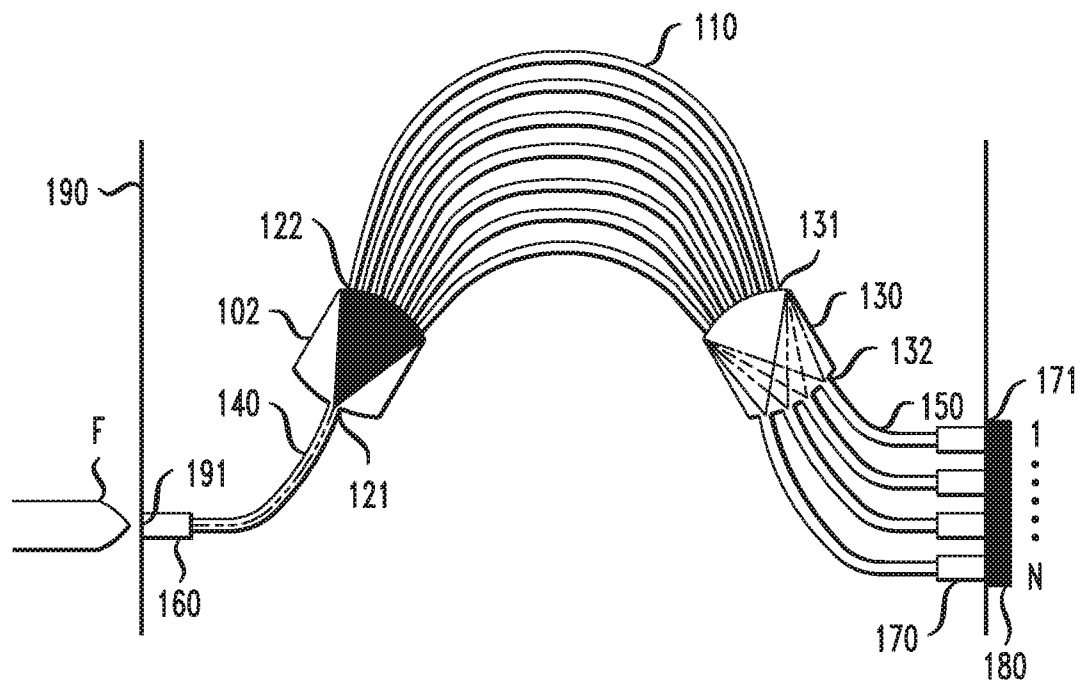
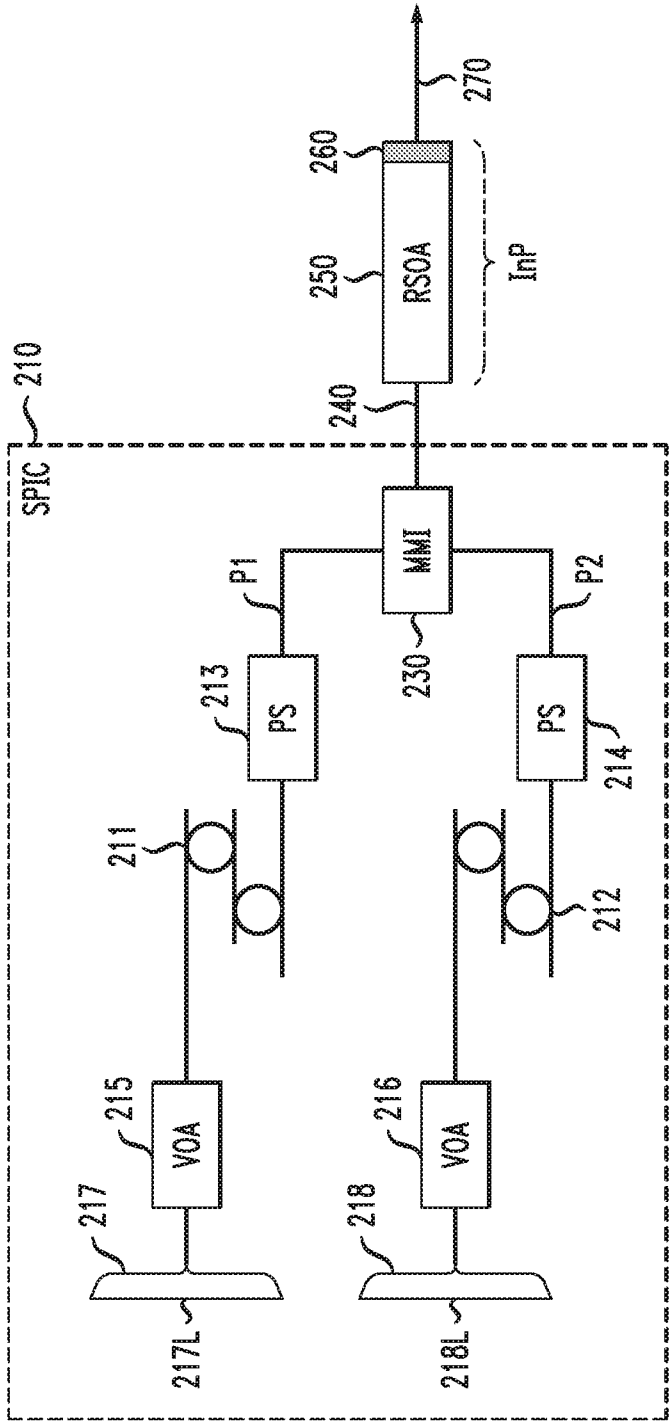


FIG. 2

200



3/4

FIG. 3

300

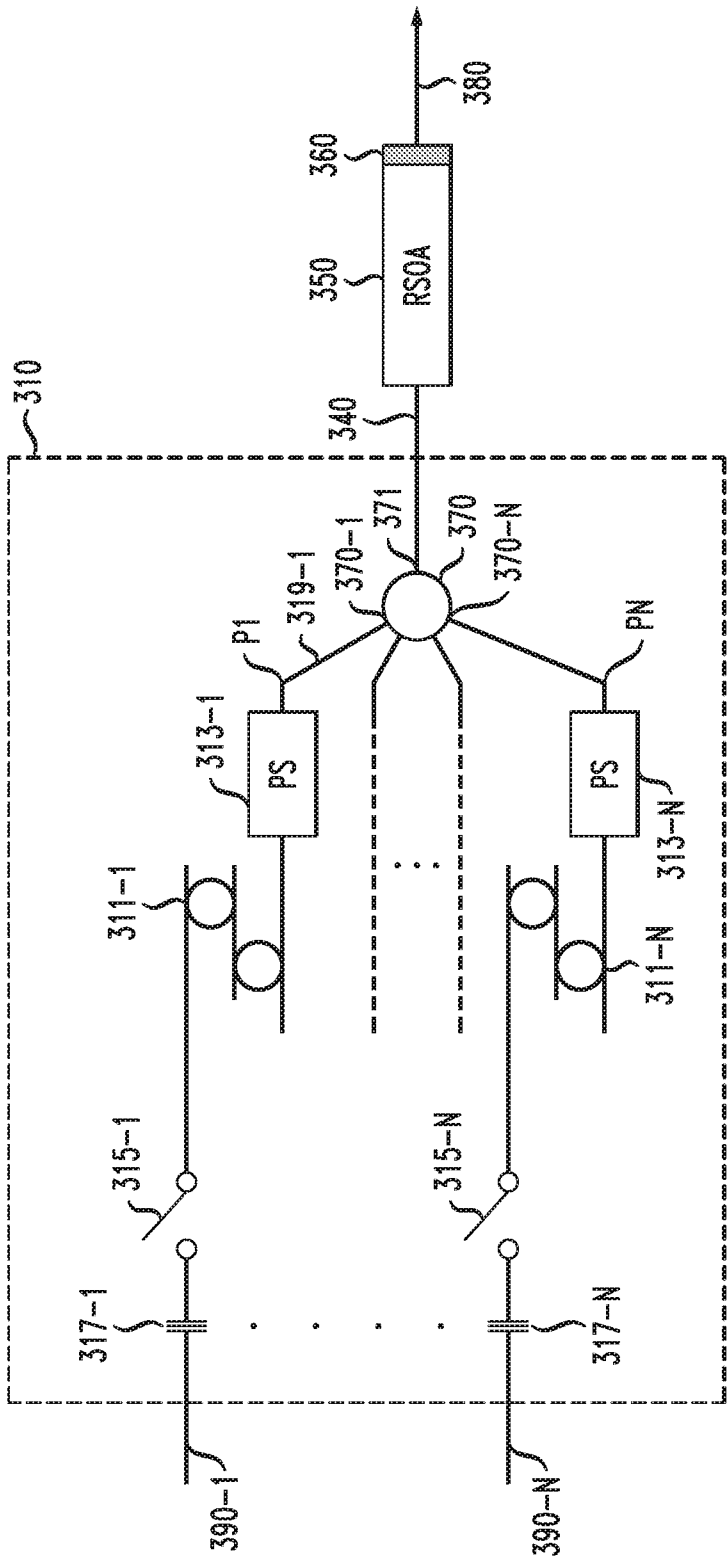
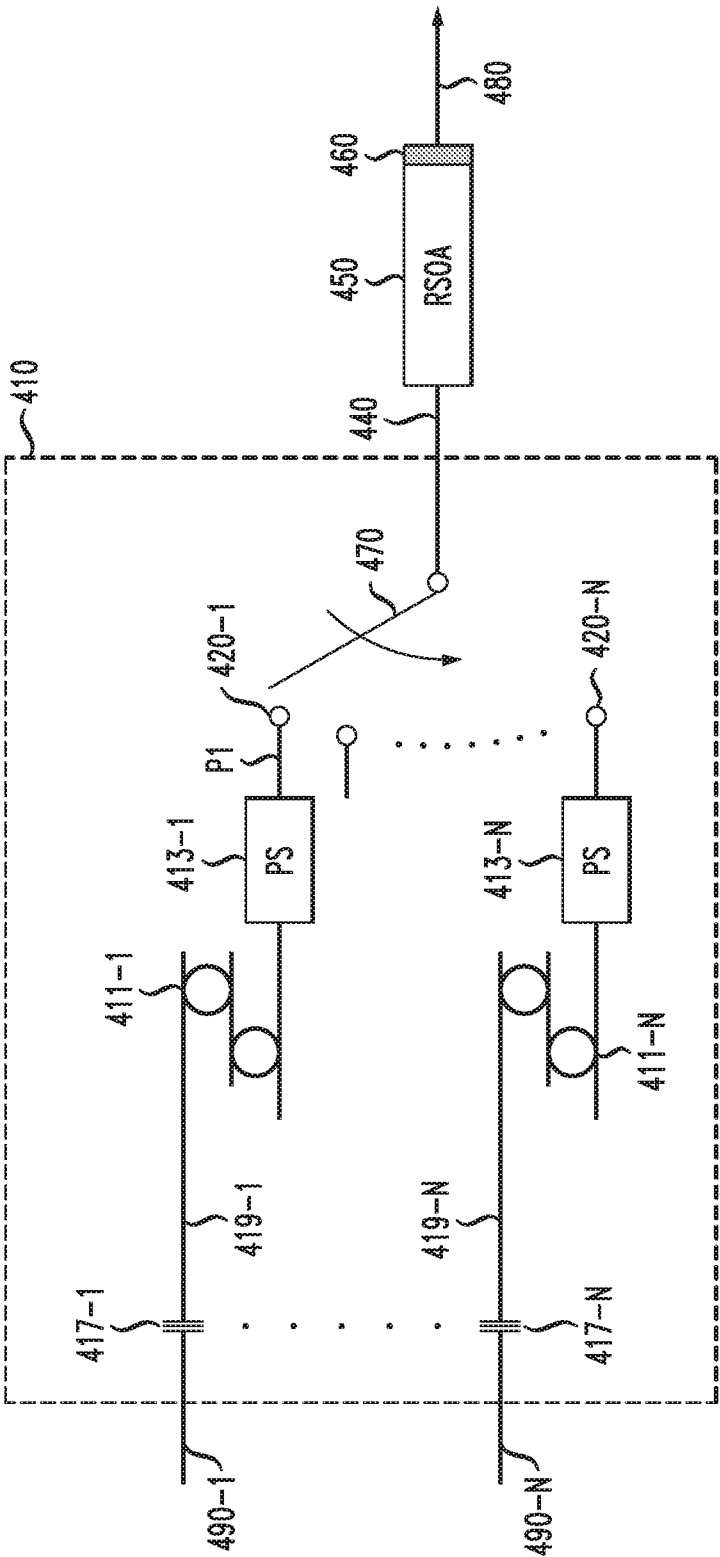


FIG. 4

400



INTERNATIONAL SEARCH REPORT

International application No
PCT/US2016/066439

A. CLASSIFICATION OF SUBJECT MATTER		
INV. H01S5/02	G02B6/12	H01S5/026 H01S5/10 H01S5/14
ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols) H01S G02B		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, INSPEC, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2014/133511 A1 (TANAKA SHINSUKE [JP]) 15 May 2014 (2014-05-15) abstract; figures 1,9 paragraph [0047] -----	1-19
Y	DE 10 2012 002077 B3 (FRAUNHOFER GES FORSCHUNG [DE]) 4 April 2013 (2013-04-04) abstract; figure 1 -----	1-19
Y	US 2015/207291 A1 (RICKMAN ANDREW [GB] ET AL) 23 July 2015 (2015-07-23) abstract; figures 1,11,12 -----	1-19
☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
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Date of the actual completion of the international search 27 March 2017		Date of mailing of the international search report 05/04/2017
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Lendroit, Stéphane

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2016/066439

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2014133511 A1	15-05-2014	CN 103733448 A	16-04-2014
		JP 5692387 B2	01-04-2015
		JP WO2013021421 A1	05-03-2015
		US 2014133511 A1	15-05-2014
		WO 2013021421 A1	14-02-2013

DE 102012002077 B3	04-04-2013	DE 102012002077 B3	04-04-2013
		EP 2810346 A1	10-12-2014
		US 2015023382 A1	22-01-2015
		WO 2013113437 A1	08-08-2013

US 2015207291 A1	23-07-2015	CN 106104947 A	09-11-2016
		GB 2522252 A	22-07-2015
		US 2015207291 A1	23-07-2015
		US 2016164246 A1	09-06-2016
		WO 2015107366 A2	23-07-2015
