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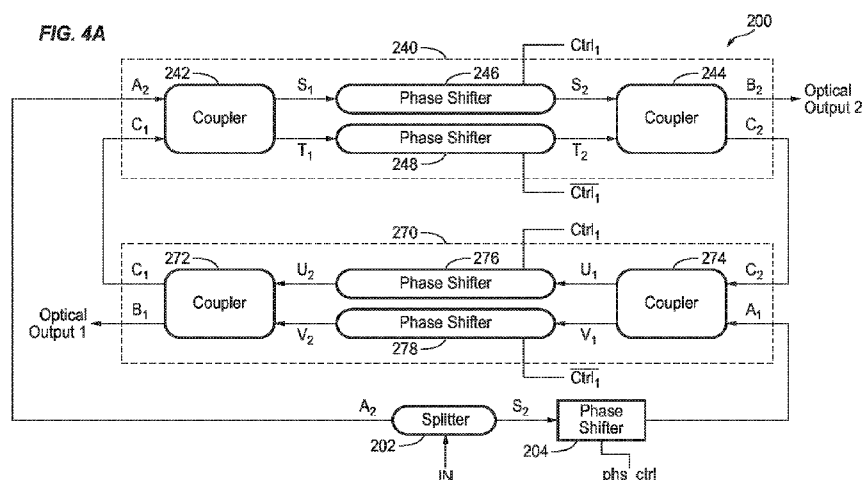
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(54) Title: DIFFERENTIAL RING MODULATOR



(57) **Abstract:** A differential optical modulator includes, in part, a splitter splitting an incoming optical signal into first and second input signals, a first variable coupler generating a first differential output signal in response to the first input signal, and a second variable coupler generating a second differential output signal in response to the second input signal. The first variable coupler includes, in part, first and second couplers and a phase shifter disposed therebetween. The first coupler generates a pair of internal signals in response to the first input signal. The second coupler generates the first differential output signal. The second variable coupler includes, in part, third and fourth couplers and a phase shifter disposed therebetween. The third coupler generates a pair of internal signals in response to the second input signal. The fourth coupler generates the second differential output signal.



DIFFERENTIAL RING MODULATOR

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims benefit under 35 USC 119 (e) of U.S. provisional Application No. 62/133,849, filed March 16, 2015, entitled “Differential Ring Modulator”, the content of which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[0002] The present invention relates to optoelectronic devices, and more particularly to optical ring modulators.

BACKGROUND OF THE INVENTION

[0003] Electro-optic modulators (EOM) are commonly used in optical communication networks. A phase-modulating EOM may be used in a Mach-Zehnder interferometer to modulate the amplitude of an incoming optical signal. As is known, Mach-Zehnder based opto-electronic modulators have a relatively high power consumption, are large and require a high drive voltage.

[0004] Improving the bandwidth-density product in an integrated silicon photonic system requires a corresponding improvement in the performance of the optical modulator disposed in such a system. Optical modulation in conventional optical ring modulators is achieved either by varying the coupling level or by changing the index of refraction of the ring, either by injecting excess minority carriers in the associated PIN junction or by changing the reverse bias voltage applied to the PN junction. The change in the index of refraction causes a change in the optical path length of the ring, in turn changing the resonance frequency of the ring.

[0005] As is well known, conventional optical ring modulators are susceptible to temperature fluctuations. Furthermore, as the Quality factor (Q) of a conventional optical ring modulator increases to achieve lower power consumption and enhanced energy efficiency, the bandwidth of

the optical ring modulator decreases. In other words, there is a trade-off between the optical bandwidth and power consumption of a conventional optical ring modulator.

[0006] Figure 1A is a top schematic view of an optical ring modulator 100, as known in the prior art. Optical ring modulator 100 is shown as including, in part, a waveguide 20, and an optical ring 30. The optical signal entering waveguide 20 through its input port 10 is coupled to optical ring 30.

[0007] Optical ring 30 includes an intrinsic silicon region 36, a highly doped n+ region 32 encompassing silicon region 36, and a highly doped p+ region 34 formed within the inner area of silicon region 36. Figure 1B is a cross-section view of optical ring 30 showing intrinsic silicon region 36, and the highly doped n+ and p+ regions 32 and 34, respectively. By changing the voltage applied between n+ region 32 and p+ region 34, the refractive index of the optical ring 30 is varied. The interference between the optical signals travelling through waveguide 20 and optical ring 30 modulates the optical signal at the output port 12 of optical ring modulator 100. Referring to Figure 1C, signals 50 (delivered via input port 10) and 52 (delivered via output port 20) are exemplary input and output signals of the optical modulator shown in Figure 1A.

[0008] The time-domain dynamic transmission of the ring modulator, $T(t)$ may be defined as:

$$T(t) = \sigma(t) + \frac{k(t)}{k(t-\tau)} \alpha(t) \exp[-i\varphi(t)] [\sigma(t-\tau)T(t-\tau) - 1] \quad (1)$$

where σ and k respectively represent transmission and coupling coefficients of the optical ring modulator, α represents the attenuation level, φ represents the phase shift inside the ring, and τ represents the travel time of the optical signal around the resonator, i.e., the round trip time in the resonator.

[0009] Fig. 2A shows the static transmission characteristic of a conventional optical ring modulator obtained through numerical solution of expression (1) using an iterative approach. Figure 2B shows the Q-bandwidth response of such an optical ring modulator. Plots 60 and 62 of Figure 2B respectively correspond to conventional optical modulators having Qs 3000 and 20000 respectively. It is seen that the modulator with a Q of 3000 has a wider bandwidth. Figure 2C also shows the drop-off in the frequency response as the Q of the modulator increases. Referring

concurrently to Figures 1C and 2C, it is seen that a conventional optical modulator, such as that shown in Figure 1A, has a low-pass response.

[0010] Figure 2D shows the static transmission characteristic of another exemplary optical ring modulator that receives an optical signal generated using a laser having a wavelength of nearly 1527.4 nm, as shown. Plots 70 and 72 respectively show the static transmission characteristic of the optical ring modulator for two different reverse-biased voltages. By changing the reverse-biased voltage of the P-N junction disposed in the ring, the index of refraction of the ring and hence the optical length of the ring changes, thereby resulting in a shift in the resonance frequency of the ring. In plot 70, the resonance frequency is shown to occur at wavelength of nearly 1527.2 nm associated with a reverse bias voltage of V_1 . In plot 72, the resonance frequency is shown to occur at wavelength of nearly 1527.3 nm associated with a reverse bias voltage of V_2 . The modulator's transmission value is seen to change from -9 dB (associated with an optical output of zero) to -3dB (associated with an optical value of one) defining an extinction ratio of 6dB. In other words, a change of $\pm(V_2 - V_1)$ in the voltage applied to the reverse-biased p-n junction disposed in the modulator causes the optical output signal of the modulator to switch between one and zero.

[0011] Figure 3A shows a schematic diagram of an optical modulator 150 that includes a variable coupler 160, as is also known in the prior art. Figure 3B shows exemplary input/output signals of optical modulator 150. Output signal 175 supplied at output port 185 of optical ring modulator 200 is generated in response to optical input signal 170 delivered to input port 180 of the modulator. The modulation of optical signal 185 is achieved by changing the coupling ratio between optical path 190 of the modulator and optical path of 195 of the ring using variable coupler 160. As is seen from Figure 3B, the relatively long sequence of input 1s at the input port of the optical modulator causes an energy droop in the ring and output signal degradation. Accordingly, optical modulator 150 may be characterized as having a highpass response. A need continues to exist for an improved optical ring modulator.

BRIEF SUMMARY OF THE INVENTION

[0012] A differential optical modulator, in accordance with one embodiment of the present invention includes, in part, a splitter and a pair of variable optical couplers. The splitter is adapted to split an incoming optical signal into first and second input signals. A first one of the variable couplers is adapted to generate a first differential output of the optical modulator in response to the first input signal. A second one of the variable couplers is adapted to generate a second differential output of the optical modulator in response to the second input signal. The first variable coupler is further adapted to generate a first internal signal applied to the second variable coupler, and the second variable coupler is further adapted to generate a second internal signal applied to the first variable coupler.

[0013] In one embodiment, the first variable coupler includes, in part, first and second couplers and a first phase shifter disposed between the first and second couplers. The first coupler is adapted to generate third and fourth internal signals in response to the first input signal and the second internal signal. The second coupler is adapted to generate the first differential output signal and the first internal signal in response to the first coupler.

[0014] In one embodiment, the second variable coupler includes, in part, third and fourth couplers and a first phase shifter disposed between the third and fourth couplers. The third coupler is adapted to generate fifth and sixth internal signals in response to the second input signal and the first internal signal. The fourth coupler is adapted to generate the second differential output signal and the second internal signal in response to the third coupler.

In one embodiment, the differential optical modulator further includes, in part, a thermal phase shifter adapted to match phases of the first and second input signals. In one embodiment, each of the first and second phase shifters includes, in part, a p-n junction adapted to vary the phase shifter's optical length in response to a voltage applied thereto. In one embodiment, the second phase shifter receives a complement of a first voltage applied to the first phase shifter.

[0015] In one embodiment, the first variable coupler includes, in part, a third phase shifter disposed between the first and second couplers. In one embodiment, the second variable coupler includes, in part, a fourth phase shifter disposed between the third and fourth couplers. In one

embodiment, each of the third and fourth phase shifters includes, in part, a p-n junction adapted to vary the phase shifter's optical length in response to a voltage applied to the phase shifter.

[0016] In one embodiment, the third phase shifter receives the first voltage and the fourth phase shifter receives the complement of the first voltage. In one embodiment, each of the first, second, third and fourth couplers is a 3-dB coupler. In one embodiment, each of the first and second variable couplers has an associated optical ring. In such embodiments, at any given point in time either the first variable coupler couples the optical power it receives to the first coupler's associated ring, or the second variable coupler couples the optical power it receives to the second coupler's associated ring.

[0017] A method of modulating an incoming optical signal, in accordance with one embodiment of the present invention includes, in part, splitting the incoming optical signal into first and second input signals, generating a first optically modulated differential output signal in response to the first input signal, and generating a second optically modulated differential output signal in response to the second input signal. In one embodiment, the first optically modulated differential output signal is generated by a first coupler, and the second optically modulated differential output signal is generated by a second coupler. In such embodiments, the first coupler is responsive to the second coupler, and the second coupler is responsive to the first coupler.

[0018] In one embodiment, the method of modulating the incoming optical signal, further includes, in part, generating first and second internal signals using a third coupler responsive to the second coupler, and generating third and fourth internal signals using a fourth coupler responsive to the first coupler. In one embodiment, the method of modulating the incoming optical signal, further includes, in part, delaying the phase of the first internal signal to generate a first delayed signal, and applying the first delayed signal to the first coupler. The method further includes, in part, delaying the phase of the fourth internal signal to generate a second delayed signal, and applying the second delayed signal to the second coupler. In one embodiment, the method further includes, in part, generating the first delayed signal in response to a first voltage, and generating the second delayed signal in response to a complement of the first voltage.

[0019] In one embodiment, the method further includes, in part, delaying the phase of the second signal to generate a third delayed signal, and applying the third delayed signal to the first coupler. The method further includes, in part, delaying the phase of the third signal to generate a fourth delayed signal, and applying the fourth delayed signal to the second coupler.

[0020] In one embodiment, the method further includes, in part, generating the third delayed signal in response to the complement of the first voltage, and generating the fourth delayed signal in response to the first voltage. In one embodiment, each of the first, second, third and fourth couplers is a 3-dB coupler. In one embodiment, each of the first and second variable couplers has an associated optical ring. In such embodiments, at any given point in time, either the first variable coupler couples the optical power it receives to the first coupler's associated ring, or the second variable coupler couples the optical power it receives to the second coupler's associated ring.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] Figure 1A is a top schematic view of an optical ring modulator as known in the prior art.

[0022] Figure 1B is a cross-section view of the optical ring modulator of Figure 1A.

[0023] Figure 1C shows an example of the input/output optical signals of the optical ring modulator of Figure 1A.

[0024] Figure 2A shows an example of the static transmission characteristic of a conventional optical ring modulator.

[0025] Figure 2B shows the frequency responses as a functions of the Q of a conventional optical ring modulator.

[0026] Figure 2C shows the drop-off in the frequency response as a function of the Q of a conventional optical ring modulator.

[0027] Figure 2D shows an example of the static transmission characteristic of a conventional optical ring modulator.

[0028] Figure 3A is top schematic diagram of an optical modulator having a variable coupler as is known in the prior art.

[0029] Figure 3B is an example of the input/output optical signals of the optical ring modulator of Figure 3A.

[0030] Figure 4A is a simplified high-level block diagram of a differential optical ring modulator, in accordance with one embodiment of the present invention.

[0031] Figure 4B is a simplified high-level block diagram of a differential optical ring modulator, in accordance with another embodiment of the present invention.

[0032] Figure 5 is a simplified high-level block diagram of a differential optical ring modulator, in accordance with another embodiment of the present invention.

[0033] Figure 6 is a simplified high-level block diagram of a differential optical ring modulator, in accordance with another embodiment of the present invention.

[0034] Figure 7 is a top layout view of the optical modulator of Figure 6, in accordance with one embodiment of the present invention.

[0035] Figure 8 is a top layout view of the optical modulator of Figure 4B, in accordance with one embodiment of the present invention.

[0036] Figure 9 shows a setup used to measure the performance characteristics of an integrated differential optical ring modulator, in accordance with one embodiment of the present invention.

[0037] Figures 10A and 10B respectively show the measured eye diagrams of the differential optical ring modulator of Figure 9 at the rates 5Gb/s and 10Gb/s respectively.

[0038] Figure 11 shows the measured static transmission characteristics of the differential optical ring modulator of Figure 9.

DETAILED DESCRIPTION OF THE INVENTION

[0039] Figure 4A is a simplified high-level block diagram of a differential optical ring modulator 200, in accordance with one embodiment of the present invention. Differential optical ring modulator (hereinafter alternatively referred to as modulator) 200 is shown as including, in part, a splitter (such as a Y-junction splitter) 202, a phase shifter 204, and a pair of variable

couplers 240, 270. Variable couplers 240, 270 are adapted to operate out of phase and as such when the coupling level of variable coupler 240 increases, the coupling level of variable coupler 270 decreases. Conversely, when the coupling level of variable coupler 240 decreases, the coupling level of variable coupler 270 increases.

[0040] Variable coupler 240 is shown as including, in part, couplers 242, 244, and phase shifters 246, 248. Variable coupler 270 is shown as including, in part, couplers 272, 274, and phase shifters 276, 278. In one embodiment, each of couplers 242, 244, 272 and 274 is a 3dB-coupler.

[0041] Optical signal IN received by splitter 202 is split into optical signals A_2 and S_2 . Optical signal (hereinafter alternatively referred to as signal) A_2 is delivered to coupler 242. Phase shifter 204 is adapted to vary the phase of signal S_2 and generate a phase-shifted signal A_1 . The degree of phase shift introduced by phase shifter 204 is such that the phase of signal A_2 at the input of coupler 242 matches the phase of signal A_1 at the input of coupler 274. In one embodiment, phase shifter 204 may be a thermal phase shifter that generates a phase shift by changing its temperature via signal Phs_Ctrl.

[0042] As is seen from Figure 4A, coupler 274 also receives signal C_2 supplied thereto by coupler 244. In response coupler 274 generates signals U_1 and V_1 . In one embodiment, signals U_1 and V_1 have amplitudes and phases defined by the amplitudes and phases of signals A_1 and C_2 , as shown below:

$$\begin{pmatrix} U_1 \\ V_1 \end{pmatrix} = \begin{pmatrix} \sqrt{1-\alpha} & j\sqrt{\alpha} \\ j\sqrt{\alpha} & \sqrt{1-\alpha} \end{pmatrix} \begin{pmatrix} C_2 \\ A_1 \end{pmatrix}$$

where α has a value of 0.5 for a 3dB directional coupler.

[0043] Optical phase shifters 276 and 278 form a first differential phase shifter adapted to receive and delay phases of signals U_1 and V_1 by $\frac{\Delta\varphi}{2}$ and $-\frac{\Delta\varphi}{2}$ respectively. Accordingly, signals U_2 and V_2 generated by phase shifter 276, 278 have a relative phase shift of $\Delta\varphi$. The phase delay $\frac{\Delta\varphi}{2}$ generated by phase shifter 276 may be changed by varying the voltage signal $Ctrl_1$ applied

across the reverse-biased P-N junction (not shown) disposed in phase shifter 276. In a similar manner, voltage signal $\overline{Ctrl_1}$ applied to phase shifter 278 is used to vary the phase $-\frac{\Delta\varphi}{2}$ associated with optical signal U_2 . In the embodiment shown in Figure 4A, voltage signals $Ctrl_1$ and $\overline{Ctrl_1}$ are complementary signals.

[0044] Coupler 272 is adapted to receive signal U_2 , V_2 and generate signals C_1 , B_1 in response. Signals C_1 , B_1 have equal amplitudes defined by the amplitudes of signals U_2 and V_2 . Signal B_1 is a first differential optical output signal of differential optical modulator 200. In one embodiment, signals C_1 and B_1 have amplitudes and phases defined by the amplitudes and phases of signals U_2 and V_2 , as shown below:

$$\begin{pmatrix} C_1 \\ B_1 \end{pmatrix} = \begin{pmatrix} \sqrt{1-\alpha} & j\sqrt{\alpha} \\ j\sqrt{\alpha} & \sqrt{1-\alpha} \end{pmatrix} \begin{pmatrix} U_2 \\ V_2 \end{pmatrix}$$

where α has a value of 0.5 for a 3dB directional coupler.

[0045] Coupler 242 receives signals C_1 and A_2 and in response generates output signals S_1 and T_1 . Signals S_1 and T_1 have equal amplitudes defined by the amplitudes of signals A_2 and C_1 . In one embodiment, signals S_1 and T_1 have amplitudes and phases defined by the amplitudes and phases of signals A_2 and C_1 , as shown below:

$$\begin{pmatrix} S_1 \\ T_1 \end{pmatrix} = \begin{pmatrix} \sqrt{1-\alpha} & j\sqrt{\alpha} \\ j\sqrt{\alpha} & \sqrt{1-\alpha} \end{pmatrix} \begin{pmatrix} A_2 \\ C_1 \end{pmatrix}$$

where α has a value of 0.5 for a 3dB directional coupler.

[0046] Optical phase shifters 246 and 248 form a second differential phase shifter adapted to receive and delay phases of signals S_1 and T_1 by $\frac{\Delta\varphi}{2}$ and $-\frac{\Delta\varphi}{2}$ respectively. Accordingly, signals S_2 and T_2 generated by phase shifter 246, 248 have a relative phase shift of $\Delta\varphi$. The phase delay $\frac{\Delta\varphi}{2}$ generated by phase shifter 246 may be changed by varying the voltage signal $Ctrl_1$ applied

across the reverse-biased P-N junction disposed in phase shifter 246. In a similar manner, voltage signal $\overline{Ctrl_1}$ applied to phase shifter 248 is used to vary the phase $-\frac{\Delta\varphi}{2}$ associated with optical signal T_2 .

[0047] In one embodiment, each of the phase shifters 246, 248, 276, and 278 is an optical waveguide having a p-n junction. By changing the voltage used to reverse bias each such p-n junction (using either voltage $Ctrl_1$ or $\overline{Ctrl_1}$), the refractive index and hence the length of the optical path through which the associated optical signal travels is varied, thereby generating the required phase shift.

[0048] Coupler 244 is adapted to receive signal S_2 , T_2 and generate signals C_2 , B_2 in response. Signals C_2 and B_2 have equal amplitudes defined by the amplitudes of signals S_2 and T_2 . Signal B_2 is a second differential optical output signal of differential optical modulator 200. Since signals B_1 and B_2 are differential optical signals, when signal B_1 has a value of one, signal B_2 has a value of zero. Conversely, when signal B_1 has a value of zero, signal B_2 has a value of one. In one embodiment, signals B_2 and C_2 have amplitudes and phases defined by the amplitudes and phases of signals S_2 and T_2 , as shown below:

$$\begin{pmatrix} B_2 \\ C_2 \end{pmatrix} = \begin{pmatrix} \sqrt{1-\alpha} & j\sqrt{\alpha} \\ j\sqrt{\alpha} & \sqrt{1-\alpha} \end{pmatrix} \begin{pmatrix} S_2 \\ T_2 \end{pmatrix}$$

where α has a value of 0.5 for a 3dB directional coupler.

[0049] Differential optical ring modulator 200 has a substantially lower V_π compared to a conventional MZI modulator, where V_π is defined as the voltage required to achieve a differential phase shift $\Delta\varphi$ of π either between phase shifters 276, 278, or between phase shifters 246, 248. At resonance, the static transmission characteristic of differential optical ring modulator 200 may be defined by the following expression:

$$\left| \frac{B_1}{A_1} \right|^2 = \frac{a - \left| \cos \frac{\Delta\varphi}{2} \right|^2}{\left(1 - a \left| \cos \frac{\Delta\varphi}{2} \right| \right)^2} = \frac{(a - \left| \cos \frac{V}{2V_x} \pi \right|)^2}{\left(1 - a \left| \cos \frac{V}{2V_x} \pi \right| \right)^2} \quad (2)$$

where a is the loss factor and V is the voltage required to achieve a differential phase shift $\Delta\varphi$ of π either between phase shifters 276, 278, or between phase shifters 246, 248.

[0050] Critical coupling, defined as the point at which $\frac{B_1}{A_1}$ has a value of zero (i.e., to achieve a substantially maximum extinction ratio such that B_2/B_1 is 1/0 or 0/1) occurs when the voltage applied to the phase shifters has the following value:

$$V_{\pi,DRM} = \frac{2V_{\pi}}{\pi} \cos^{-1}(a) \quad (3)$$

Therefore, for a Q of 32,000 (giving rise to a of about .98) $V_{\pi,DRM}$ is approximately 8 times smaller than V_{π} .

[0051] The amplitudes of signals C_1 and C_2 when the differential output data switches from 1 to 0 or vice versa may be defined as:

$$|C_1|^2|_{Data=0} = |C_1|^2|_{Data=1} = |C_2|^2|_{Data=0} = |C_2|^2|_{Data=1} = \frac{\sin\frac{\Delta\phi}{2}(1+\frac{a^2}{4}\cos^2\frac{\Delta\phi}{2})}{(1-\frac{a^2}{4}\cos^2\frac{\Delta\phi}{2})} \quad (4)$$

[0052] As is seen from expression (4), differential optical ring modulator 200 maintains the energy stored in its ring substantially constant. In other words, for any given $\Delta\varphi$, the square of the amplitudes of signals C_1 and C_2 remain constant as the differential output data B_1/B_2 is changed from 1 to 0 or vice versa. Consequently, by modulating couplers 240 and 270 differentially, the overall coupling in the ring remains substantially constant, thereby minimizing the energy variation stored in the optical ring modulator.

[0053] Figure 4B is a simplified high-level block diagram of a differential optical ring modulator 250, in accordance with another embodiment of the present invention. Differential optical ring modulator 250 is similar to differential optical modulator 200 except that differential optical modulator 250 does not include a thermal phase shifter 204. Accordingly, in differential optical ring modulator 250, phase matching between signals A_1 and A_2 is achieved geometrically by matching the lengths of the optical paths through which signals A_1 and A_2 travel.

[0054] Figure 5 is a simplified high-level block diagram of a differential optical ring modulator 300, in accordance with another embodiment of the present invention. Differential optical ring modulator 300 is similar to differential optical ring modulator 200 except that in differential optical ring modulator 300 each of variable couplers 240 and 270 includes only a single phase shifter. Accordingly, in optical ring modulator 300, the phase difference between optical signals U_1 and V_2 at the input ports of coupler 272 is controlled by the voltage applied to phase shifter 278 via signal $\overline{\text{Ctrl}}_1$. Likewise, the phase difference between optical signals S_2 and T_1 at the input ports of coupler 244 is controlled by the voltage applied to phase shifter 246 via signal Ctrl_1 .

[0055] Figure 6 is a simplified high-level block diagram of a differential optical ring modulator 400, in accordance with another embodiment of the present invention. Differential Optical ring modulator 400 is similar to differential optical ring modulator 300 except that differential optical ring modulator 400 does not have a thermal phase shifter. Accordingly, in differential optical ring modulator 400, phase matching between signals A_1 and A_2 is achieved geometrically by matching the lengths of the optical paths through which signals A_1 and A_2 travel.

[0056] Figure 7 is a top layout view of the differential optical modulator 400 shown in Figure 6, in accordance with one embodiment of the present invention. Y-junction 202 splits the incoming optical signal IN into two optical signals A_1 and A_2 that are delivered respectively to optical paths (also referred to herein as optical links or waveguides) 405 and 410. For simplicity and clarity, the remaining signal names shown in Figure 6 are not shown in Figure 7.

[0057] The optical signal travelling through optical path 405 is delivered to 3dB coupler 242. Coupler 242 receives the output signal of 3dB coupler (also referred as coupler) 272 via its second input port. A first output signal (S_1) of coupler 242 is delivered to phase shifter 246 via optical path 415. A second output signal (T_1) of coupler 242 is delivered to coupler 244 via optical path 410. Coupler 244 is also shown as being coupled to the output port of phase shifter 246 via optical path 425.

[0058] Coupler 244 generates a first differential optical output signal B_2 of the modulator via its first output terminal 465. A second optical output signal (C_2) of coupler 244 is delivered to coupler 274 via optical path 450. In response to these received signals, coupler 274 generates and

delivers a first optical signal (U_1) to coupler 272 via optical path 440, and a second optical signal (V_1) to phase shifter 278 via optical path 435. The phase-shifted output signal of phase shifter 278 is delivered to coupler 242 via optical path 445. Coupler 272 generates a second differential optical output signal B_1 of the modulator via its first output terminal 475. A second output signal of coupler 272 is delivered to coupler 274 via optical path 460. Both phase shifters 246 and 278 include a positively doped (P) region and a negatively doped region (N). By controlling the reverse voltage applied between each such P-N junction, the magnitude of the phase shift generated by the phase shifter may be varied. Accordingly, by varying the voltages applied to phase shifters 246 and 278, the differential output signals B_1 and B_2 are changed such that when signal B_1 has an optical value of one, signal B_2 has an optical value of zero, and vice versa. Differential optical modulator is also shown as including a resistive heating element 490 used to thermally heat differential optical modulator 400 so as to account for process variations that occur during manufacturing of the differential optical modulator. By changing the voltage applied to heating element 490, the notch frequency of the ring is matched to the frequency of the laser.

[0059] Figure 8 is a top layout view of the optical modulator 250 shown in Figure 4B, in accordance with one embodiment of the present invention. Y-junction 202 splits the incoming optical signal IN into two optical signals A_1 and A_2 that are delivered respectively to optical paths 405 and 410. For simplicity and clarity, the remaining signal names shown in Figure 4B are not shown in Figure 8.

[0060] The optical signal (A_2) travelling through optical path 405 is delivered to 3dB coupler 242. Coupler 242 receives the output signal (C_1) of 3dB coupler 272 via its second input port. A first output signal (S_1) of coupler 242 is delivered to phase shifter 246 via optical path 475. A second output signal (T_1) of coupler 242 is delivered to coupler 244 via phase shifter 248. Coupler 244 is also shown as being coupled to the output port of phase shifter 246 via optical path 476.

[0061] Coupler 244 generates a first optical output signal (B_2) of the differential modulator via its first output terminal 465. A second optical output signal (C_2) of coupler 244 is delivered to

coupler 274 via optical path 450. In response to receiving these two signals, coupler 274 generates and delivers a pair of optical signals (U_1 , V_1) to coupler 272 via optical phase shifters 276 and 278 respectively. Coupler 272 generates a second optical output signal B_2 of the differential modulator via its first output terminal 475. A second optical output signal (C_1) of coupler 272 is delivered to coupler 242 via optical path 460. Each of phase shifters 246, 248, 276 and 278 includes a positively doped (P) region and a negatively doped region (N). By controlling the reverse voltage applied between each such P-N junction, the magnitude of the phase shift generated by the phase shifter may be varied. Accordingly, by varying the voltages applied to the phase shifters, the differential output signals B_1 and B_2 are changed such that when B_1 has an optical value of one, B_2 has an optical value of zero, and vice versa. Differential optical modulator is also shown as including a resistive heating element 490 used to thermally heat differential optical modulator 400 so as to account for process variations that occur during manufacturing of the differential optical modulator. By changing the voltage applied to heating element 490, the notch frequency of the ring is matched to the frequency of the laser.

[0062] Figure 9 shows a measurement setup used to measure the performance characteristics of a differential optical modulator 600 formed as an integrated photonic circuit and having an area less than 0.35 mm^2 . Grating couplers 602 and 604 respectively deliver optical signals to and receive optical signals from differential optical modulator 600. A resistive heater formed near the center of optical modulator ring 600 (see, e.g., Figure 7) provides a uniform temperature throughout the modulator ring. A second resistive heater formed near the differential modulator's Y-junction is used to match the phases of the input signals at the input ports of differential modulator (see, e.g. Figure 4A). The currents through the heaters are controlled using heater control unit 660.

[0063] Optical modulator ring 600 is shown as being wire-bonded to PCB 610 that carries high-speed and DC signals. A tunable laser source 620, an Erbium doped fiber amplifier (EDFA) 630, and gating coupler 602 are used to deliver an input optical signal to differential modulator 600. The output signal of the differential modulator ring is delivered to optical scope 640 via grating coupler 604. The high-speed differential data signals were driven by a PRBS 31

sequence using a pattern generator 650. The voltage swing for each single-ended signal was 1.75V peak-to-peak. Bias voltage generator 680 is used to control the voltages applied to the phase shifters disposed in the optical modulator, as described above.

[0064] Figures 10A and 10B respectively show the measured eye diagrams of the differential optical modulator 600 at the rates 5Gb/s and 10Gb/s respectively. The extinction ratio of the output optical data is measured to be 6.2dB. A portion of the noise seen at the output is associated with the EDFA noise and limited sensitivity of the optical sampling scope.

[0065] Figure 11 shows the measured static transmission of the differential optical modulator 600 near one operational wavelength bias points. From this measurement, the Q of the ring is determined to be approximately 32,000. The tunability of the optical modulator ring was measured by varying the input voltage of the heater and determined to be 12.3pm/mW.

[0066] The above embodiments of the present invention are illustrative and not limitative. Embodiments of the present invention are not limited by any specific frequency or wavelength of the optical signal. Embodiments of the present invention are not limited by the type of optical signal splitter, coupler, phase shifter, and the like that may be used in a differential optical modulator. Other additions, subtractions or modifications are obvious in view of the present disclosure and are intended to fall within the scope of the appended claims.

WHAT IS CLAIMED IS:

1. A differential optical modulator comprising:
 - a splitter adapted to split an incoming optical signal into first and second input signals;
 - a first variable coupler adapted to generate a first differential output of the optical modulator in response to the first input signal;
 - a second variable coupler adapted to generate a second differential output of the optical modulator in response to the second input signal, wherein said first variable coupler is further adapted to generate a first internal signal applied to the second variable coupler, and wherein said second variable coupler is further adapted to generate a second internal signal applied to the first variable coupler.
2. The differential optical modulator of claim 1 wherein said first variable coupler comprises:
 - a first coupler adapted to generate third and fourth internal signals in response to the first input signal and the second internal signal;
 - a second coupler adapted to generate the first differential output signal and the first internal signal in response to the first coupler; and
 - a first phase shifter disposed between the first and second couplers.
3. The differential optical modulator of claim 2 wherein said second variable coupler comprises:
 - a third coupler adapted to generate fifth and sixth internal signals in response to the second input signal and the first internal signal;
 - a fourth coupler adapted to generate the second differential output signal and the second internal signal in response to the third coupler; and
 - a second phase shifter disposed between the third and fourth couplers.

4. The differential optical modulator of claim 3 further comprising:
a thermal phase shifter adapted to match phases of the first and second input signals.
5. The differential optical modulator of claim 4 wherein each of the first and second phase shifters comprises a p-n junction adapted to vary the phase shifter's optical length in response to a voltage applied thereto.
6. The differential optical modulator of claim 5 wherein the second phase shifter receives a complement of a first voltage applied to the first phase shifter.
7. The differential optical modulator of claim 6 wherein said first variable coupler comprises a third phase shifter disposed between the first and second couplers, and wherein said second variable coupler comprises a fourth phase shifter disposed between the third and fourth couplers.
8. The differential optical modulator of claim 7 wherein each of the third and fourth phase shifters comprises a p-n junction adapted to vary the phase shifter's optical length in response to a voltage applied thereto.
9. The differential optical modulator of claim 8 wherein said third phase shifter receives the first voltage and the fourth phase shifters receives the complement of the first voltage.
10. The differential optical modulator of claim 9 wherein each of the first, second, third and fourth couplers is a 3-dB coupler.
11. The differential optical modulator of claim 1 wherein each of said first and second variable couplers has an associated optical ring, wherein at any given time either the first variable coupler or the second variable coupler couples power to the coupler's associated ring.

12. A method of modulating an incoming optical signal, the method comprising:
splitting the incoming optical signal into first and second input signals;
generating a first optically modulated differential output signal in response to the first input signal; and
generating a second optically modulated differential output signal in response to the second input signal.

13. The method of claim 12 further comprising:
generating the first optically modulated differential output signal via a first coupler; and
generating a second optically modulated differential output signal via a second coupler, wherein said first coupler is responsive to the second coupler, and wherein said second coupler is responsive to the first coupler.

14. The method of claim 13 further comprising:
generating first and second internal signals via a third coupler responsive to the second coupler; and
generating third and fourth internal signals via a fourth coupler responsive to the first coupler.

15. The method of claim 14 further comprising:
delaying a phase of the first internal signal to generate a first delayed signal; and
applying the first delayed signal to the first coupler.

16. The method of claim 15 further comprising:
delaying a phase of the fourth internal signal to generate a second delayed signal;
and

applying the second delayed signal to the second coupler.

17. The method of claim 16 further comprising:
generating the first delayed signal in response to a first voltage; and
generating the second delayed signal in response to a complement of the first voltage.

18. The method of claim 17 further comprising:
delaying a phase of the second signal to generate a third delayed signal; and
applying the third delayed signal to the first coupler.

19. The method of claim 18 further comprising:
delaying a phase of the third signal to generate a fourth delayed signal; and
applying the fourth delayed signal to the second coupler.

20. The method of claim 19 further comprising:
generating the third delayed signal in response to the complement of the first voltage; and
generating the fourth delayed signal in response to the first voltage.

21. The method of claim 20 wherein each of the first, second, third and fourth couplers is a 3-dB coupler.

22. The method of claim 13 wherein each of said first and second variable couplers has an associated optical ring, wherein at any given time either the first variable coupler or the second variable coupler couples power to the coupler's associated ring.

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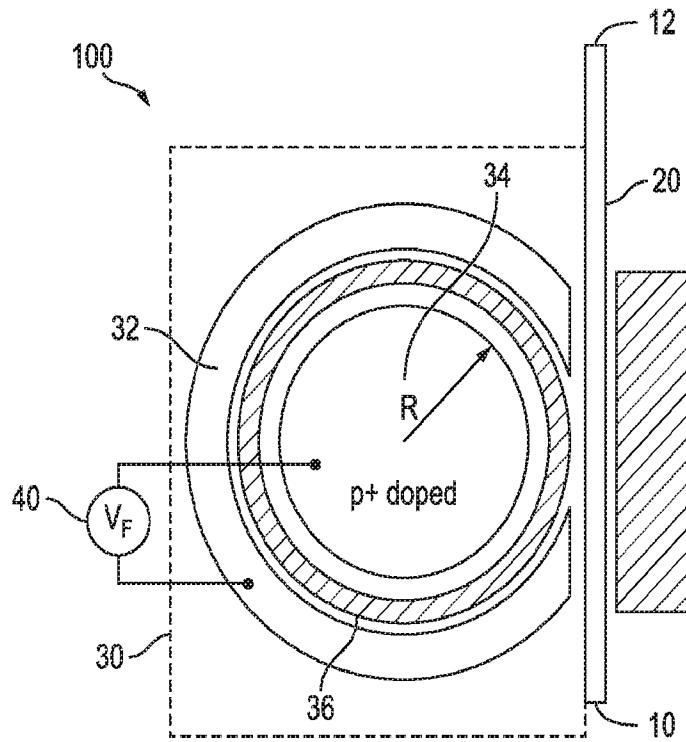


FIG. 1A

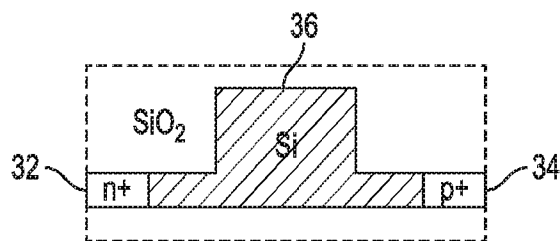


FIG. 1B

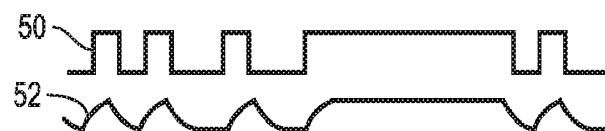


FIG. 1C

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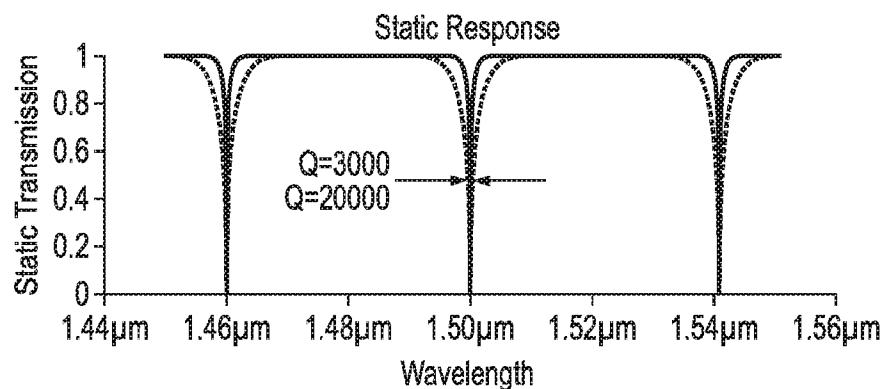


FIG. 2A

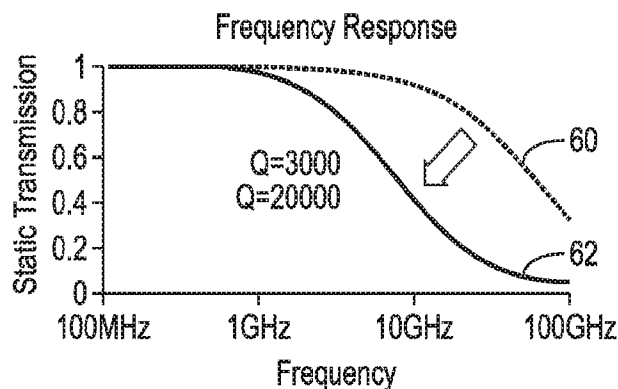


FIG. 2B

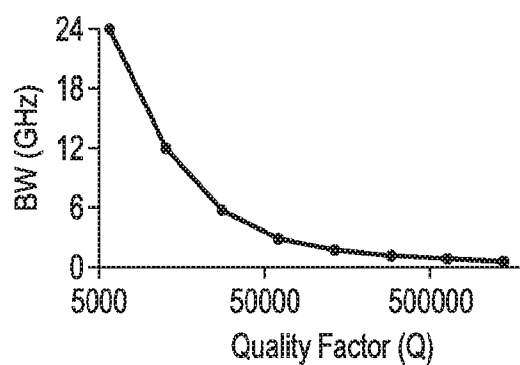


FIG. 2C

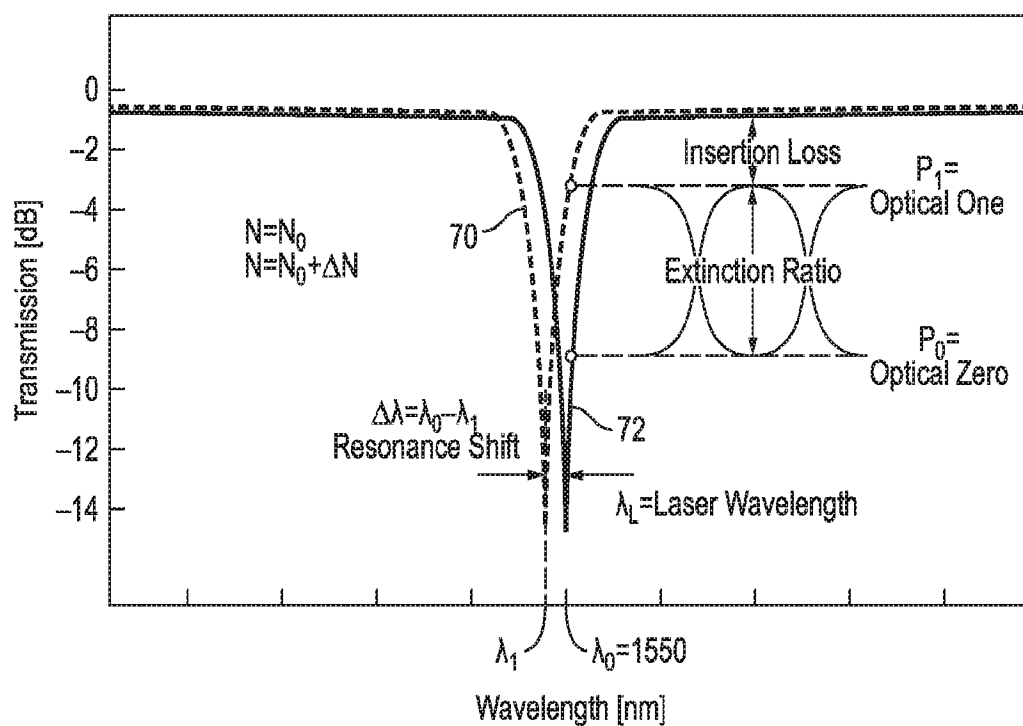


FIG. 2D

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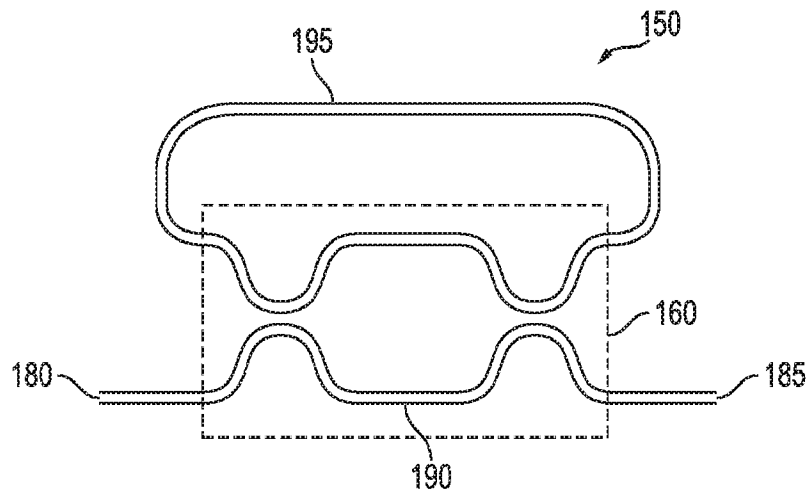


FIG. 3A

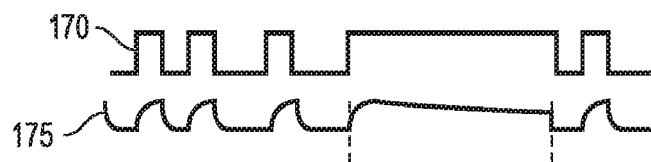


FIG. 3B

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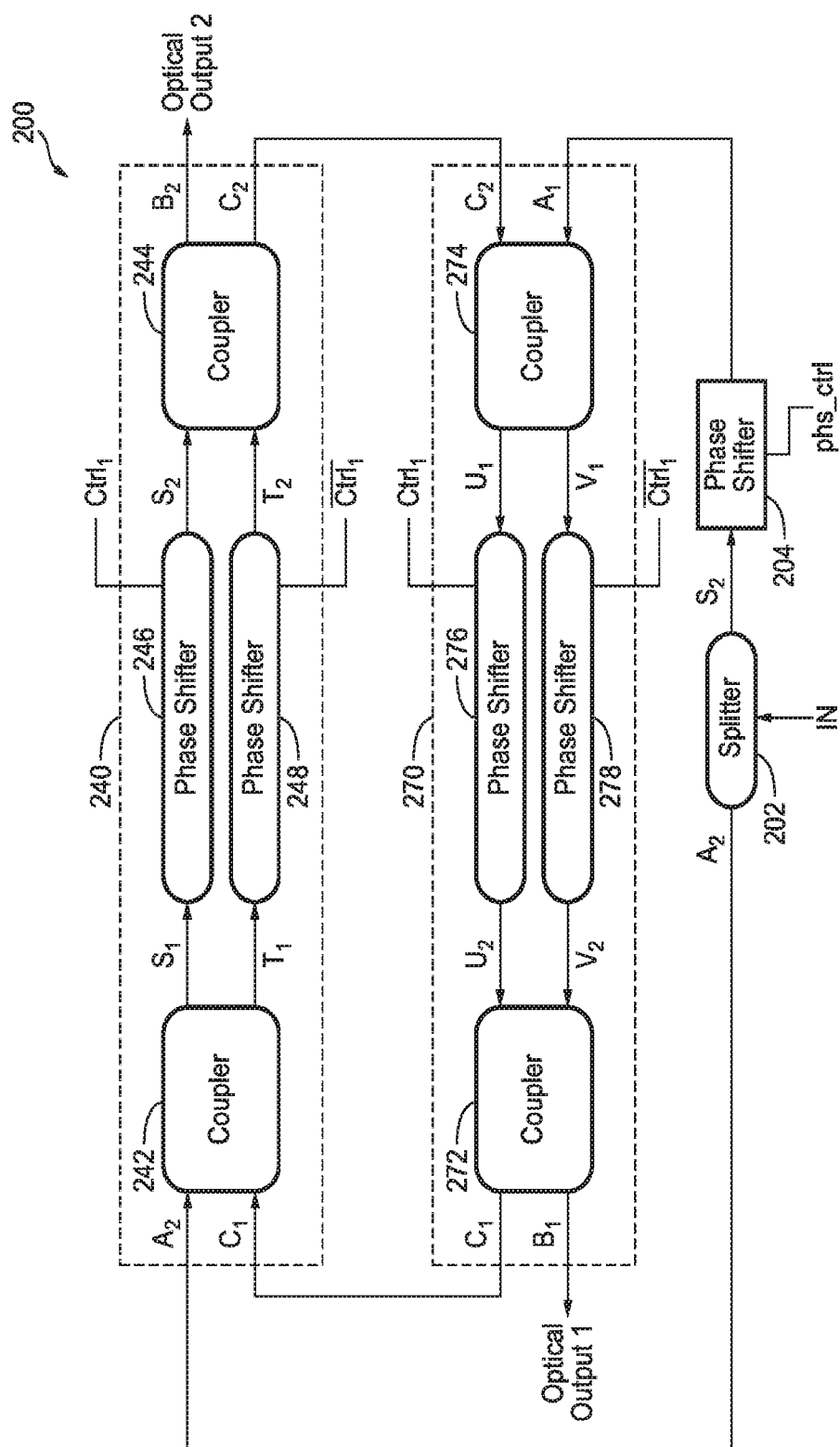


FIG. 4A

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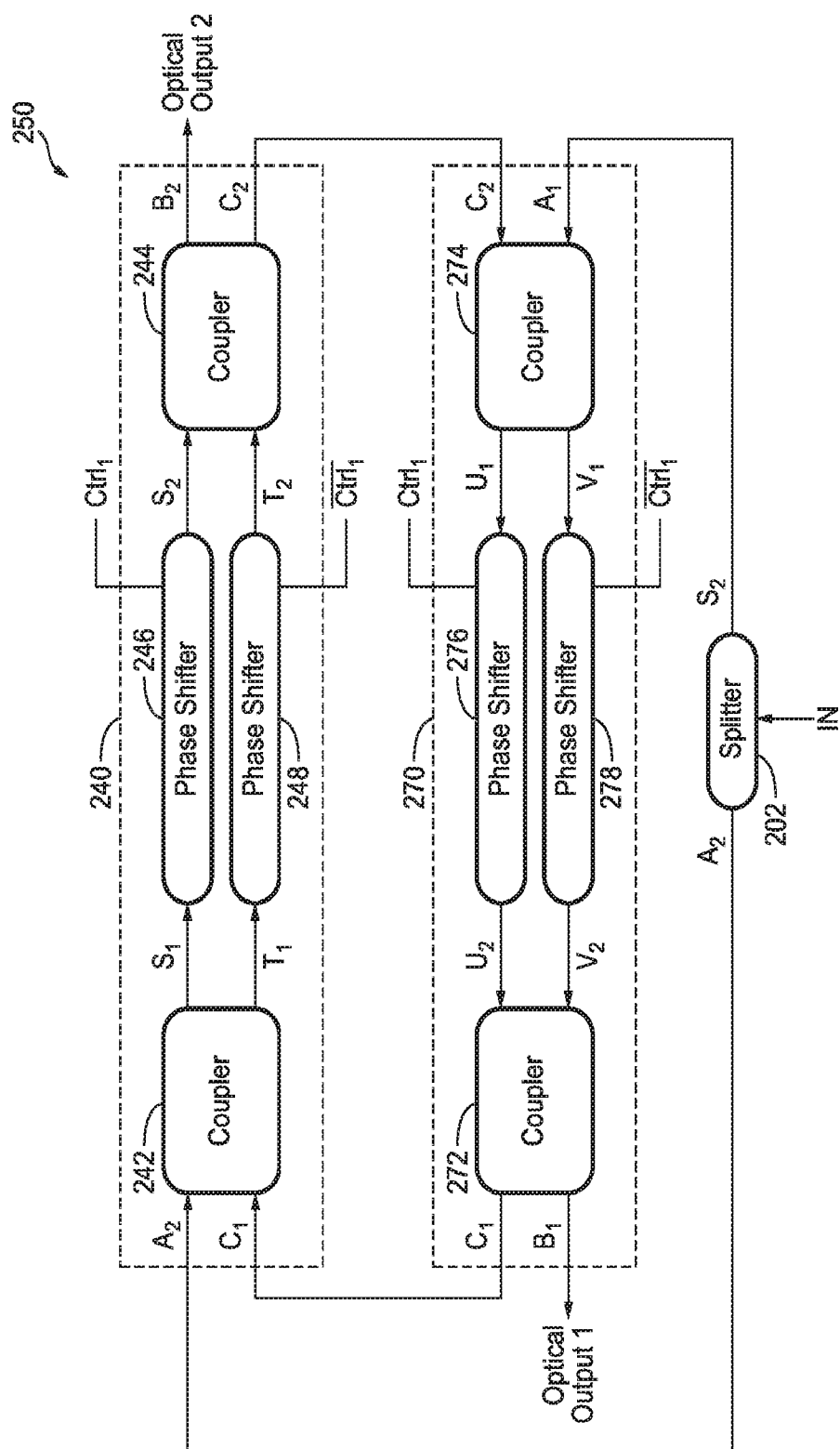


FIG. 4B

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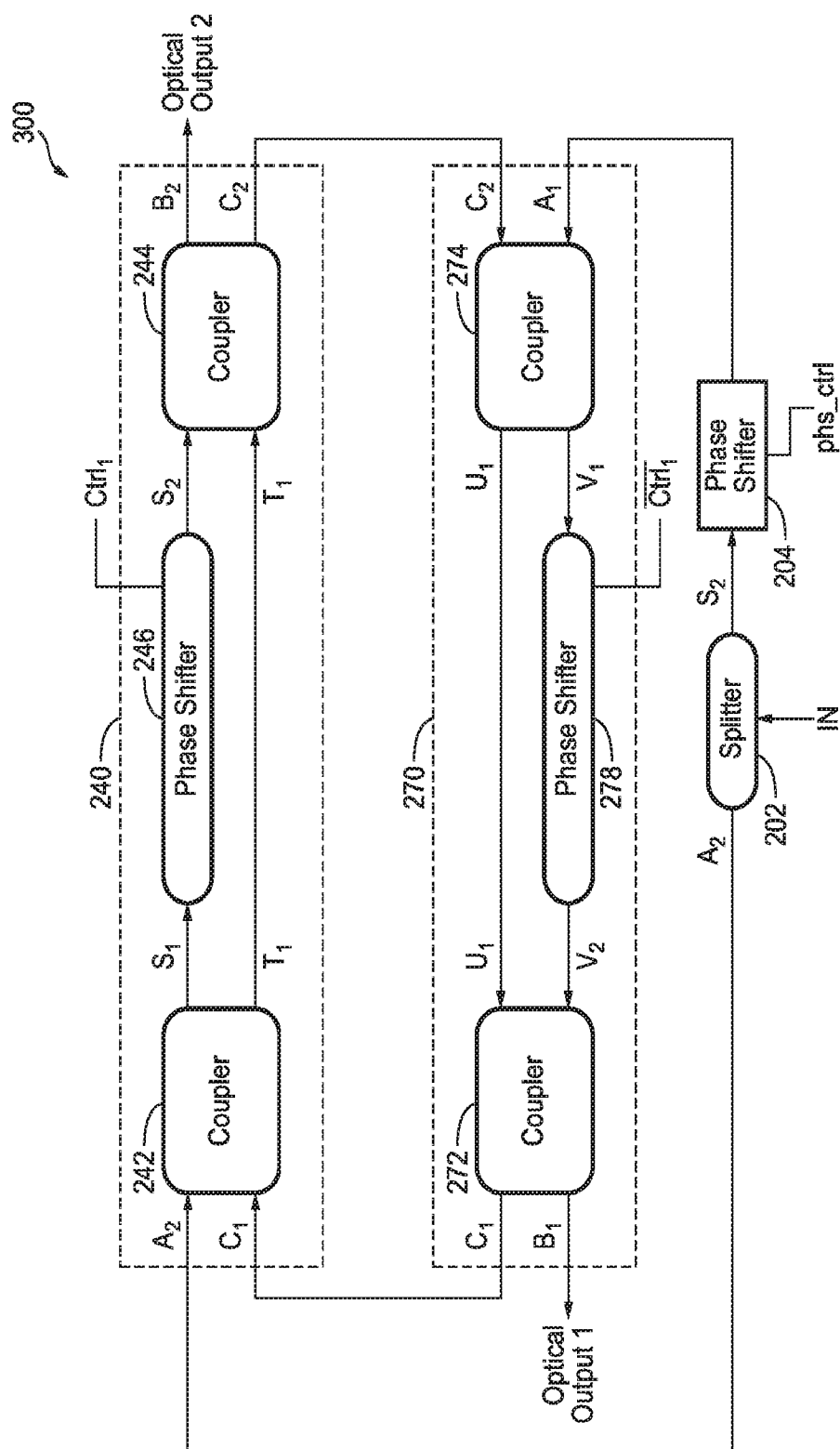


FIG. 5

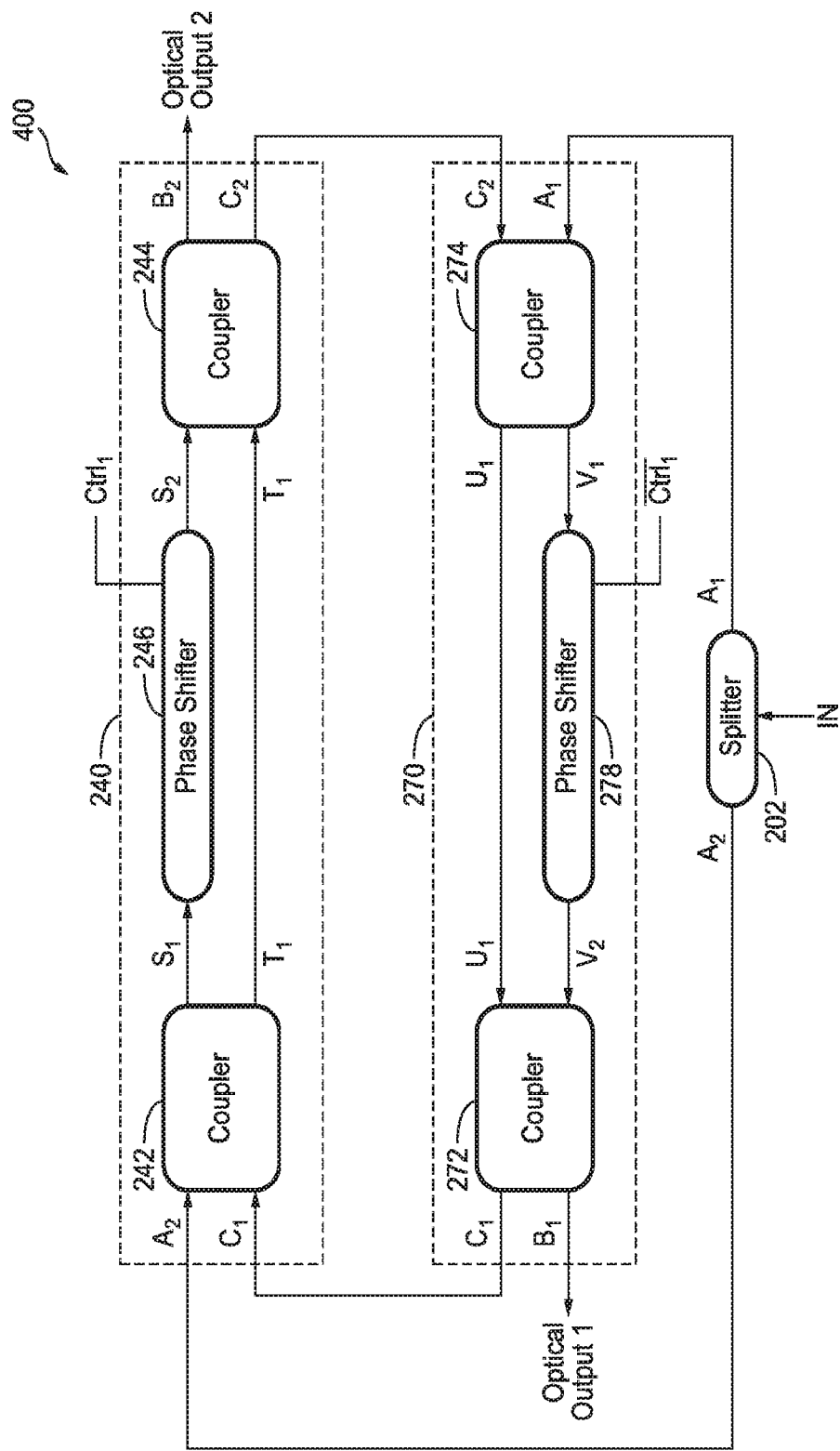


FIG. 6

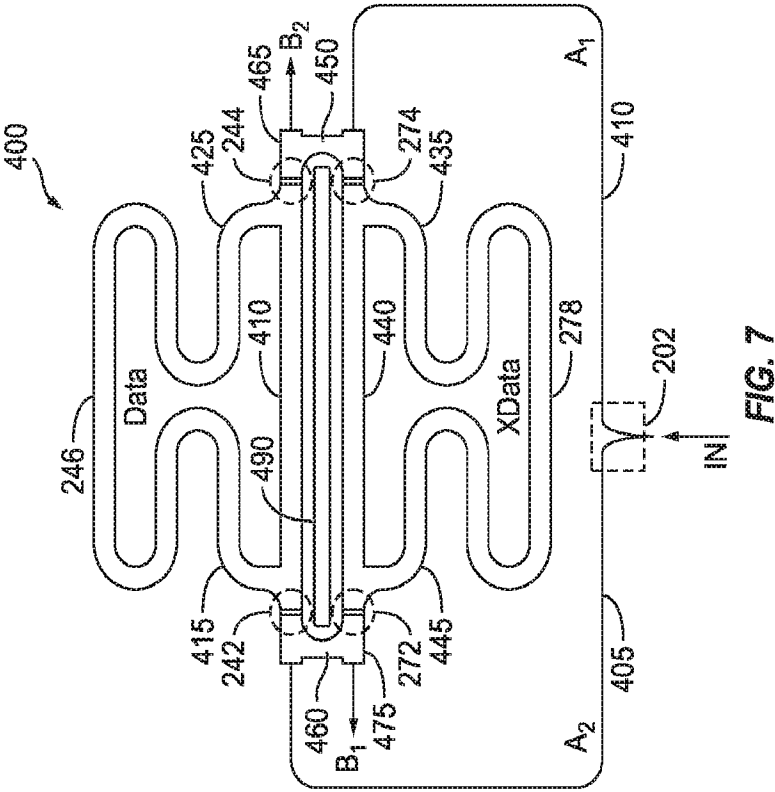


FIG. 7

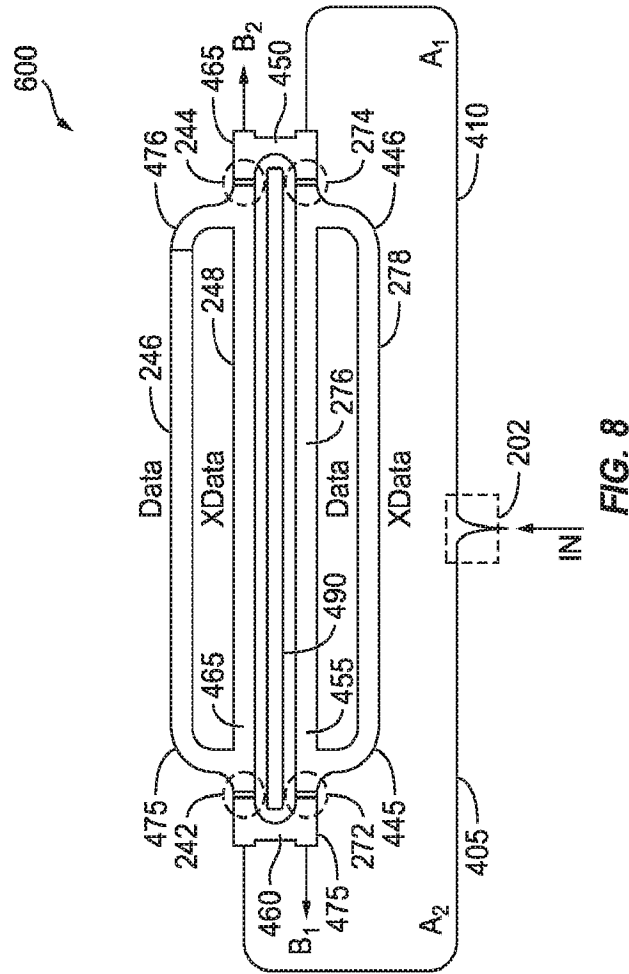


FIG. 8

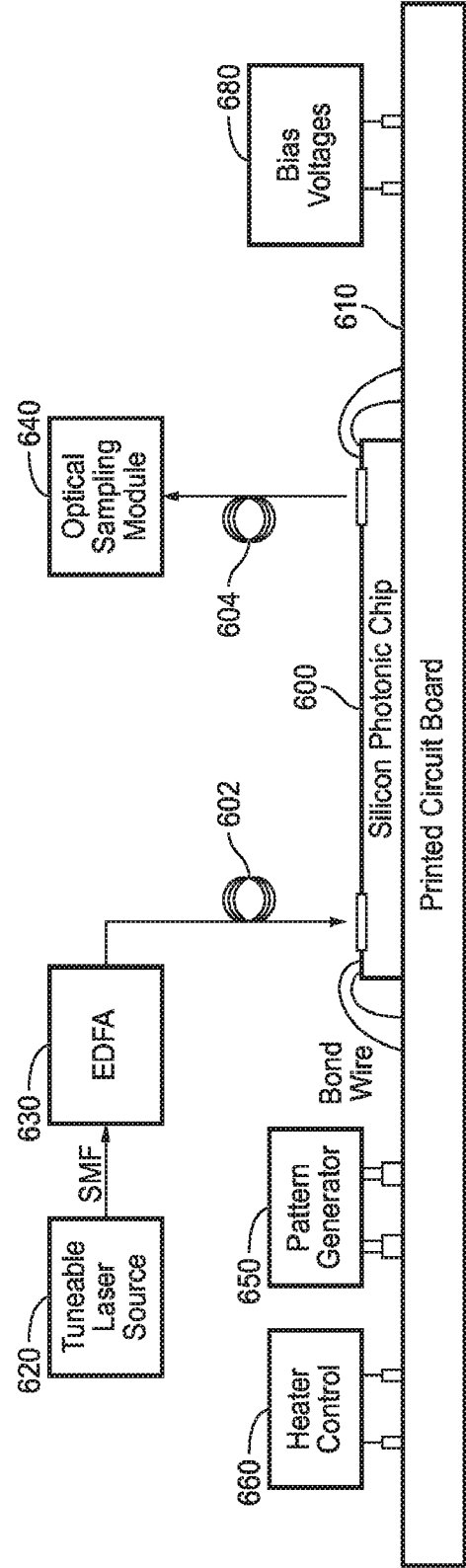
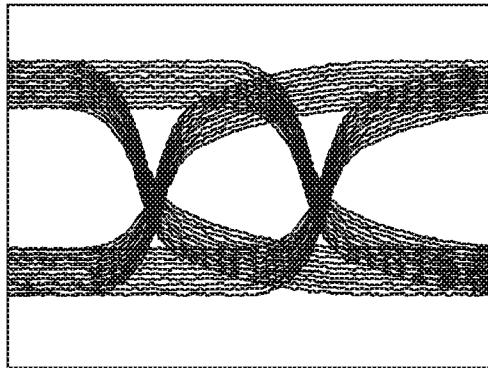
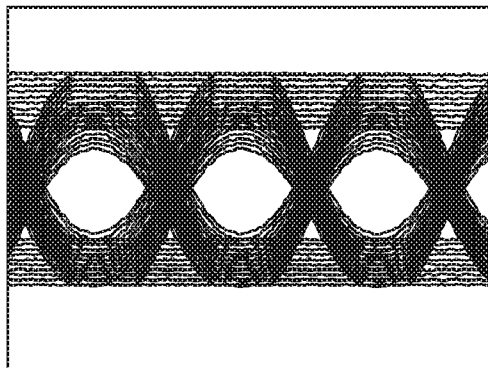
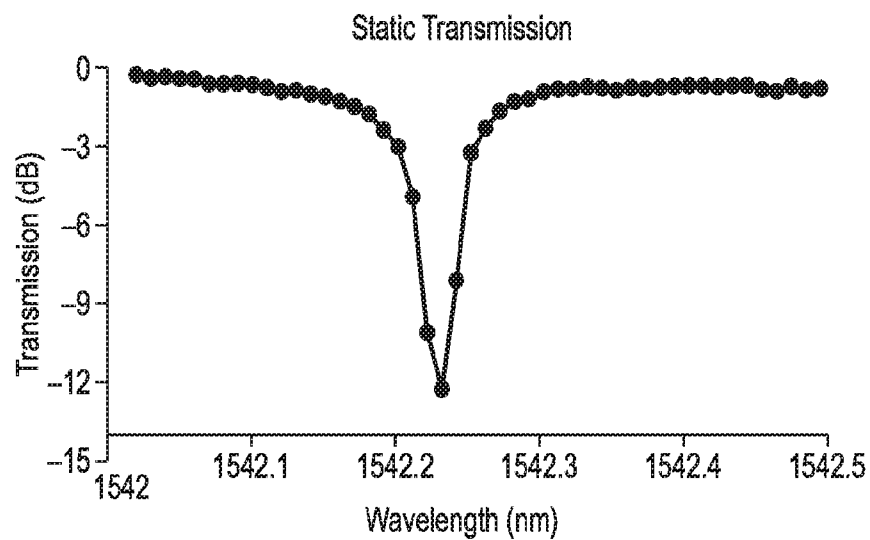


FIG. 9

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**FIG. 10A****FIG. 10B****FIG. 11**

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/022504**A. CLASSIFICATION OF SUBJECT MATTER****G02B 6/293(2006.01)i, H01S 3/08(2006.01)i, H01S 3/067(2006.01)i, G02B 6/38(2006.01)i**

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)

G02B 6/293; G02F 1/095; H04L 27/20; G02B 6/42; G02B 6/12; H04B 10/04; G02F 1/01; H01S 3/08; H01S 3/067; G02B 6/38

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: modulator, ring, differential, output, input, coupler, shift, optic

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2008-0181332 A1 (TIAN et al.) 31 July 2008 See paragraphs [0024], [0030] and figure 2A.	12
A		1-11, 13-22
A	US 2012-0155888 A1 (JI et al.) 21 June 2012 See paragraphs [0068], [0100], [0107] and figures 5A-5D.	1-22
A	US 2010-0303122 A1 (POPOVIC) 02 December 2010 See paragraphs [0058]-[0067] and figures 4A-4C.	1-22
A	US 2012-0243828 A1 (SUZUKI) 27 September 2012 See paragraphs [0040]-[0046] and figures 1-2.	1-22
A	JP 2014-211550 A (TOHOKU UNIV.) 13 November 2014 See paragraphs [0028]-[0039] and figures 1(a)-1(c).	1-22



Further documents are listed in the continuation of Box C.



See patent family annex.

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

20 June 2016 (20.06.2016)

Date of mailing of the international search report

21 June 2016 (21.06.2016)

Name and mailing address of the ISA/KR

International Application Division

Korean Intellectual Property Office

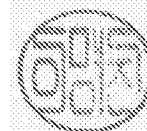
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/022504

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2008-0181332 A1	31/07/2008	JP 2008-187713 A JP 4946891 B2 US 7912378 B2	14/08/2008 06/06/2012 22/03/2011
US 2012-0155888 A1	21/06/2012	CN 102546027 A DE 102011088358 A1 JP 2012-133363 A KR 10-2012-0089895 A US 8818203 B2	04/07/2012 21/06/2012 12/07/2012 16/08/2012 26/08/2014
US 2010-0303122 A1	02/12/2010	US 8483521 B2 WO 2010-138849 A1	09/07/2013 02/12/2010
US 2012-0243828 A1	27/09/2012	JP 2012-198465 A JP 5455955 B2	18/10/2012 26/03/2014
JP 2014-211550 A	13/11/2014	None	