Proof of concept of directed OR/NOR and AND/NAND logic circuit consisting of two parallel microring resonators

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We propose and demonstrate a directed OR/NOR and AND/NAND logic circuit consisting of two parallel microring resonators (MRRs). We use two electrical signals representing the two operands of the logical operation to modulate the two MRRs through the thermo-optic effect, respectively. The final operation results are represented by the output optical signals. Both OR/NOR and AND/NAND operations at 10 kbps are demonstrated. © 2011 Optical Society of America

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Generally, the traditional logic for the implementation of the specific logical operations needs a Boolean logic gate. Such a logic gate has two input signals and only one output signal, and the inputs that determine the state of the element must pass through the preceding elements. Thus, it is not only dissipative in information and energy, but also delayed in processing time. In contrast, the directed logic proposed by Hardy and Shamir performs computation by an optical switching network, in which the operation of each element is independent of the operations of other elements and all elements perform their operations simultaneously [1–3]. Furthermore, a directed logic gate inherently performs both an operation and its complementary one simultaneously. Therefore, the directed logic has potential advantage over the traditional logic in the power consumption and the processing speed [1–3].

It is well known that basic logical operation is very important for optical signal processing and computing; since more complex logical operations can be performed by properly cascading some basic logical operations. We have reported directed XOR/NXOR logic circuit in our previous work [4]. In this Letter, we propose another directed logic circuit consisting of two parallel microring resonators (MRRs) that can perform OR/NOR or AND/NAND operations simultaneously.

A MRR based on silicon-on-insulator is an attractive structure due to its outstanding performance, compact size, and complementary metal oxide semiconductor-compatible fabrication process. Until now, many traditional logic gates based on MRRs have been proposed and fabricated [5–8]. Most of the demonstrated logic gates are based on the nonlinear effects of silicon, which need a strong optical control pulse; thus, it is not easy to realize large-scale integration. Here, we use the switching functions of the MRRs based on the thermo-optic effect of silicon to achieve a directed logic circuit, which does not need a strong optical control pulse. The proposed architecture consisting of two parallel MRRs is shown in Fig. 1(a). A monochromatic continuous optical wave with a working wavelength of $\lambda$ is modulated by the two electrical pulse trains $X$ and $Y$ applied to the MRR1 and MRR2, respectively. We regard the $X$ and $Y$ as a sequence Boolean 0 and 1s and do not care about their actual voltage amplitude. The 0 and 1 represent the low and high levels of the electrical pulse. The optical pulse trains are outputted at the drop and through ports of the device.

Before the discussion on the principle of the device, we first introduce the definition of the MRR’s resonant states. For simplicity, we only introduce the definition of MRR1’s resonant state. The same definition is also effective for MRR2. MRR1 is on resonance at the wavelength of $\lambda$ and the signal light is downloaded at the drop port of MRR1 when the applied voltage is at the high level ($X = 1$). MRR1 is off resonance at the wavelength of $\lambda$ and the signal light is exported at the through port of the MRR1 undisturbedly when the applied voltage is at the low level ($X = 0$). Thus, we can employ $X$ and $\bar{X}$ to represent the output optical pulse trains at the drop and through ports of the MRR1, respectively ($\bar{X}$ is the inverse of $X$). According to the above definition, the signal light is exported at the through port when $X = 0$ and $Y = 0$, and the signal light is downloaded at the drop port when $X = 0$ and $Y = 1$. Figure 1(a) shows the pulse trains $X + Y$ and $X + Y$ are achieved at the drop and through ports of the device, respectively. Note that the plus sign represents logical operation OR here.

The device is fabricated on an 8 in. (20.3 cm) silicon-on-insulator substrate with a 220 nm top silicon layer and a 2 $\mu$m buried SiO$_2$ layer. The micrograph of the device is shown in Fig. 1(b). In order to maintain the single mode and single polarization propagation in the waveguides and reduce the loss and reflection in the MRRs, a ridge waveguide with 400 nm in width, 220 nm in height, and 70 nm in slab thickness is utilized. The radius of each ring waveguide is 10 $\mu$m and the gaps between the ring waveguides and the straight waveguides are 325 nm. After the waveguides are fabricated, two microheaters with 200 nm titanium layers are formed. After that, 50 $\mu$m wide Al traces and 120 x 120 $\mu$m$^2$ pads are fabricated. A
thermo-optic modulating scheme is adopted for the proof of concept since it demands less complex device layer structure and consequently yields easier fabrication steps.

An amplified spontaneous emission source, an optical spectrum analyzer (OSA), and two tunable voltage sources are used to characterize the static response of the fabricated device. The broadband light is coupled into the device through a lensed fiber. The output light is collected by another lensed fiber and fed into an OSA. The two tunable voltage sources are used to drive the two heaters above the MRRs. When the MRRs are heated up, the effective refractive index of the ring waveguides increases and the resonant wavelengths of the MRRs shift to the longer wavelength.

The static response spectra at the drop and through ports of the device are shown in Figs. 2 and 3. The 1565.850 nm wavelength was chosen as the working wavelength because there is a minimum (representing 0) at the drop port of the device when the voltages applied to the MRRs are both 0 V [see Fig. 2(a)]. We also observe a dip at 1563.378 nm, which originates from the super-mode formed by the coupling between MRR1 and MRR2 [9]. However, the presence of the supermode has no effect on the operation of the device since the working wavelength is far from the dip. Interestingly, such a characteristic can be utilized to acquire the XOR and NXOR operations, which is left for future work. The resonant wavelength of MRR2 shifts to 1565.850 nm when an appropriate voltage (2.20 V) is applied and the resonant wavelength of MRR1 does not change since no voltage is applied [see Fig. 2(b)]. Therefore, a maximum appears there (representing 1). The resonant peak of MRR1 shifts from 1563.455 to 1565.850 nm when the voltage applied to it is 2.14 V and the resonant peak of the MRR2 does not change when the voltage applied is 0 V [see Fig. 2(c)]. Therefore, a maximum appears there. There is only one peak in Fig. 2(d), which means that the two resonant peaks of MRR1 and MRR2 are same when the voltages applied are 2.14 and 2.20 V. From Fig. 2, we observe clearly ripples on the sides of the resonance peak, which originate from the interference effect due to the coupling of the two MRRs. The static response spectra at the

Fig. 2. Static response at the drop port with the voltages applied to MRR1 and MRR2 being (a) both 0 V, (b) 0 and 2.20 V, (c) 2.14 and 0 V, (d) 2.14 and 2.20 V.

Fig. 3. Static response at the through port with the voltages applied to MRR1 and MRR2 being (a) both 0 V, (b) 0 and 2.20 V, (c) 2.14 and 0 V, (d) 2.14 and 2.20 V.

Fig. 4. (Color online) Signals applied to (a) MRR1 and (b) MRR2. (c) OR result at the drop port and (d) NOR result at the through port of the device.
through port in all four statuses are shown in Fig. 3. The status of the device is characterized with the resonant peak in Fig. 2 and the resonant dip in Fig. 3. Except for the above difference, the static response spectra at the through port of the device can be discussed with the same process. The power consumption is about 18.2 and 15.1 mW for MRR1 and MRR2, respectively, when the voltages applied to them are at the high level.

After the working wavelength and the analog voltages representing logical 1 are determined, a monochromatic light at $\lambda$ from a tunable laser is coupled into the fabricated circuit and the output light at the drop and through ports of the fabricated circuit is fed into a detector. The electrical signals transformed by the detector and the two electrical signals applied to the two MRRs are fed into a four-channel oscilloscope for waveform observation. Two pseudorandom binary sequence $2^4 - 1$ non-return-to-zero signals at 10 kbps are converted to two analog voltages applied to MRR1 and MRR2. (The high levels of the electrical pulses are 2.14 and 2.20 V for MRR1 and MRR2, respectively. The low levels of the electrical pulses are both 0 V for MRR1 and MRR2.) We use the two analog voltages to modulate the corresponding MRRs. From Fig. 4, we can see clearly that the OR result and the NOR result of the two electrical signals are achieved at the drop and through ports of the device simultaneously. Some sharp small dips appear between the two continuous logical 1. It is mainly because the two continuous logical 1 are from the different resonant state combinations of the two MRRs. For example, the first logical 1 is from the combination of the off-resonance MRR1 and the on-resonance MRR2 ($X = 1, Y = 0$) while the second logical 1 is from the combination of the on-resonance MRR1 and the off-resonance MRR2 ($X = 1, Y = 0$). The reason for the sharp small peaks in Fig. 4(d) is the same as that for the sharp small dips in Fig. 4(c).

Interestingly, the other two operations can be achieved with the proposed architecture if we use another definition of the MRRs’ resonant states. In this definition, the MRRs are on resonance when the electrical pulses applied to them are at the low level (representing 0) and the MRRs are off resonance when the electrical pulse applied to them are at the high level (representing 1). The dynamic response of the device is shown in Fig. 5. (Note that we assume the low levels of the electrical pulses to be $-2.14$ and $-2.20$ V for MRR1 and MRR2, respectively, and the high levels of the electrical pulses to be 0 V for both MRR1 and MRR2.) We can see clearly that the NAND operation at the drop port of the device and the AND operation at the through port of the device can be carried out correctly.

In conclusion, we have proposed and fabricated a directed logic circuit using two parallel MRRs. According to the different definitions of the microrings’ resonant states, the directed logic circuit can perform four kinds of logical operations including OR, NOR, AND, and NAND. Moreover, the OR and NOR operations or the AND and NAND operations can be carried out at two different output ports simultaneously. So far, the directed logic architectures proposed by us can perform all common logical operations, including OR/NOR, AND/NAND, and XOR/NXOR operations. To achieve faster operations, we can employ other advanced modulation schemes, such as the plasma dispersion effect or the electric field effect to modulate the MRRs [19].

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References