

Design of Micro-Ring Resonator Based All Optical Signal Routers

Rakesh Choudhary¹, Sushanta Mahanty², Ajay Kumar³, Rajiv Kumar⁴ and Basudeba Behera⁵

Department of Electronics & Telecommunication Engineering

NIT Jamshedpur^{1, 2, 3, 5}, IIT Ranchi⁴

E-mail:- rakesh082008@gmail.com¹, nitsushant@gmail.com², ajay.ece@nitjsr.ac.in³, rajiv@iitranchi.ac.in⁴, basudeb.ece@nitjsr.ac.in⁵

DOI: - <https://doi.org/10.47531/MANTECH/ECC.2021.48>

Abstract

The analysis of digital circuits in optical field is one of the key aspects of emerging technologies. The proposed article shows the effective method for implementing the micro-ring resonator structure in all-optical signal routers. First of all, we explained in details how the resonator arrangement of the micro-ring resonator can be used in optical switching. This paper contains the detailed description and layout design of the all-optical signal router proposed. Finally, the theories suggested are tested with the MATLAB simulation software. The various fields of optical computing open up the door to a high-speed signal processing which has some important optical communication advantages like smaller size, lesser attenuation, wider bandwidth, lower cost computation and more immune to EMI.

Keywords: - Micro-ring resonator, All-optical signal routers, Optical switching

INTRODUCTION

New aspects of high-speed data networking are evident from the various areas of optical communication-based switching. By adapting some creative method, the contemporary communication system incorporates the benefits of an optical communication system. A significant number of researchers have shown considerable interest in the field of ultra-fast optical communication by implementing the various digital logic functionalities in this domain. The implementation of digital logic circuits in optical domain provides several other advantages apart from making our communication system more efficient. The benefits provided by optical domain computation are reduced transmission loss, very compact size, more bandwidth, and less EMI, etc. Several authors have also expressed their interest in the area of optical logic technology and obtained very appreciable results. During many researches, to incorporate multiple combinational and sequential functionalities, the idea of linear electro-optic effect (Pockels effect) was successfully employed. A complete overview of realization of optical signal routing using electro-optic effect is given in [1], AND, exclusive OR/exclusive NOR logic gates [2], optical full adder/subtractor [3], gray code converter and parity checker (even) [4], and optical NAND and

NOR logic gates [5]. Similarly, implementation of MZI based sequential circuit, optical clock D flip-flop and its application as optical shift register and ripple counter is reported in [6]. The principle of linear electro-optic effect, in which semiconductor optical amplifiers (SOA) are not used to implement logical functionality, is discussed by all theoretical work affiliated with [1]-[6]. The research is thus free from all the difficulties related to the SOA. But many authors have proposed the logical functionality based on SOA, which provides some more advantages for computation methods. A technique is being analysed for the use of SOA for quantum-dot active layers in realizing all-optical Boolean logic functions AND, XOR and NOT [7]. The implementation of photonic crystal based XOR, XNOR, NAND and OR gate structures is given in [8]. Similarly, implementation of some combinational digital circuits like binary half adder/subtractor based on dark-bright soliton conversion is given in [9]. The technique of soliton conversion reflects the high level of accuracy in the optical area. Besides that, a huge effort was made for the implementation of logical gates, XOR/XNOR in optical domain using dark-bright soliton conversion [10] and the experimental method for the development of all optical logic gate in micron-size silicon ring resonator based on the free-carrier dispersion

effect in silicon [11]. The idea of the all optical flip-flop consisting of two silicone-on-insulation micro-ring resonators coupled to straight waveguides by exploiting the optical bi-stability behaviour due to the nonlinear Kerr effect is described in [12].

Logical gates in the packet switching system based on the MMI waveguide for BPSK modulation layout are addressed in [13]. For future optical signal processing and optical computation, photonic crystals are appealing technology. An efficient technique to design OR and XOR gate using 2D photonic crystal reported in [14]. Experimental illustration of an all-optical digital processing circuit that can handle the complete addition of binary optical words and may be used in applications such as the processing of packet headers is explained in [15]. All-optical modeling strategies for S-R and D-flip flop, accomplished by means of an optical addition / drop filter and based on the dark and bright soliton conversion can be observed in [16].

A scheme is being studied in [17] to explain the Boolean all-optical logical functions like AND, XOR and NOT using SOA amplifier with active quantum dot layers. In order to implement various digital logic functions, however, Micro-ring-resonator-based switching phenomena is also used. The detailed description of switching phenomena using Micro-ring resonator (MRR) and the implementation of various combinational and sequential logic devices through proper arrangements of a number of MRRs has been well explained in [18]. The proposed paper describes one of the efficient techniques, which provides the all optical signal functionality. The section I include the relevant technical background describing the importance of the proposed design technique and important previous research articles, which shows the utility of the all optical functionality. The section II describes the switching activity of the Micro-ring resonator structure.

The MRR can be used as the all optical switching device. Hence, we have discussed the mathematical aspects of the switching functionality of the micro-ring resonator architecture. In the section III, we have described the efficient mechanism to perform the all optical signal routing functionality, which consists of three identical types of MRR structures. The section III includes the detailed description of the all optical signal router with its layout structure and it is verified using the MATLAB simulation software. Finally, in the section IV, we have

observed that, the discussed scheme can be suitable for the all optical signal routing functionality.

Basic Principle and Switching Mechanism of Micro- Ring Resonator (Mrr)

The principle underlying the optical ring resonators are the same as that of whispering galleries but unlike whispering galleries, ring resonator uses the light signal and comply with the characteristics of light like total internal reflection and constructive interference. Micro-ring resonators (MRR) are a set of waveguides where minimum one is coupled in closed- loop to some light input and output. If the light signal from the input waveguide having a resonant wavelength, travels through the loop then due to the property of constructive interference, it builds up in intensity over multiple round-trips which will appear at the output waveguide. The layout diagram of a micro-ring resonator is shown in fig.1 below.

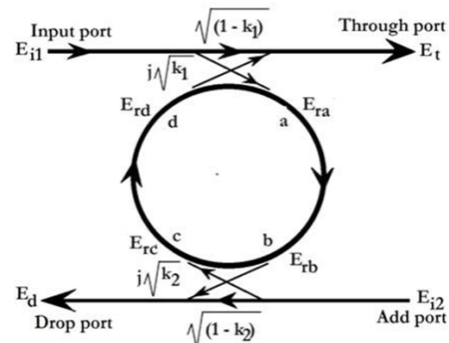


Fig. 1: Layout diagram of a single micro ring resonator (MRR)

In the MRR structure, the coupling between the ring and the input waveguide is always unidirectional. We can observe from the above figure that a total of three waveguides (two straight waveguides and one ring) has been used to construct the ring resonator diagram. The coupling coefficients between top waveguide & ring are denoted by k_1 and between ring & bottom waveguide is denoted by k_2 . The term 'r' is used to represent the radius of the ring. When the optical input signal of continuous nature is provided to the input port of MRR then some portion of this signal is transferred to the ring also due to the coupling effect.

The constructive interference is being formed and the ring resonator is said to be 'On Resonance' if it satisfies the condition that the total effective path length of the ring will be multiple of the operating wavelength. As a result of this, periodic fringes will appear. The signal which is now rotating in the ring is also transferred to the drop port with a fraction of k_2 due to the coupling effect. Therefore, the drop port of MRR reflects

maximum transmission in this condition and the ring exhibits minimum resonance in the through the port. We can obtain the excellent optical switching if the MRR is designed using some nonlinear materials like gallium arsenide/aluminium gallium arsenide. Here, an effective refractive index is the function of the intensity of the light signal which is flowing in MRR. When the MRR is excited by applying the optical LASER signal from the top of the ring, carriers of high density will be generated due to the total absorption of the light signal.

As a result of this, the refractive index is reduced by a significant amount which in turn leads to blue shift phenomena. Let us further assume the following parameters associated with the ring resonator structure: - L denotes the circumference of the ring and its equal to $2\pi r$, where $2r$ is the diameter of the ring. α denotes the attenuation coefficients of the ring, γ represents the insertion loss and kn denotes the wave propagation constant which is equal to $(2\pi/\lambda)n_{eff}$ where λ is the resonant wavelength. $n_{eff} = n_0 + \frac{n_2}{2} P$, where n_0 & n_2 are the linear and nonlinear refractive indexes, I & P are the intensity and power of the optical pump signal. The values of k_1 and k_2 are taken as 0.25, attenuation coefficient (α) = 0.0005 micro/meter, effective cross-sectional area = 0.25 micro/meter² and the resonator wavelength as $\lambda = 1.55$ micro-meter. Again, let E_{i1} and E_{i2} are the input and add port field respectively. The field at the points a, b, c and d are E_{ra} , E_{rb} , E_{rc} and E_{rd} can be expressed as [18],

$$E_{ra} = (1 - \gamma)^{1/2} [j\sqrt{k_1}E_{i1} + \sqrt{(1 - k_1)}E_{rd}] \quad (1)$$

$$E_{rb} = E_{ra} \exp(-\alpha L/4) \exp(j k_n L/2) \quad (2)$$

$$E_{rc} = (1 - \gamma)^{1/2} [j\sqrt{k_2}E_{i2} + \sqrt{(1 - k_2)}E_{rb}] \quad (3)$$

$$E_{rd} = E_{rc} \exp(-\alpha L/4) \exp(j k_n L/2) \quad (4)$$

Through port output of MRR is expressed as

$$E_t = (1 - \gamma)^{1/2} [\sqrt{(1 - k_1)}E_{i1} + j\sqrt{k_1}E_{rd}] \quad (5)$$

Drop port output of MRR is expressed as

$$E_d = (1 - \gamma)^{1/2} [\sqrt{(1 - k_2)}E_{i2} + j\sqrt{k_2}E_{rb}] \quad (6)$$

Let us take into consideration the following assumptions for the simplification purpose,

$$D = (1 - \gamma)^{1/2}, \quad x = D \exp(-\alpha \frac{L}{4}) \text{ and } \phi = \frac{k_n L}{2}$$

Now putting the above values in the equations 5 & 6 and solving the equations from 1 to 6, we will

get the through port (E_t) and drop port (E_d) field intensity as

$$E_t = \frac{D\sqrt{1 - k_1} - D\sqrt{1 - k_2}x^2 \exp^2(j\phi)}{1 - \sqrt{1 - k_1}\sqrt{1 - k_2}x^2 \exp^2(j\phi)} E_{i1} + \frac{-D\sqrt{k_1 k_2} x \exp(j\phi)}{1 - \sqrt{1 - k_1}\sqrt{1 - k_2}x^2 \exp^2(j\phi)} E_{i2} \quad (7)$$

$$E_d = \frac{-D\sqrt{k_1 k_2} x \exp(j\phi)}{1 - \sqrt{1 - k_1}\sqrt{1 - k_2}x^2 \exp^2(j\phi)} E_{i1} + \frac{D\sqrt{1 - k_1} - D\sqrt{1 - k_2}x^2 \exp^2(j\phi)}{1 - \sqrt{1 - k_1}\sqrt{1 - k_2}x^2 \exp^2(j\phi)} E_{i2} \quad (8)$$

We can achieve the switching characteristics of the ring resonator by using the above equations and at the same time, these equations are very important for analysing the cascaded structure of MRRs. The MATLAB simulation output of a single MRR as shown in fig.1 which depicts its switching action is shown in fig.2 below

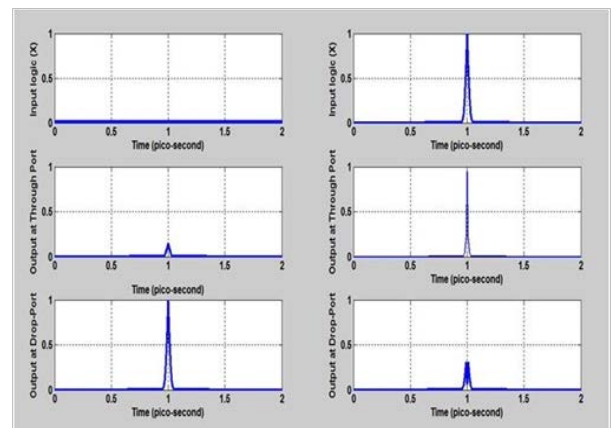


Fig. 2: MATLAB output characteristics curve of a micro ring resonator (MRR)

The first row in the fig.2 denotes the optical pulse train which is assumed as a sequence of binary 0s and 1s. This optical pulse signal is used to modulate the ring-resonator. Similarly, 2nd and 3rd rows denote the output optical signal at through port and drop port of MRR respectively. From the fig,2, it is evident that if we modulate the ring resonator by applying the optical pump signal as equal to binary zero, then the input optical CW signal will appear at the drop port of the MRR. Alternatively, if we provide binary one as control optical signal then then the input optical CW signal will appear at the through port of the MRR.

Design Of 1 × 4 All Optical Signal Routers Using the Micro-Ring Resonator Structure

The signal routers can be used to transmit the input optical signal at any specified port among the several numbers of the output port. The basic

layout design of 1×4 optical signal router can be represented using the fig. 3.

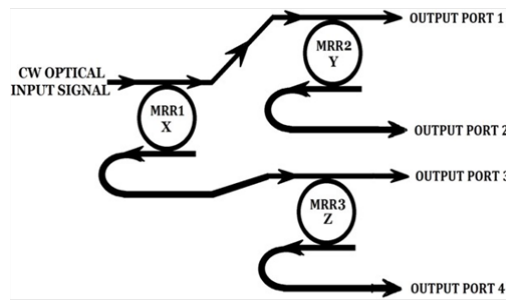


Fig. 3: Optical layout design of 1×4 signal routers using the three micro-ring resonator structures

The figure 3 represents the optical design of 1×4 optical signal routers using the 3 micro-ring resonators. The implementation displays the intelligent application of the optical switching functionality of the MRR as discussed in the fig. 2. The MRR1, MRR2 and MRR3 are modulated using the optical LASER signal X, Y and Z, respectively. The optical control pump signal has the ability to shift the CW input optical signal either on the through port or the drop port. In all the MRR structure, no optical signal is additionally provided. Therefore, the selection of a particular output port among the four ports can be achieved by selecting a particular combination of optical pump signal. The table: 1 shows the different combination of the optical control pump signal.

Table 1: Various combinations of control pump signal X, Y and Z for all the four output ports of 1x4 signal router

Selection of the output ports	Status of the optical control pump signals		
	X	Y	Z
Output Port1	1	1	0
Output Port2	1	0	0
Output Port3	0	0	1
Output Port4	0	0	0

Now, based on the eq. (1) – (8), we can generate the MATLAB simulation result of the proposed device.

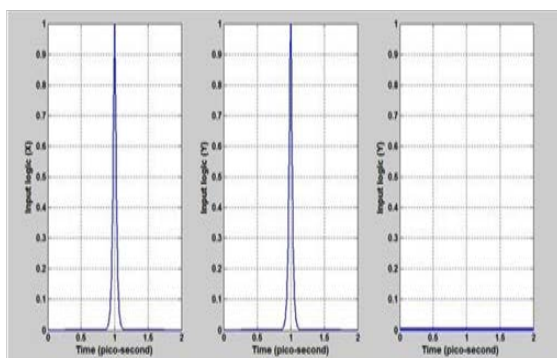


Fig. 4: The optical control signal to transmit the CW optical input signal on the output port1

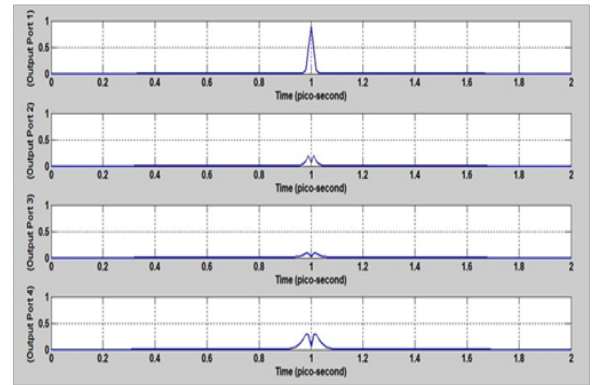


Fig. 5: The status of the output port 1, output port 2, output port 3 and output port 4 under the effect of optical control signal $\rightarrow 110$ as shown in the fig 4.

The status of optical control signals X, Y and Z used to modulate the three ring resonators (MRR1, MRR2 & MRR3) is shown in fig.4. Hence, the fig. 5 represents the status of the output ports under the effect of XYZ $\rightarrow 110$. It can be easily observed that Continuous wave (CW) optical input signal can be transmitted to the output port 1. The theoretical analysis suggests, as we modulate the MRR1 using the control signal through X $\rightarrow 1$, the CW optical signal is transmitted to the through port of the MRR1. Now, the optical signal obtained at the through port of the MRR1 behaves as the optical input signal applied at the input port of the MRR2. Now, if we apply the modulating signal as Y $\rightarrow 1$, then the CW optical input signal will appear at through port of the MRR2, which is assigned as the output port 1.

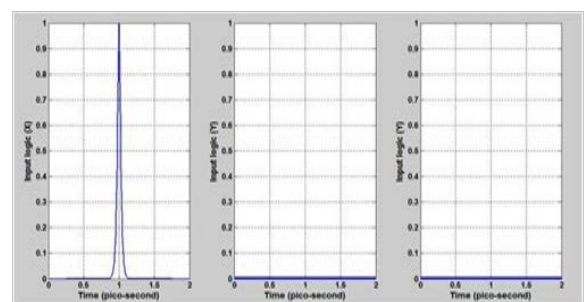


Fig. 6: The optical control signal to transmit the CW optical input signal on the output port2

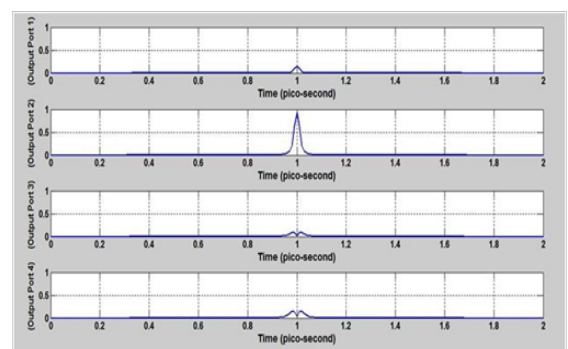


Fig. 7: The status of the output port 1, output port 2, output port 3 and output port 4 under the effect of optical control signal $\rightarrow 100$ as shown in the fig 6.

Fig.6 is representing the combination of control signals X, Y & Z to achieve the shifting of input CW signal to the output port of the proposed device. The discussed combination can be justified using the fig. 7. This figure specifies the MATLAB output of the proposed device for the condition $XYZ \rightarrow 100$. The layout of the proposed device suggests that, if we modulate the MRR1 using the optical control pump signal $X \rightarrow 1$, then the input signal will be appeared at the through port of the MRR1, which is nothing but the input signal for MRR2. Now, as we modulate the MRR2 using the $Y \rightarrow 0$, the optical signal can be shifted to the drop port of the MRR2, which is assigned by the output port 2.

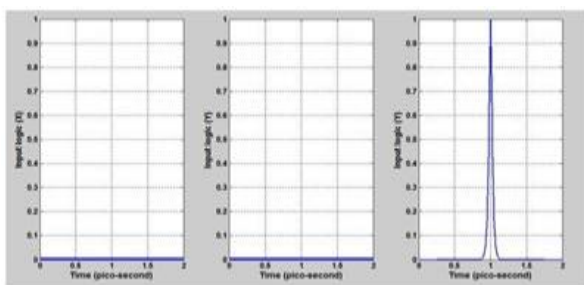


Fig. 8: The optical control signal to transmit the CW optical input signal on the output port3

The fig. 8 shows the MATLAB simulation result describing the combination of optical control pump signal, which enables to select the output port 3 of the proposed device. In order to select the output port 3 of the proposed device, the optical control signal must $\rightarrow 001$. The status of the all the output ports under the effect of the optical control pump signal $\rightarrow 001$ can be described using the fig. 9.

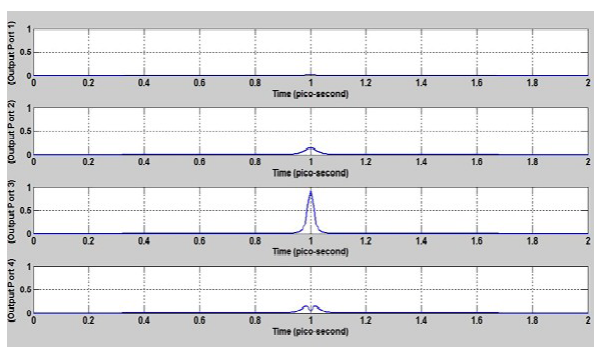


Fig 9: The status of the output port 1, output port 2, output port 3 and output port 4 under the effect of optical control signal $\rightarrow 001$ as shown in the fig 8.

If we modulate the MRR1 using the optical control pump signal $\rightarrow 0$, then we can observe the CW optical input signal at the drop port of the MRR1, which is applied as the input signal to the input port of the MRR3. Now, the MRR3 can be modulated using the $\rightarrow 1$ in order to shift the continuous wave optical input signal at the through

port of the MRR3, which can be assigned as the output port 3.

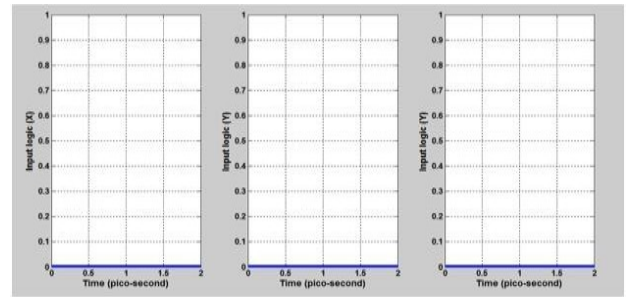


Fig. 10: The optical control signal to transmit the CW optical input signal on the output port 4

Figure 10 suggests the combination of the optical control pump signal set in order to shift the optical input signal at the fourth output port of the proposed device. The validity of the suggested optical control pump signal using the fig. 11.

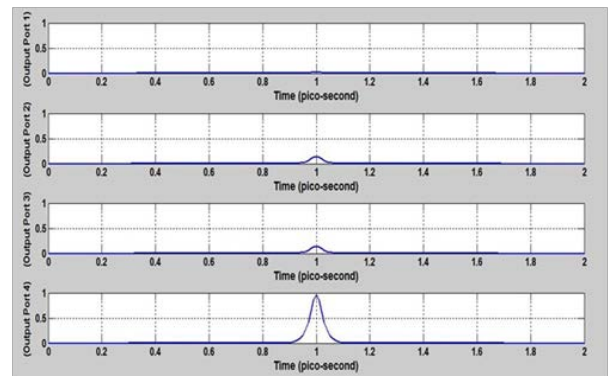


Fig 11: The status of the output port 1, output port 2, output port 3 and output port 4 under the effect of optical control signal $\rightarrow 000$ as shown in the fig 10.

The MATLAB result reported in fig. 11 shows that, we can select the output 4 of the proposed device, if we modulate the MRR1, MRR2 and MRR3 using the optical control pump $\rightarrow 0$, $\rightarrow 0$ and $\rightarrow 0$, respectively. The fig. 11 suggests that, if we modulate the MRR1 using the control signal $\rightarrow 0$, the signal shifts at the drop port of the MRR1, which behaves as the input of the MRR2 applies at its input terminal. Now the modulation of the MRR3 using the optical control pump signal involves the further shifting of the CW optical input signal and finally optical input signal could be seen at the drop port of the MRR3, which behaves as the output port 4 of the proposed device. Hence, the proposed scheme provides the suitable mechanism to shift the input signal at any of the output ports, which depends upon the specific set of optical control pump signal.

CONCLUSION

This article deals with the basic working principle of an optical MRR and its switching characteristics. The paper covers the detail

mathematical description of the ring resonator required for the switching activity and it is verified by MATLAB simulation software. The suggested technique in this paper is an excellent application of the switching characteristics of ring resonator for a cascaded ring resonator structure. There are total three similar type of ring resonators used for designing the desired optical 1×4 signal router. Finally, the proposed structure is verified by using MATLAB simulation software. Therefore, the proposed system can be very helpful in the domain of ultra-fast communication.

REFERENCES

1. S. K. Raghuvanshi, Ajay Kumar, Santosh Kumar, "1 × 4 Signal Router Using 3 Mach-Zehnder Interferometers," *Optical Engineering (SPIE)*, 52(3), 035002 (2013).
2. Ajay Kumar, Santosh Kumar, S. K. Raghuvanshi, "Implementation of XOR/XNOR and AND logic gates using Mach-Zehnder interferometers," *Optik (Elsevier)*, 125, 5764 – 5767(2014).
3. Ajay Kumar, Santosh Kumar, S. K. Raghuvanshi, "Implementation of full adder and full-subtractor based on electro-optic effect in Mach-Zehnder interferometers," *Optics Communications (Elsevier)*, 324, 93-107(2014).
4. Ajay Kumar, Sanjeev Kumar Raghuvanshi, "Implementation of optical gray code converter and even parity checker using the electro-optic effect in the Mach-Zehnder interferometer structure" *Optical and Quantum Electronics (Springer)* DOI 10.1007/s11082-014-0087-9.
5. Sanjeev Kumar Raghuvanshi, Ajay Kumar, Azizur Rahman, "Implementation of high speed optical universal logic gate using the electro-optic effect based Mach-Zehnder interferometer," *Journal of Modern Optics (Taylor and Francis)* <http://dx.doi.org/10.1080/09500340.2015.1015636> (2015).
6. Sanjeev Kumar Raghuvanshi, Ajay Kumar, Nan K Chen, "Implementation of sequential logic circuit using the Mach-Zehnder interferometer based on electro-optic effect," *Optics Communications(Elsevier)*, 333, 193-208(2014).
7. Shaozhen Ma, Zhe Chen, Hongzhi Sun, Niloy K. Dutta, "High speed all optical logic gates based on quantum dot semiconductor optical amplifiers," *OPTICS EXPRESS*, 18, 6417 – 6422, 15 March 2010.
8. Weijia Liu, Daquan Yang, Guansheng Shen, Huiping Tian, Yuefeng Ji, "Design of ultra compact all-optical XOR, XNOR, NAND and OR gates using photonic crystal multi-mode interference waveguides," *Optics & Laser Technology*. 50, 55-64, (2013).
9. Sappasit Thongmee, and Preecha P.Yupapin, "All Optical Half Adder/Subtractor using Dark-bright Soliton Conversion Control," 2nd International Science, Social-Science, Engineering and Energy Conference 2010 Engineering Science and Management Procedia Engineering. 8, 217–222, (2011).
10. Muhammad Arif Jalil, Iraj Sadegh Amiri, Chat Teeka, Jalil Alib, P. P. Yupapin, "All-optical logic XOR/XNOR gate operation using microring and nanoring resonators," *PHYSICS EXPRESS*. 1, February (2011).
11. Qianfan Xu and Michal Lipson, "All-optical logic based on silicon micro-ring resonators," *Opt. Exp.* 15, 924-929, February (2007).
12. P. Nadimi, D. D. Caviglia, and E. Di Zitti, "Exploiting Silicon-on-Insulator Microring Resonator Bistability Behavior for All Optical Set-Reset Flip-Flop," *World Academy of Science, Engineering and Technology*. 71, 2012.
13. Ishizaka Yuhei, Kawaguchi Yuki, Koshiba Masanori, "Design of optical XOR, XNOR, NAND, and OR logic gates based on multi-mode interference waveguides for binary-phase-shift-keyed signal." *Journal of Lightwave Technology* 2011;29 (18):2836–46.
14. Kabilan AP, Susan Christina X, Elizabeth Caroline P. Photonic crystal based all optical OR and XO logic gates. *International Conference on Computing Communication and Networking Technologies*, 2010, pp. 1–4.
15. A. J. Poustie, K. J. Blow, A. E. Kelly and R. J. Manning, All optical full-adder with bit differential delay, *Opt. Commun.* 156, 22–26 (1998).
16. K. Luangxaysana, P. Phongsanam, S. Mitatha, M. Yoshida, N. Komine, P.P. Yupapin, "Novel All-optical Flip-Flop using Dark-Bright Soliton Conversion Control", *Information Technology Journal*, 11(10) 1470-1476(2012).
17. Shaozhen Ma, Zhe Chen, Hongzhi Sun, Niloy K. Dutta, "High speed all optical logic gates based on quantum dot semiconductor optical amplifiers," *OPTICS EXPRESS*, 18, 6417 – 6422, 15 March 2010.
18. Ajay Kumar, Sanjeev Kumar Raghuvanshi, "Implementation of some high speed combinational and sequential logic gates using micro-ring resonator," *Optik (Elsevier)*, 127, 8751-8759, 14 June 2016.