Design of micro-ring resonator based all optical universal reconfigurable logic circuit

G. K. BHARTI, U. BISWAS, J. K. RAKSHIT*

Department of Electronics & Instrumentation Engineering, National Institute of Technology Agartala, Tripura, India

All optical universal reconfigurable logic circuit is proposed and described using micro-ring resonator based optical switching array which can perform any combinatorial logic operations. Optical pump signals with low pump power are used to control the MRRs switching status. For proof of concept, a number of logic functions of four-operand with 67 Gbps operation speed are simulated successfully. A combination of feasible OMRR radius and coupling coefficient is identified through numerical simulation and analyzed the system performance of the scheme which confirms the feasibility of the design. The device is useful in order to reduce the complexity of the circuit.

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1. Introduction

The current computing technology and industry is facing a lot of problems because of bandwidth and speed limitation of silicon electronics. Recent expansion of silicon photonics gear up in optical computing and signal processing due to the high bandwidth, high speed, low power consumption, parallelism properties of light and CMOS compatible fabrication process [1-2]. More attention is given in silicon photonics in various field and successfully demonstrated different optical devices such as filters, multiplexers, router, sensors, optical logic devices and optical modulators etc. [3-5].

In recent years, different all optical logic circuits have been proposed and demonstrated based on several different schemes including semiconductor optical amplifier (SOA) [6], quantum-dot SOA [7], Mach–Zehnder inter-ferometer(MZI) [8], four-wave mixing process in SOA [9] or cross gain (XGM) or cross phase (XPM) modulation [10], highly nonlinear fibers (HNLF) [11], periodically poled lithium niobate (PPLN) [12] and micro-ring resonator [13-14] etc.

Recently optical micro-ring resonator (OMRR) is widely used in silicon photonics as a basic component in high speed optical computing and information processing system due to its unique advantages like compact size, sharp resonances, low power consumption, reduced switching threshold and large-scale integration.

Previously reported most of the existing all-optical logic circuits have been designed to perform a single function, but recent technologies recommend that a single device may also be able to perform multiple logic operations. All optical reconfigurable logic plays an important role in optical information processing and computing which can carry out any combinatorial logic functions. Recently, many researchers get attracted much more interest to construct reconfigurable logic circuits which can perform various logic operations due to its flexibility for networking operations and potentially low cost. The reconfigurable all optical logic gates come together some new innovations along with some existing technologies to realize its novel functionality.

Recently, many reconfigurable logic circuits have been proposed and demonstrated in [15-17]. Reconfigurable logic circuit proposed in [17] has been used MRR based optical multiplexer as basic element which increases the complexity of the logic circuits and they only can perform several specific logic operations, which definitely limit their practical applications in the future. The reconfigurability between logic operations was achieved solely by adjusting the select lines of the multiplexer. But, in the proposed manuscript, the universal reconfigurable logic circuit is proposed which can execute any combinatorial logic operations according to the logic expressions using OMRR-based optical switch array. Reconfigurable logic circuit has also been demonstrated using micro-ring resonator with electro-optic method at very low operation speed [18-19].

In this paper, we propose and describe another all optical reconfigurable logic circuit which can execute any combinatorial logic operations according to the logic expressions using OMRR-based optical switch array using pump-probe configuration at very high operational speed.

2. Switching operation of micro-ring resonator

The switching structure for the reconfigurable logic circuit is composed of unit cells of 1 × 1 switch that is constructed on silicon micro-ring resonator. In this subsection, the switch structure will be discussed and implementation of three operation modes of the switch will also be discussed. OMRR-based optical switch consisting of a single waveguide and one OMRR is shown in Fig. 1 which is a basic building block for the proposed Universal reconfigurable logic circuit.

A continuous optical wave with a working wavelength of λ_i is injected to the input port of OMMR and the optical signal is modulated by an optical pump pulse fed into the OMRR. When the optical pump pulse is at a low level, the MRR is on-resonance at λ_i and through port output shows low transmission; i.e., OMRR block the input signal at the working wavelength. When optical pump pulse fed into the OMMR is at a high level, OMRR is off-resonance at λ_i which shows high transmission at the through-port at the working wavelength. Again, when the pump pulse is released, the resonance wavelength shifts back to its original position producing low transmittance at the through-port of the ring [20]. The through port output electric field can be written as [21-22],

$$E_t = \frac{\sqrt{1-\kappa} - \exp(-\frac{\alpha}{2}.L - jk_n.L)}{1-\sqrt{1-\kappa}\exp(-\frac{\alpha}{2}.L - jk_n.L)} E_{i1} \quad (1)$$

where, $\kappa_n = \frac{2\pi}{\lambda} n_{eff}$, is wave propagation constant, L is length of the ring, E_{i1} is the input field.

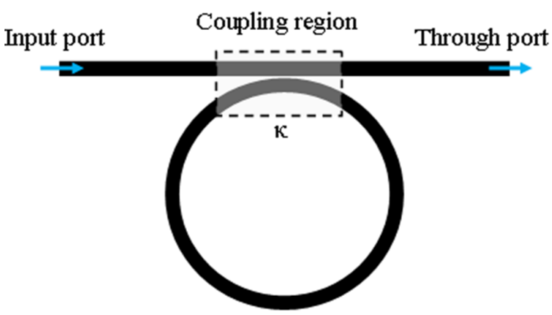

Fig. 1. Single waveguide coupled micro-ring resonator

This configuration of micro-ring resonator is the fundamental of a 1 × 1 switch that can be utilized as the unit cell of the proposed reconfigurable logic circuit. When the light pass through the straight waveguide resonates with the micro-ring resonator and light couples from the waveguide to the ring and the optical transmission at the through port reach a minimum. Thus the through port of the micro-ring resonator shows a sharp dip at the resonant wavelength as shown in Fig. 2. By pumping the ring resonator, resonant wavelength of the resonator can be changed and hence the transmission of light at the through port at a given working wavelength λ_L can be changed from low to high or vice versa, resulting in the off and on states of the 1 × 1 switch. The three operation modes of the reconfigurable switch are shown in Fig. 2(a)-2(c). The pump/control signal tunes the resonant wavelength between λ_1 (when the logic signal is '0') and λ_0 (when the logic signal is '1'). The position of λ_1 with respect to the laser working wavelength λ_L is controlled by the reconfiguration signal. When λ_L line up with λ_1 (Fig. 2(a)), the switch is in the off/on mode. The OMRR switch works in off/on mode is called on-resonance at the working wavelength when the applied pump power is 0 (logic 0). When λ_L line up with λ_0 (Fig. 2(b)), the switch is in the on/off mode. The on/off mode is just the opposite to off/on mode. In Fig. 2(b), the input single wavelength optical signal will be directed to the output port when OMRR is pump by 1.82 mW control signal. When λ_L line up with neither λ_0 nor λ_1 (Fig. 2(c)), the switch is in the on/on mode.

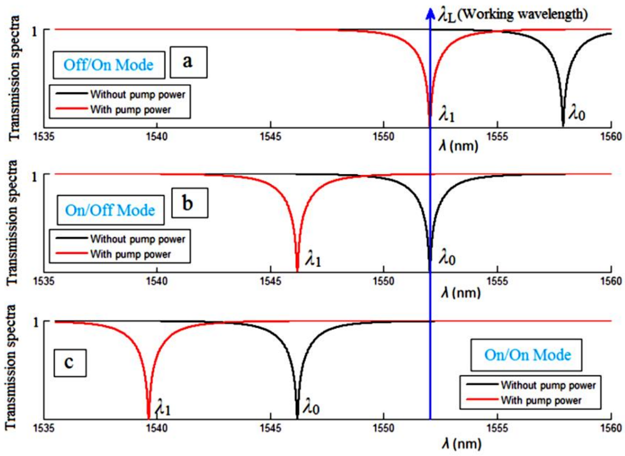

Fig. 2. The transmission spectra of a switch for light with the wavelength of λ_L (a) in off/on mode, (b) in on/off mode, (c) in on/on mode

3. Working principle and design of micro-ring resonator based reconfigurable logic circuit

We know that any logical function can be expressed as sum of product format. Each product term is a logical 'AND' operation of the input logic signals, where each input optical signal appear only once in either it's original or inverted form. The sum is the result of an OR function of all the product terms. For example, any logic function Y can be expressed as Y= x_1+ x_2+ x_3+-----+ x_n, where x_n indicates the product of variables, such as x= $p_1 \overline{p_2} p_3 \ldots\ldots \overline{p_n}$, where $\overline{p_n}$ represents the inverted logic value of p_n.

The proposed reconfigurable logic circuit (Fig. 3(d)) is composed of optical switch array consisting of N OMRR-based optical switches and one waveguide. In order to describe the operation principle of the proposed model, we first explain the operation principles of Fig. 3(a)–(c).

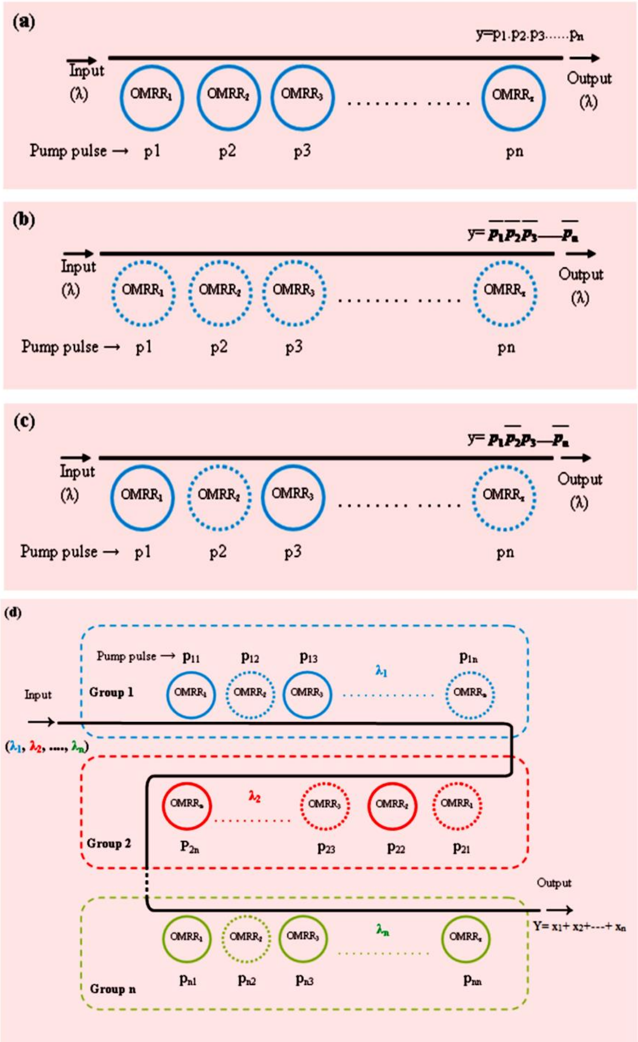

Fig. 3. Logic circuit of (a) OMRRs working in off/on mode with single working wavelength, (b) OMRRs working in on/off mode with single working wavelength, (c) OMRRs working in the on/off or off/on mode with single working wavelength and, (d) the proposed reconfigurable logic circuit. The solid line ring resonator indicates OMRR works in the off/on mode, the dot line ring resonator indicates OMRR works in the on/off mode, OMRRs with the same color work at the same working wavelength

A monochromatic CW light with the working wavelength of λ is coupled into the input port of logic circuits (Fig. 3(a)–(c)) and then modulated by the optical pump pulse sequences p_1; p_2; p_3; . . . ; p_n applied to $OMRR_1$; $OMRR_2$; $OMRR_3$; . . . ; $OMRR_n$, respectively. As we known, as long as one of all $OMRR_s$ is on-resonance in Fig. 3(a), i.e, as long as one of N operands (p_1; p_2; p_3; . . . ; p_n) is logic 0, the light transmitted in the straight waveguide is blocked (off). Therefore, low level optical power is detected at the output port and logic 0 is realized at the output port of the logic circuit. Based on the above discussions of the operation modes of OMRR-based optical switches, we identify the operation modes of all $OMRR_s$ as the off/on mode. Therefore, the AND operation of N operands can be realized by the logic circuit of Fig. 3(a) and the operation result y can be written as $y = p_1p_2p_3\ldots p_n$. Similarly, the AND operation of N inverse operands can also be performed if all OMRRs work in the on/off mode and the operation result can be written as $y = \overline{p_1}\,\overline{p_2}\,\overline{p_3}......\overline{p_n}$ (Fig. 3(b)). If some OMRRs work in the off/on mode and other OMRRs work in the on/off mode, the logic circuit can also perform the AND operation of N operands either in true or complement form. For example, if we define $OMRR_2$ and $OMRR_n$ work in the on/off mode and the other OMRRs work in the off/on mode in Fig. 3 (c), the operation result y can be written as $y = p_1\overline{p_2}p_3....\overline{p_n}$. If another continuous monochromatic wave of different wavelength λ_1 is coupled into the input port of the above mentioned logic circuits (Fig. 3 (a) - (c)), the OMMRs switch work as the on/on mode. In general, if a continuous monochromatic wave coupled into the logic circuit, the product of any N variables can be realized at the output port according to the definitions of OMRR different operation modes.

In the proposed configuration of Fig. 3(d), wavelength division multiplexing (WDM) technology can be used to realize reconfigurable logic operation. Multi-wavelength signal lights with the wavelength of λ_1, λ_2, λ_3, ... λ_n are coupled into the input port of the device simultaneously. In the logic circuit OMRRs are divided into different groups, in one group all OMRRs work at the same wavelength. In brief, every group can execute the product of any variables. The operation results of all groups are multiplexed together at last. Note that numbers of OMRRs in every corresponding group are equal to the numbers of operands in every product term. The final output of logic Y can be written as $Y = x_1 + x_2 + x_3 + ... + x_n$, where, x_n denotes the product of any variables. It is also to be noted that the number of groups are equal to the numbers of the working wavelengths.

For the proof of the concept, four optically tunable OMRRs based all optical reconfigurable logic circuit is designed which can perform any logic operations of four operands. In the proposed logic circuit four OMRRs are divided into two different groups, in each group two OMRRs work at the same wavelength. The radii of four OMRRs are considered as 2.88 µm, 2.97 µm, 3.05 µm, and 3.13 µm in order to four OMRRs have different initial resonance wavelengths. Thus the overall length to width of the substrate for four optically tunable OMRRs may at least 27µm × 8 µm. The spectral response of the device with no pump pulse applied to OMRRs is shown in Fig. 4. The resonant wavelengths of four cascaded OMRRs are 1539.65 nm, 1546.20 nm, 1552.04 nm, and 1557.90 nm, respectively. There are many different logic operations can be performed using four operands. As a proof of concept, only a few logic operations of four operands are explained here and shown in Fig. 5. $OMRR_1$ and $OMRR_2$ form the first group and the working wavelength, λ_1 is chosen as 1539.65 nm. $OMRR_3$ and $OMRR_4$ form the second group and the working wavelength, λ_2 is chosen as 1552.04 nm.

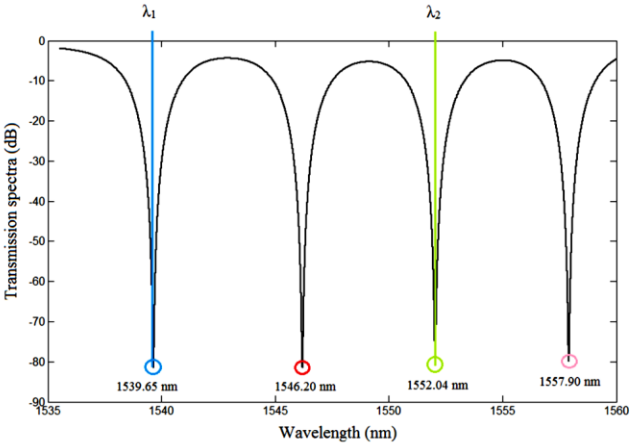

Fig. 4. The spectral response of the device with no pump pulse applied to OMRRs

Let us consider, two laser sources with the wavelengths of λ_1 and λ_2 are coupled into the input port of the circuit simultaneously. The $OMRR_1$ is controlled by operand A in the on/off mode and the $OMRR_2$ is controlled by operand B in the on/off mode also; the $OMRR_3$ is controlled by operand C in the off/on mode and the $OMRR_4$ is controlled by operand D in the off/on mode also. Therefore, the circuit can perform the logic operation of $\overline{A}\overline{B}+CD$ which is shown in Fig. 5(a). Similarly, other logic operations can also be realized based on different operation modes of OMRRs, and several other models are shown in Fig. 5(b) –(g).

Our proposed design is compatible with electron beam lithography technology on SOI substrate. Despite slow, it is an accurate fabrication processes and it is widely used for research purposes. In this paper we suggested the deep ultraviolet (DUV) e-beam lithography which is better suited for mass production, as suggested by P. Dumon et al [23].

The advantage of silicon waveguide based MRR is that the overall losses can be relatively low [24]. Pure silicon has an absorption loss much smaller than 0.1 dB/cm at a wavelength of 1.55 µm. Scattering loss is also very low. Curvature loss is in negligible levels. Insertion loss is also very low at the wavelength of 1.55 µm. The losses including coupling losses, attenuation losses and the round trip losses are the factors that need to be reduced in order to obtain optimum value of Extinction ratio, Contrast ratio and the Amplitude Modulation. We have optimized the different parameters in numerical simulations and obtained the losses of nearly 2dB.

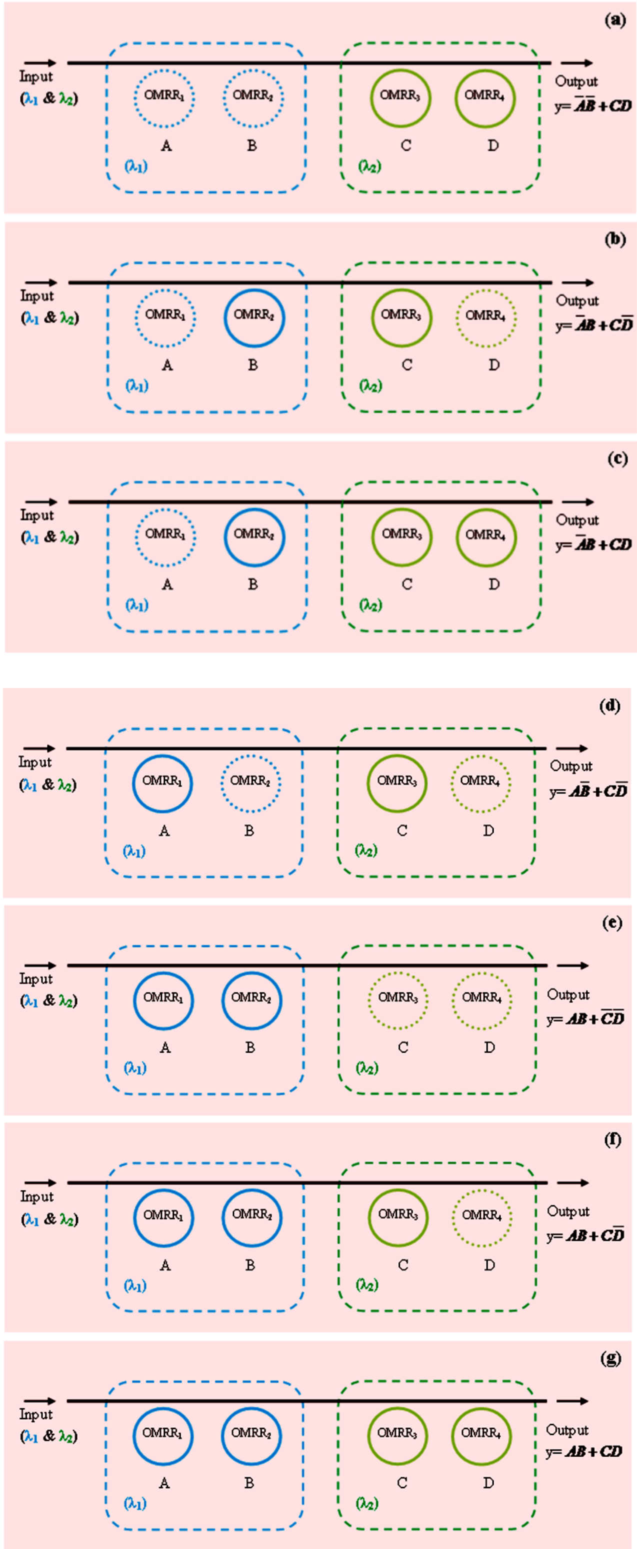

Fig. 5. Logic circuit diagrams for different four-input logic operations

4. Simulation results

To validate the proposed reconfigurable logic circuit and analyze the performance, we have conducted numerical simulations. The simulation work of all optical reconfigurable logic circuit is carried out on silicon waveguide based micro-ring resonator. Data rate of the circuit for simulation is considered as 67 Gbps. We choose probe input beam power 0.1mW such that there is no variation of refractive index of the material of OMRRs for input probe beam. A continuous light wave with the working wavelengths of 1539.65 nm and 1552.04 nm from a two-channel tunable laser sources are simultaneously coupled into the device through a 2 × 1 combiner. Four actively mode locked ring laser can be used to generate four binary sequences of non-return-to-zero (NRZ) optical control pulses which are applied to $OMRR_1$, $OMRR_2$, $OMRR_3$ and $OMRR_4$, respectively. Four OMRRs are firstly divided into two groups. The first group includes $OMRR_1$ and $OMRR_2$, and its working wavelength is 1539.65 nm. The second group includes $OMRR_3$ and $OMRR_4$, and its working wavelength is 1552.04 nm. And the other parameters [22], [25] used in simulation is summarized in Table 1.

Table 1. Parameters and their optimum values used in simulation

Sl. No.	Parameter(s)	Optimized Value
1.	K_s (coupling coefficient for OMRRs)	0.22
2.	Effective cross sectional area	450 × 250 nm^2
3.	n_2= (non-linear refractive index)	4 ×10^{-18} m^2/W
4.	Average pump energy	1.82 mW

The dynamic response results of the device for different four-input logic operations are shown in Fig. 6. Fig. 6 (e) shoes the logic operation of $\overline{A}\overline{B}+CD$, where low and high level pump signals are applied to OMRRs. To achieve other different logic operations, OMRRs' operation mode can be changed through the application of pump pulse sequence applied to OMRRs from low to high or vice-versa. The simulation results of Fig. 5(b) – 5(g) are shown in Fig. 6 (f) – 6(k) respectively. Therefore, the proposed device of Fig. 5 can implement any four operand logic operations. Therefore, the proposed logic circuit can perform reconfigurable logic operation through WDM technology.

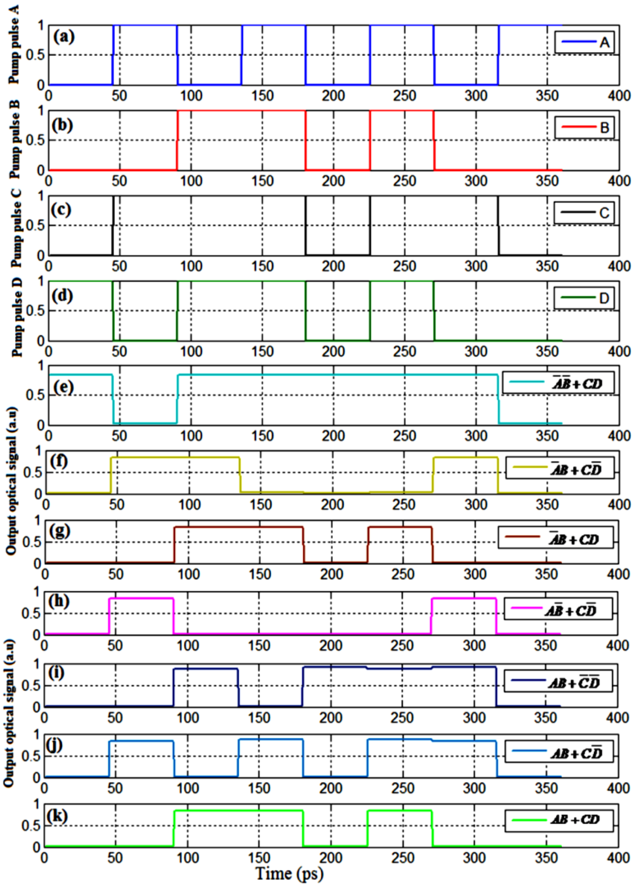

Fig. 6. Simulation results of reconfigurable logic circuit with four-operand; ((a)–(d)) represent the optical pump pulses applied to OMRRs, and ((e)–(k)) represent different logic operation results

5. Discussion

In order to obtain the permissible range of various parameters in the design to obtain same results, variation of Extinction Ratio (ER), Contrast Ratio (CR) and Amplitude Modulation (AM) have been determined with respect to various parameters [26-27] and described below:

(i) Extinction Ratio (ER): ER describes the ultra-fast switching performance between output states. The high value of ER is desirable to distinguish very clearly between the high level to the low level [28-30]. The ER can be defined as

$$\text{ER (dB)} = 10\log\left(\frac{P_{\min}^{1}}{P_{\max}^{0}}\right)$$, Where $P_{\min}^{1}$ and $P_{\max}^{0}$

are the minimum and maximum values of the peak passion of high ('1') and low ('0') level respectively. We have plotted ER against the different coupling coefficient with constant radius of the ring for the above reconfigurable logic gates and are shown in Fig. 7(a). Similarly we have also plotted ER against the different radius of one of the ring resonator with constant coupling coefficient (0.22) for the above logic gates and are shown in Fig. 7(b). From

Fig. 7(a,b), the maximum value of ER is obtained as 15.62 dB at the optimum operating point which is more than adequate for all-optical logic applications. In practice, the ‘1’s can be sufficiently distinguished from the ‘0’s if the ER exceeds 10 dB [26-27]. So, 10%-12% variation in various parameters may be permitted in the design to obtain same results.

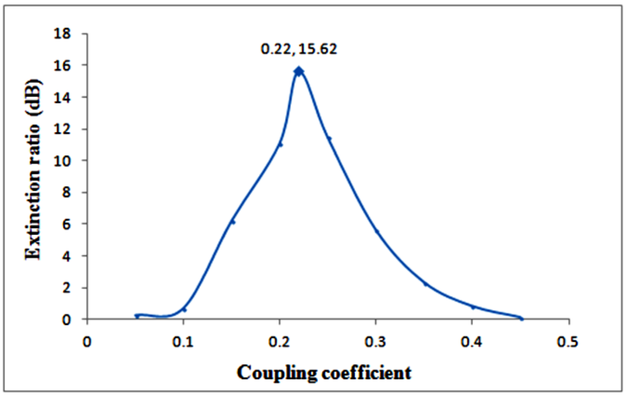

Fig. 7(a). Extinction ratio against coupling coefficient

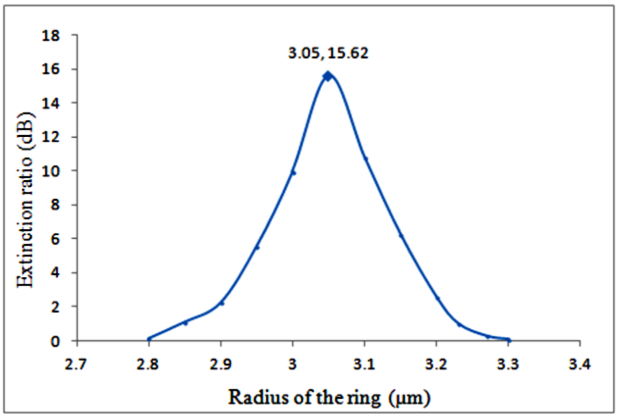

Fig. 7(b). Extinction ratio against radius of the ring

(ii) Contrast Ratio (CR): The contrast ratio (CR) is defined as the ratio of mean value of output intensity for ‘1’(P^1_{mean}) to the mean output intensity for ‘0’ (P^0_{mean}) and given as

$$CR(dB)= 10\ \log(\frac{P^1_{mean}}{P^0_{mean}})$$

We have plotted CR against the different coupling coefficient with constant radius of the ring for the above logic circuits and are shown in Fig. 8(a). Similarly we have also plotted CR against the different radius of one of the ring resonator with constant coupling coefficient for the above seven reversible logic gates and are shown in Fig. 8(b). From Fig. 8(a,b), the maximum value of CR is obtained as 20.31 dB at the optimum operating point.

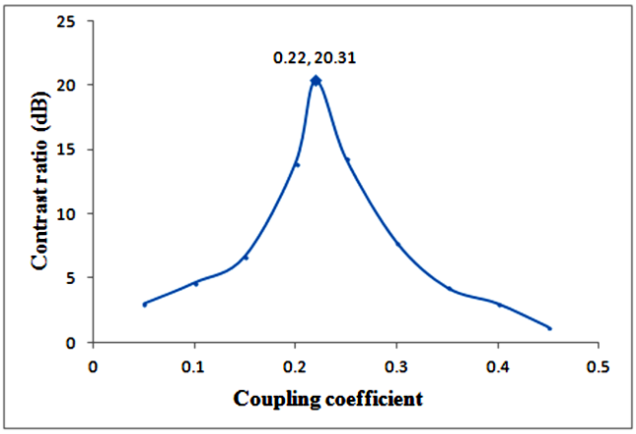

Fig. 8(a). Contrast ratio against coupling coefficient

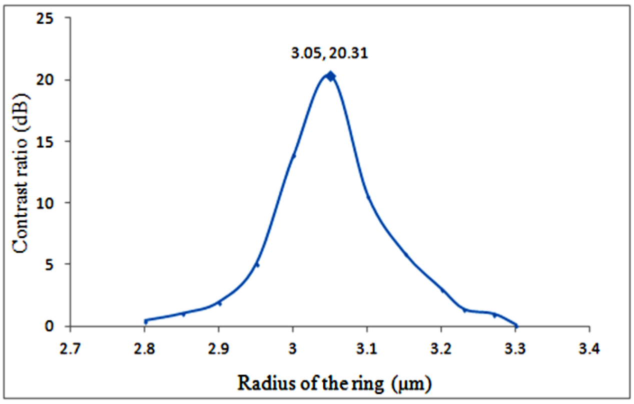

Fig. 8(b). Contrast ratio against radius of the ring

(iii) Amplitude Modulation (AM): The amplitude modulation (AM) can be defined as,

$$AM(dB)=10\log(\frac{P^1_{\max}}{P^1_{\min}})$$, where $P^1_{\max}$ and $P^1_{\min}$ are the maximum and minimum value of intensity at high (‘1’) level.

We have plotted AM against the different coupling coefficient with constant radius of the ring for the above logic circuits and are shown in Fig. 9(a). Similarly we have also plotted CR against the different radius of one of the ring resonator with constant coupling coefficient for the above reconfigurable logic gates and are shown in Fig. 9(b). From Fig. 9(a,b), the minimum value of AM is obtained as 0.75 dB at the optimum operating point.

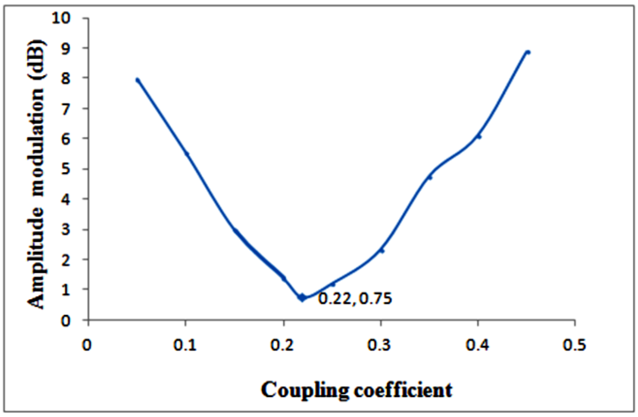

Fig. 9(a). Amplitude modulation against coupling coefficient

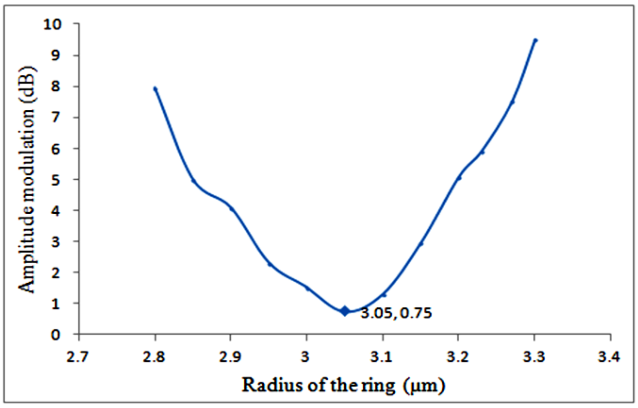

Fig. 9(b). Amplitude modulation against radius of the ring

6. Conclusion

In conclusion, the paper have described the application of cascaded OMRR-based optical switch array for the implementation of all optical high speed reconfigurable logic circuit which can implement any logic operations. The proposed design of all optical reconfigurable logic circuit is simple, compact, and easy to cascade with the integrated optical circuits as it uses only OMRR in its design. A pump-probe scheme is employed to modulate the OMRRs in order to realize a high operation speed. As a proof of concept, cascaded OMRR based four-input reconfigurable logic circuit is considered and several typical logic operations of four-operand with an operation speed of 67 Gbps are successfully described through numerical simulation. The performance of the design is determined by calculating various 'figure of merits'. The device may be useful in order to reduce the complexity of the circuit in various integrated photonic networks devices. The proposed device may be used for all-optical logic switch, all-optical logic based information processing. The developed theoretical model indicates its feasibility of all-optical computing and information processing in near future.

References

[1] H. J. Caulfield, S. Dolev, Nature Photonics **4**(5), 261 (2010).
[2] L. Yang, R. Ji, L. Zhang, J. Ding, Q. Xu, Optics Express **20**(12), 13560 (2012).
[3] F. Xia, M. Rooks, L. Sekaric, Y. Vlasov, Optics Express **15**(19), 11934 (2007).
[4] A. Liu, L. Liao, D. Rubin, H. Nguyen, B. Ciftcioglu, Y. Chetrit, N. Izhaky, M. Paniccia, Optics Express **15**(2), 660 (2007).
[5] L. Yang, L. Zhang, C. Guo, J. Ding, Optics Express **22**(3), 2996 (2014).
[6] X. Chen, L. Huo, Z. Zhao, L. Zhuang, C. Lou, IEEE Photon. Technol. Lett. **28**, 2463 (2016).
[7] D. Kastritsis, K. E. Zoiros, E. Dimitriadou, Journal of Computational Electronics **15**(3), 1046 (2016).
[8] S. Kumar, Optics Communications **395**, 221 (2017).
[9] S. K. Chandra, S. Biswas, S. Mukhopadhyay, IET Optoelectronics **10**(1), 1 (2016).
[10] Q. Li, J. Song, X. Chen, M. Bi, M. Hu, S. Li, Applied Optics **55**(25), 6880 (2016).
[11] K. Singh, G. Kaur, M. L. Singh, Optical and Quantum Electronics **48**(9), 418 (2016).
[12] J. Wang, J. Sun, Q. Sun, Optics Express **15**(4), 1690 (2007).
[13] Y. Tian, D. Li, Z. Liu, H. Xiao, G. Zhao, J. Yang, Y. Zhao, G. Han, X. Gao, IEEE Photonics Journal **8**(2), 1 (2016).
[14] J. K. Rakshit, J. N. Roy, Photonic Network Communications **34**(1), 84 (2017).
[15] D. K. Gayen, J. N. Roy, C. Taraphdar, R. K. Pal, Optik-International Journal for Light and Electron Optics **122**(8), 711 (2011).
[16] P. Sethi, S. Roy, Special Issue on Reversible Computing, Springer Transactions on Computational Science XXIV, LNCS **8911**, 21 (2014).
[17] J. K. Rakshit, J. N. Roy, Optics Communications **321**, 38 (2014).
[18] Y. Tian, Z. Liu, H. Xiao, G. Zhao, G. Liu, J. Yang, J. Ding, L. Zhang, L. Yang, Scientific Reports **7**(1), 6410 (2017).
[19] Y. Tian, G. Zhao, Z. Liu, A. Guo, H. Xiao, X. Wu, Y. Meng, L. Deng, X. Guo, G. Liu, J. Yang, IEEE Photonics Journal **8**(2), 1 (2016).
[20] G. K. Bharti, J. K. Rakshit, Photonic Network Communications **35**(3), 381 (2018).
[21] J. K. Rakshit, J. N. Roy, Optica Applicata **46**(4), 517 (2016).
[22] J. K. Rakshit, J. N. Roy, Journal of Computational Electronics **15**(4), 1450 (2016).
[23] P. Dumon, et al. IEEE Photonics Technology Letters **16**, 1328 (2004).
[24] G. K. Bharti, J. K. Rakshit, Optoelectron. Adv. Mat. **13**(1-2), 10 (2019).
[25] L. Chun-Fei, D. Na, Chinese Physics Letters **26**(5), 054203 (2009).

[26] E. Dimitriadou, K. E. Zoiros, 2012 8th IEEE International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP) (2012).
[27] E. Dimitriadou, K. E. Zoiros, Journal of Optics **14**(10), (2012).
[28] J. K. Rakshit, J. N. Roy, Optica Applicata **44**(1), 39 (2014).
[29] Z. V. Rizou, K. E. Zoiros, Optical and Quantum Electronics **49**(3), 119 (2017).
[30] R. P. Webb, J. M. Dailey, R. J. Manning, Optics Express **18**(13), 13502 (2010).

*Corresponding author: jayantarakshit.eie@nita.ac.in