Design of all optical 1-bit and 2-bit magnitude comparator using micro-ring resonator

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***Abstract*— The feasibility of implementing all-optical 1-bit and 2-bit magnitude comparator is theoretically investigated using Silicon waveguide based micro-ring resonator (MRR). The MRRs are modulated by optical pump signals, which represent the binary numbers to be compared. The proposed model has high extinction ratios of 13 dB at very low pump powers of 1.82 mW.**

Keywords*— *optical computing, Optical logic devices, micro-ring resonator.

I. Introduction

High-performance digital systems that address services like asynchronous transfer mode, IP/Tag switching and multiprotocol label switching (MPLS), signal regeneration, data encoding and encryption motivate the development of high-speed all-optical switches due to its key features of huge bandwidth, high speed, massive parallel interconnectivity, electromagnetic interference (EMI) immunity and low power consumption [1]. To achieve potential requirements, researchers have shown great interest to implement different combinational and sequential logic circuits using various schemes both theoretically and experimentally in all optical domain [2-6]. However, almost all of these are complex and bulky in volume.

Silicon micro-ring resonator (MRR) has attracted much attention due to its compact footprint, low power consumption and is considered as an ideal element to construct complex optical switch network. Owing to which various authors have shown their keen interest in implementing a number of logical circuits using micro-ring resonator based optical switch [7-8]. Optical comparator is another important element for optical computing, which can be utilized for decision making, threshold circuits and to construct various complex optical logic circuits. Several optical digital comparators circuits based on various schemes, such as SOA based MZI, cross gain modulation (XGM), Single mode Fabry–Pérot laser diodes (SMFP-LDs), $LiNbO_3$ based MZI have been proposed and verified [9-10].

In this paper, we propose and describe a scheme to design optical 1-bit and 2-bit magnitude comparators using cascaded MRRs and optical combiner, which can perform the comparison function between two digital values (1-bit and 2-bit). The proposed architecture can benefit from the features of the MRR switch, such as low-power consumption, high operation speed, high compactness, and compatibility with CMOS fabrication process [11].

The paper is organized as follows: Operational principle of all optical 2×2 switch using micro-ring resonator is discussed in Section II. In Section III, the basic working principle and design of 1-bit and 2-bit magnitude comparator circuits are explained. Simulation results and discussion of the proposed architectures are presented in Section IV. Finally section V is the conclusion of the paper.

II. Micro-Ring Resonator Based Optical Switch

The basic configuration of the silicon micro-ring resonator (MRR) consisting two straight bus waveguides coupled to a micro-ring in between is shown in Fig. 1(a) [12]. When light of the working wavelength is passed through the ring from input waveguide, it builds up in intensity over multiple round-trips due to constructive interference. The amount of light which couples in and out of the ring is determined by the input-output couplers. Then at resonance drop port shows maximum transmittance and through port shows a minimum transmittance without pump power. The resonance condition can be varied by applying pump power to the ring which induces the TPA (two photon absorption) generated free-carrier concentration change. This results in the refractive-index change and the π-phase shift in one circle of the ring, so that output light signal will be switched from drop port to through port. Thus optical switching for signal between two output ports (through port and drop port) can be realized. The transmission characteristic of a single micro-ring resonator is shown in Fig.1(b). The output electric fields at through and drop ports can be written as respectively [12],

$$E_t = \frac{\sqrt{1-\kappa_1} - \sqrt{1-\kappa_2}\,x^2 \exp^2(j\phi)}{1-\sqrt{1-\kappa_1}\sqrt{1-\kappa_2}\,x^2\exp^2(j\phi)} E_{i1} + \frac{-\sqrt{\kappa_1}\sqrt{\kappa_2}\,x\exp(j\phi)}{1-\sqrt{1-\kappa_1}\sqrt{1-\kappa_2}\,x^2\exp^2(j\varphi)} E_{i2}$$

$$E_d = \frac{-\sqrt{\kappa_1}\sqrt{\kappa_2}\,x\exp(j\phi)}{1-\sqrt{1-\kappa_1}\sqrt{1-\kappa_2}\,x^2\exp^2(j\phi)}E_{i1} + \frac{\sqrt{1-\kappa_2}-\sqrt{1-\kappa_1}\,x^2\exp^2(j\phi)}{1-\sqrt{1-\kappa_1}\sqrt{1-\kappa_2}\,x^2\exp^2(j\phi)}E_{i2}$$

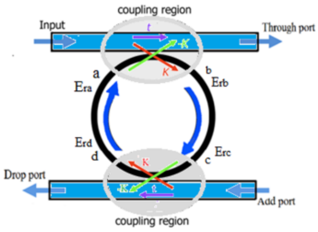

Fig.1(a): Single ring resonator

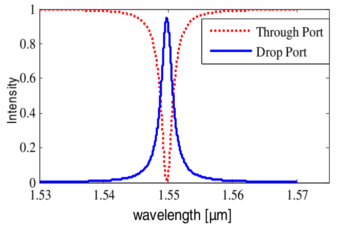

Fig.1 (b) Transmission characteristics of ring

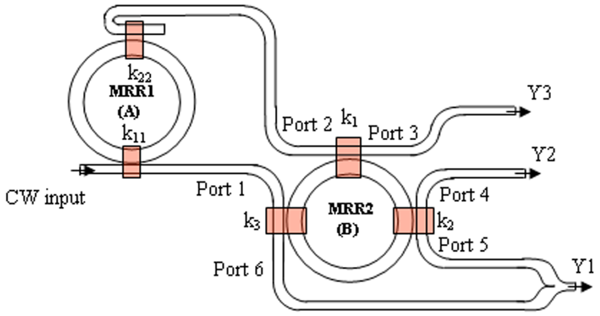

Fig. 2: Design of 1-bit comparator circuit using MRRs

Where, κ_1, κ_2 are the field coupling coefficient between the ring and input & output bus respectively and ring, κ_n is wave propagation constant, where $\kappa_n = \frac{2\pi}{\lambda}n_{eff}$, λ is the resonant wavelength of the ring, n_{eff} is effective refractive index of the material of the ring, x= $\exp(-\alpha\frac{L}{2})$, $\varphi = \frac{\kappa_n.L}{2}$, E_{i1} and E_{i2} are the input and add port field respectively. Effective refractive index of Si-waveguide ring can be expressed as n_{eff}= n_0+n_2I=n_0+ $\frac{n_2}{S}P$, where n_0 and n_2 are the linear and non-linear refractive indexes of the material respectively. I and P are the intensity and power of the optical pump signal. S is the effective cross sectional area of the ring resonator. For simplification of the calculation of fields, coupling losses does not take into account.

III. Design of Magnitude Comparators Using Micro-Ring Resonator

A combinational circuit, namely magnitude comparator, is a logic circuit which compares two binary numbers A and B and produces three outputs in terms of A = B (equality), A > B (greater than), and A < B (less than). Only one of its outputs will be high based on the input bit patterns.

A. Design of 1-bit magnitude comparator

The schematic diagram to realize an all-optical 1-bit optical comparator circuit is shown in Fig. 2. The proposed 1-bit optical comparator consists of two optically modulated MRRs and an optical combiner, which are connected by three waveguides. Monochromatic continuous optical wave at the working wavelength of λ is coupled into the input port of the device. Two MRRs are modulated by two optical pump pulse trains A and B respectively. When the optical pump signals are applied to the MRRs, the comparison results will appear at the output ports of the device in the form of optical pulse.

In order to clarify the principle of the optical comparator, we firstly introduce the principles of its two fundamental elements: MRR1 and MRR2. MRR1 behaves as the 1×2 optical switch. When a low-level optical pump signal is applied to MRR1, it is on-resonance at working wavelength λ and the optical signal coupled into its input port is directed to its drop port. When a high-level optical pump signal is applied to MRR1, it is off-resonance at λ and the optical signal coupled into its input port is directed to its through port. MRR2 also behaves as an optical switch. It has six ports and three coupling regions. In principle, any port can be considered as the input port of the optical signal. In the proposed device, only port 1 and port 2 behave as the input ports of the optical signal, and one of these two ports also behaves as the output port when the other port acts as the input port. When a low-level optical pump signal is applied to MRR2, it is on-resonance at λ. The optical signal coupled into port 2 is directed to port 5 and port 1, and the optical signal coupled into port 1 is directed to port 4 and port 2. When a high-level optical pump signal is applied to MRR2, it is off-resonance at λ. The optical signal coupled into port 1 is directed to port 6 and the optical signal coupled into port 2 is directed to port 3. Now we can easily introduce the principle of the proposed device.

When A=B=0, both MRR1 and MRR2 are on- resonance at λ. The optical signal at λ coupled into the input port of the device is firstly directed to the drop port of MRR1, and then the input optical signal to MRR2 is directed to port 5 of MRR2 and finally directed to the output port Y1 by the optical combiner. Therefore logical 1 is achieved at the output port Y1 and logical 0 is achieved at the output ports Y2 and Y3.

When A=B=1, both MRR1 and MRR2 are off-resonance at working wavelength λ. The optical signal coupled into the input port of the device firstly directed to the through port of MRR1 and act as input signal of MRR2 at port 1 and then directed to port 6 of MRR2 and finally directed to the output port Y1 by the optical combiner. Therefore logical 1 is achieved at the output port Y1 and logical 0 is achieved at the output ports Y2 and Y3.

When A=0 and B=1 (A<B), MRR1 is on-resonance and MRR2 is off-resonance at working wavelength λ. The optical signal at λ coupled into the input port of the device is firstly directed to the drop port of MRR1. Then the optical signal bypasses MRR2 and finally directed to the output port Y3. Therefore logical 1 is achieved at the output port Y3 and logical 0 is achieved at the output ports Y1 and Y2.

When A=1 and B=0 (A>*B*), MRR1 is off-resonance and MRR2 is on-resonance at working wavelength λ. The optical signal at λ coupled into the input port of the device firstly bypasses MRR1. Then the input optical signal to MRR2 is directed to port 4 of MRR2 and finally directed to the output port Y2. Therefore logical 1 is achieved at the output port Y2 and logical 0 is achieved at the output ports Y1 and Y3. So the proposed device can perform the comparison function of two binary numbers. Table 1 shows all possible combinations of the pump signals and the output optical signal obtained at the different output ports of the structure.

TABLE 1: Truth table of 1-bit magnitude comparator

Control (pump) signal		**Output signals at different ports**		
A	**B**	**Port Y1 (A=B)**	**Port Y2 (A>B)**	**Port Y3 (A<B)**
0	0	1	0	0
0	1	0	0	1
1	0	0	1	0
1	1	1	0	0

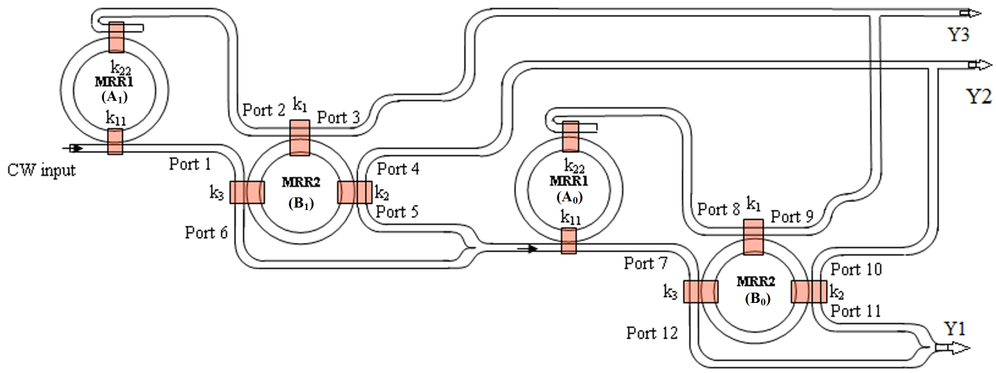

Fig. 3: Design of 2-bit comparator circuit using MRRs

B. Design of 2-bit magnitude comparator

The schematic diagram for comparing two 2-bit numbers is shown in Fig. 3. Only four number of ring resonator is being used to design the proposed structure. The proposed model for 2-bit comparator in this paper is simpler than reference [9] in terms of number of ring used.

To determine the relative magnitude of two 2-bit numbers A (A_1A_0) and B (B_1B_0), the relative magnitudes of pairs of significant bits are to be inspected from the most significant positions. If the digits of most significant position are equal, next significant pair of digits is to be compared. So the Boolean expressions for the three conditions can be written as:

$$F(A=B) = X_1 X_0 \text{, where } X_i = A_i B_i + \overline{A_i}\,\overline{B_i} = \mathrm{A\Theta B}.$$

$$F(A>B) = A_1 \overline{B_1} + X_1 A_0 \overline{B_0}$$

$$F(A<B) = \overline{A_1} B_1 + \overline{A_0} B_0 X_1$$

Monochromatic continuous optical wave at the working wavelength of λ is coupled into the input port of MRR1. First two MRRs (MRR1 and MRR2) are modulated by two optical pump pulse trains A_1 and B_1 respectively. Last two MRRs (MRR3 and MRR4) are modulated by another two optical pump pulse trains A_0 and B_0 respectively. The switching function of MRR3 and MRR4 can also be explained in a similar way as discussed for MRR2. The working principle of the proposed 2-bit comparator device is similar as discussed for 1-bit comparator. When the optical pump signals are applied to the MRRs, the comparison results will appear at the output ports of the device in the form of optical pulse. The final output Y1 for A=B is obtained by combining the optical outputs from port 11 and port 12. Output Y2 for A> B is obtained by combining the optical outputs from port 4 and port 10. Similarly output Y3 for A<B is obtained by combining the optical outputs from port 3 and port 9. Table 2 shows all possible combinations of the pump signals and the output optical signal obtained at the different output ports of the proposed 2-bit comparator.

TABLE 2: Truth table of 2-bit magnitude comparator

Control (pump) signal				**Output signals at different ports**		
A_1	**A_0**	**B_1**	**B_0**	**Port Y1 (A=B)**	**Port Y2 (A>B)**	**Port Y3 (A<B)**
0	0	0	0	1	0	0
0	0	0	1	0	0	1
0	0	1	0	0	0	1
0	0	1	1	0	0	1
0	1	0	0	0	1	0
0	1	0	1	1	0	0
0	1	1	0	0	0	1
0	1	1	1	0	0	1
1	0	0	0	0	1	0
1	0	0	1	0	1	0
1	0	1	0	1	0	0
1	0	1	1	0	0	1
1	1	0	0	0	1	0
1	1	0	1	0	1	0
1	1	1	0	0	1	0
1	1	1	1	1	0	0

IV. SIMULATION RESULTS

Silicon waveguide based micro-ring resonator is a powerful device to realize the ultra-fast all optical switch. We choose probe input beam power 0.1mW such that there is no variation of refractive index of the material of MRRs for input probe beam and the other optimized parameters for the simulation are [13]: β = 7.9x10^{-10} cm/W, resonance wavelength (λ) =

1551 nm, pump beam wavelength (λ_p)=400 nm, τ=100fs, tp=12.5 ns, hυ=49.725x10^{-20} J, L=2πr=19.16 µm, S=450x 250 nm^2, n_2=4x10^{-18} m^2/W, coupling co-efficient, ks=0.22. It can be shown that when the phase shift approaches π, the average pump power required for switching is only 1.82 mW.

Fig. 4 shows the simulation results of 1-bit magnitude comparator for different combinations of control signals 'AB' for non-return-to-zero (NRZ) data pulse format.

Fig. 5 shows the simulation results of 2-bit magnitude comparator for different combinations of control signals 'AB' for non-return-to-zero (NRZ) data pulse format.

From the simulation results we have calculated the performance parameters like extinction ratio (ER), contrast ratio (CR) and amplitude modulation (AM) of the proposed circuits and noted the optimum values are 13 dB, 17 dB and 0.26 dB respectively at the optimum operating point.

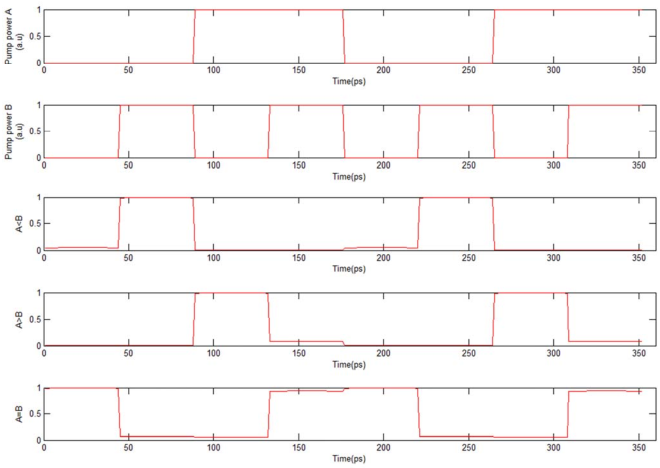

Fig. 4: simulation output of 1-bit comparator using MRRs

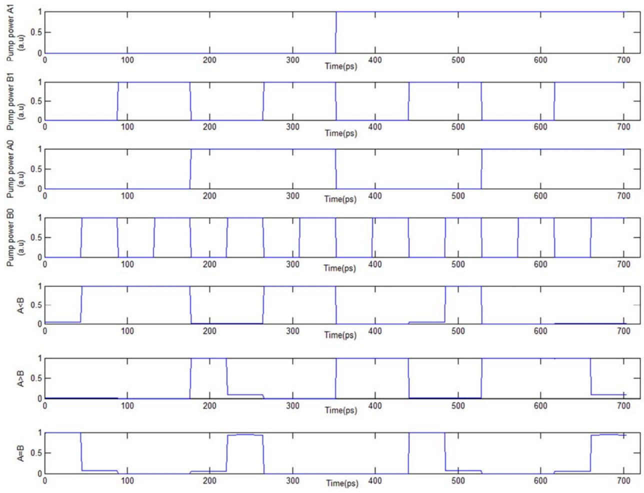

Fig. 5: simulation output of 2-bit comparator using MRRs

V. Conclusion

In conclusion, the paper describes the application of Silicon waveguide based micro ring resonator optical switching for the implementation of all optical 1-bit and 2-bit comparator based on cascaded MRRs and optical combiner with potential advantages low signal loss, signal security, larger bandwidth, high operation speed, low latency and parallel computing. Numerical simulation results confirming described methods are also given in this paper. The theoretical model developed and the numerical results obtained may help in designing all optical signal processing techniques and they are expected to play important roles in constructing future all-optical photonic networks. The performance parameters like extinction ratio (ER), contrast ratio (CR) and amplitude modulation (AM) of the proposed circuit have been calculated and noted the optimum value as 13 dB, 17 dB and 0.26 dB respectively at very low pump powers of 1.82 mW.

References

[1] A. E. Willner, S. Khaleghi, M. R. Chitgarha, O. F. Yilmaz, "All-optical signal processing", Journal of Lightwave Technology, 32(4), 660-680 (2014).

[2] L. Zhang, et al. "Demonstration of directed XOR/XNOR logic gates using two cascaded microring resonators", Optics letters, 35(10) 1620-1622 (2010).

[3] J. K. Rakshit, J. N. Roy, "All-optical ultrafast switching in a silicon microring resonator and its application to design multiplexer/demultiplexer, adder/subtractor and comparator circuit", Optica Applicata, 46(4), 517-539 (2016).

[4] J. K. Rakshit, J. N. Roy, "Design of all-optical time-division multiplexing scheme with the help of microring resonator", Optica Applicata, 44(1), 39-54 (2014).

[5] K. E. Zoiros, M. K. Das, D. K. Gayen, H. K. Maity, T. Chattopadhyay, J. N. Roy, "All-optical pseudorandom binary sequence generator with TOAD-based D flip-flops", Optics Communications, 284(19), 4297-4306 (2011).

[6] S. Kumar, C. Chauhan, "Design of reversible multiplexer using electro-optic effect inside lithium niobate-based Mach–Zehnder interferometers", Optical Engineering, 55(11), 115101-115101 (2016).

[7] L. Yang, J. Ding, Q. Chen, P. Zhou, F. Zhang, and L. Zhang, "Demonstration of a 3-bit optical digital-to-analog converter based on silicon microring resonators", Optics letters, 39(19), 5736-5739 (2014).

[8] J. K.Rakshit, J.N. Roy, and T. Chattopadhyay, "A theoretical study of all optical clocked D flip flop using single micro-ring resonator", Journal of Computational Electronics, 13(1), 278-286 (2014).

[9] S. Kumar, A. Bisht, G. Singh, K. Choudhary, K. K. Raina, A. Amphawan, "Design of 1-bit and 2-bit magnitude comparators using electro-optic effect in Mach–Zehnder interferometers", Optics Communications, 357, 127-147 (2015).

[10] L. Yang, C. Guo, W. Zhu, L. Zhang, C. Sun, "Demonstration of a directed optical comparator based on two cascaded microring resonators", IEEE Photonics Technology Letters, 27(8), 809-812 (2015).

[11] Q. Xu, and R. Soref, "Reconfigurable optical directed-logic circuits using microresonator-based optical switches," Opt. Exp., 19(6), 5244–5259 (2011).

[12] J. K. Rakshit, T. Chattopadhyay, J. N. Roy, "Design of ring resonator based all optical switch for logic and arithmetic operations–a theoretical study", Optik-International Journal for Light and Electron Optics, 124(23), 6048-6057 (2013).

[13] J. K. Rakshit, J. N. Roy, "Design of all-optical universal shift register using nonlinear microring resonators", Journal of Computational Electronics, 15(4), 1450-1461 (2016).