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Implementation of All-Optical 1x4 memory register unit using the Micro-Ring Resonator Structures

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Abstract: Implementation of switching activity in the all-optical domain is one of the most important aspects in the field of modern high-speed and secured communication technology. Micro-ring Resonator (MRR) based switching activity can be used to implement all-optical active low tri-state buffer logic and clocked D flip-flop. The paper describes the switching activity of micro-ring resonator structures and the switching activity is further used to implement the effective all-optical 4 – bit memory register using the appropriate arrangement of all-optical tri-state buffers and clocked D flip-flops with the functionality of RD and WR. The complete description of layouts and switching mechanisms of all-optical 4-bit memory registers have been explained and appropriate MATLAB simulation results are presented to observe the suitability of the proposed unit. The analysis shows that implementation of tri-state buffer logic and D flip-flop assisted 4-bit memory register in the all-optical domain includes the considerable advantages of optical communication e.g. immunity to electromagnetic interference, parallel computing, compactness, signal security, etc. The manuscript describes the detailed analysis of performance parameters e. g. extinction ratio, contrast ratio, amplitude modulation, on-off ratio, and switching speed of micro-ring resonator structures to achieve an efficient selection of device parameters and finally describes an efficient technique to implement all-optical MRR based 1×4 memory registers.

Keywords: Micro Ring Resonator, Optical clocked tri-state buffer, All-optical 4-bit memory register.

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1. Introduction

All-optical switching and computations have been widely investigated in optical digital circuits and optical sensors. Optical digital circuits and sensors possess many advantages compared with the conventional electronic circuits and sensors e.g. immunity to electromagnetic interference, parallel computing, compactness, low loss transmission, significantly more bandwidth, easier and cheaper computing, and signal security. However, several techniques have been employed to investigate optical digital computation and sensors. The electro-optic effect-based optical switching logic circuits;

optical sensors and delay units have been widely investigated to achieve optimum performance. Reconfigurable optical time delay networks are essential components. A hybrid optical time delay unit using Lithium-Niobate switches and precisely produced fiber loops are one of the most important units is described [1]. The thermal-induced refractive index variation phenomena using the silicon Mach-Zehnder waveguide is investigated. It is observed that optical switches as signal routers can be used efficiently for faster decision-making schemes [2]. The Mach-Zehnder interferometers (MZIs) can be used to perform the optical switching based on the principle of the electro-optic (EO) effect. The electro-optic effect is the phenomena, which are associated with the change in the index of refraction that is proportional to the magnitude of the externally applied electric field. The electro-optic effect-based Mach-Zehnder Interferometer (MZI) structure switching phenomena can be used to design several combinational and sequential circuits [3]-[6]. The semiconductor optical amplifiers are useful building blocks for all-optical gates as wavelength converters and OTDM de-multiplexers. The development of simple gates using the cross gain modulation and four-wave mixing to the integrated interferometric gates using cross-phase modulation is described [7]. Scheme to realize all-optical Boolean logic functions AND, XOR, and NOT using semiconductor optical amplifiers with quantum-dot active layers is studied where nonlinear dynamics including carrier heating and spectral hole-burning are taken into account with the rate equation. The analysis shows that the scheme is suitable for high-speed high-speed Boolean logic function [8]. Implementation of all-optical XOR gate for 160 Gb/s return to zero data signal using a single quantum dot semiconductor optical amplifier are discussed and analyzed in [9]. The scheme involves the detuning optical amplifier, which shows its importance in the field of all-optical signal processing and its application. The nonlinear effect of two-photon absorption (TPA) on the performance of all-optical XOR gates using quantum-dot semiconductor optical amplifier (QDSOA) assisted Mach-Zehnder interferometer is numerically analyzed and investigated at a data rate of 2 Tb/s [10]. The dependence quality factor (QF) on the critical parameters is investigated. Similarly, photonic crystal fibers are one of the advanced technologies and have been a major area of interest for many scientists and researchers. A new set of configurations is proposed to implement simple and highly compact photonic crystal-based all-optical logic AND and OR gates [11]. The design of two types of on-chip logic gates in 2D silicon photonic crystal slab is investigated and the suitable result associated with AND and XOR logic gate function at different frequencies are verified [12]. The technique is based on the scheme that, center directional emitting cavity and different input/output direction can lead to different logic operations without non-linearity and magnetism. All-optical clocked J-K flip-flop, SR, and T flop is proposed and described using silicon waveguide-based optical micro-ring resonator (OMRR) [13]. Similarly, four-wave mixing-based switching is one of the important mechanisms to implement logical functionality. A high-speed all-optical NAND logic gate is proposed and experimentally demonstrated using four-wave mixing Bragg scattering in highly nonlinear fiber [14]. The scheme describes the implementation at two wavelengths by encoding logic inputs on two pumps via on-off keying. Similarly, the possibility of

effective creation of quantum gates based on polarization photon qubits using a Kerr non-linear medium in a cavity is described [15]. It describes the mechanism to implement the four-wave mixing technique for the creation quantum C-NOT gate. Similarly, the electro-optic effect-based logic gates using a single micro-ring resonator structure is one of the efficient techniques. A novel technique to realize directed optical digital logic gate based on the structure-based free carrier distribution principles, changes in the refractive index of the waveguide, and the scattering analysis on the micro-ring resonator coupling region, are clearly described [16]. A novel analysis of a micro-ring resonator structure is presented, which includes the mathematical as well as simulation analysis on the modulated signals in [17]. In the analysis of [17], simulation results are generated to investigate some important parameters e. g. the full width at half-maximum, quality factor (Q-factor), and depth of the resonance at the different modulated voltage. Simulation and analysis of the digital and photonic positive edge-triggered JK flip-flop using a single micro-ring resonator as basic building blocks are investigated in [18]. In this scheme, the basic single micro-ring resonator structure uses free-carrier plasma dispersion electro-optic effect properties in its ring waveguide, which is structured as a PIN diode. A novel design technique to implement the photonic D-type flip-flop based on silicon micro-ring resonator as basic building blocks are investigated and it was observed that, carrier injection forward-biased PIN waveguide resonance phenomena can be used to generate the logic of D flip-flops [19]. A novel Micro-ring resonator-based switching activity can be effectively used for several optical logic computations and sensor design. Micro-ring resonator switching activity has been efficiently used for the implementation of the all-optical gray code converter [20], NAND logic gate, Half-adders [21], and some well-known combinational and sequential circuits [22]. The manuscript describes a theoretical mechanism to implement the all-optical 1×4 memory register using the ultra-fast switching activity of the micro-ring resonator (MRR) structure. In section 1, the relevant introduction associated with the modern optical switching schemes and related technology is discussed. Section 2 includes the basic idea of 1 bit and 4 bits memory registers, which includes the specific arrangement of clocked D flip-flop and active low tri-state buffers. In this section, we have shown the implementation of micro-ring resonator structure as powerful all-optical switches. The device parameters are analyzed in detail, which show the suitability of the proposed unit in the all-optical domain. The important performance effecting parameters e. g. free spectral range, 3-dB bandwidth (FWHM), Finesse, Quality factor, On-off ratio, Extinction ratio (ER), Contrast ratio (CR), Amplitude modulation (AM), and switching speed are optimized by selecting the appropriate values of the most important device parameter of MRR, which is coupling coefficients (k_1, k_2) and radius of MRR. Now, based on the parameter analysis, the basic idea of optically clocked D flip-flop and all-optical active low tri-state buffer is described. Finally, the layout of the proposed MRR switching-based all-optical 1×4 memory registers is discussed. In section 2, it is observed that the selected device parameters provide the suitable result and it is verified using the appropriate MATLAB simulation result and proper mathematical modeling. The suitability of the results is also represented in a tabular manner. The design technique

involves the additional advantage of all-optical units. The proposed scheme represents the WRITE, READ, and MEMORY-related operation without the conversion of signals from optical to electrical and electrical to optical. It completely resolves the complexities related to optical to electrical and electrical to optical conversions. Hence, the proposed scheme theoretically describes the application of an ultra-fast MRR based memory register which provides the optimum results including the additional advantage of all-optical switching phenomena.

2. Design of all-optical 4-bit memory register using the optical active low tri-state buffer logic and clocked D flip-flops

2.1 Introduction to 1 bit and combined 4-bit memory register

Memory registers are one of the most essential parts of complex and sequential digital circuits. The memory registers play a vital role in the storing mechanism of bit information. Mainly, the R/W memory shows wide applications in the field of combinational and sequential computation. The R/W memory comprises a group of flip-flops or field-effect transistors, which stores bits of information [23]. Flip-flop or latch can be used as the basic memory element. The basic block diagram of the 1-bit storing memory element can be represented in fig. (1). Active low tri-state buffers are associated with the input and output terminals of clocked D-flip flop, which provides controlled R/W operation.

Fig 1: Two Active low tri-state buffers and one clocked D flip-flop assisted single bit memory register

The input bits can be read-only, if the output buffer is enabled, otherwise the output Q and output terminal D_{out} remains isolated. Similarly, one active low tri-state buffer logic gate can be associated with the input segment of the clocked D flip-flop. The data can be written at the input terminal by enabling the input buffer. Hence, figure 1 shows the simple layout of the one-bit R/W memory cell. The single-bit memory cell can be arranged to implement the controlled 4-bit storing mechanism, as shown in fig. 2. It behaves as 4 bit or 1×4 bit memory register, which consists of 4 I/O lines and two control line $\overline{RD}$ and $\overline{WR}$. Fig 2 shows that controlling terminals of all the four input buffers are combined, which provides controlled writing. Similarly, controlled reading can be observed in the form of combined output buffer control terminals.

Fig 2 Layout diagram of 4-bit memory register unit using 8 active low tri-state buffer logic and 4 clocked D flip-flop

However, In this paper we have represented an ideal technique to implement the all-optical 1×4 R/W memory register, using a simple micro-ring resonator structure as a switching element.

2.2 The Micro-Ring Resonator Structure as Basic Switching Element

Now a day, the micro-ring resonator (MRR) structures are widely used for several all-optical signal processing e.g. filtering, multiplexing, de-multiplexing, switching, etc. The MRR as a switch finds wide application in the field of all-optical computational and decision-making units. The basic MRR structures are mainly associated with the ring waveguide, which is closely coupled with one or two waveguides. In fig. 3, the fraction k_1 and k_2 represents the fraction of the incoming field transferred to the ring. 'R' is the radius of the circle. Constructive interference of the signal can be observed if the total optical path length is an integral multiple of the effective wavelength. The phenomenon is termed as the "On resonance", which can be observed as multiple fringes at the output ports. Hence, resonance shows the maximum transmission at the drop port and minimum at the through the port. The introduction of non-linear material can open the door to logical switching phenomena. The non-linear effect leads to an appreciable change in the effective refractive index due to the appropriate introduction of a green laser as a control pump signal. A green laser control pump signal is applied from the top of the ring, which introduces the change in the effective index of the ring resonator section.

Fig. 3 Layout of the micro-ring resonator structure

Change in the effective index causes the temporary blue shift phenomena on the micro-ring resonance wavelength. Hence, the change in the effective index phenomena invokes appropriate switching activity at the specific resonance wavelength. In fig. 3, 'R' is the radius of the ring, k_1 and k_2 is the coupling coefficient between the ring structure and the straight waveguide section. The effective index of the ring structure can be represented as $n_{\text{eff}} = n_0 + n_2 \cdot I = n_0 + \frac{n_2}{A_{\text{eff}}} P$. n_0 and n_2 are the linear and non-linear refractive index, respectively. I and P are the intensity and power of the optical pump signals. In figure 3 symbols E_{i1} and E_{i2} are the input and add the port field, respectively. Now, the electric field at points a, b, c, and d are E_{ra} , E_{rb} , E_{rc} and E_{rd} can be written as following [24]:

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

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

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

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

The field at the through-port is given by

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

The field at the drop port is given by

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

For the simplification let us consider,

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

Solving Eq. (1) - Eq. (6), we get the through port (TP) and the drop port (DP) field as

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

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

In the eq. (1) - (8), γ and α are the insertion loss coefficient and attenuation coefficient of the ring, respectively. In the same manner, $k_n = \frac{2\pi}{\lambda} n_{\text{eff}}$ is the propagation constant, where λ is the resonant wavelength of the ring. Eq. (7) - (8) can be used to show the implementation of the ring resonator structure as a perfect all-optical switch.

Fig. 4: Switching activity of Micro-ring resonator structure

The MATLAB simulation result is performed to show the perfect switching activity of MRR structures. To obtain the proper switching activity, the specific device parameters are considered based on the performance analysis of MRR structures, which are represented as shown in table 1. The MATLAB simulation result can be observed in fig. 4, which describes the switching activity. Figure 4 describes the switching of an optical signal with the application of the control signals. It is observed that the absence of the control signal shifts the signal from through port to the drop port. Similarly, as we apply the optical control pump signal vertically to the ring resonator, the gradual shifting of an optical signal from the drop port to the through the port, can be observed. Figure 5

shows the graphical representation of the transfer function of a single Micro-ring resonator (MRR) at the through and drop port. The figure shows the significant switching at the specified wavelength of 1550nm. Figure 5 describes the temporary blue shift of the micro-ring resonator wavelength. Some important parameters are assigned for the occurrence of appropriate blue shift phenomena. The parameters can be represented in table 3. Based on the specified parameters, the MATLAB simulation result can be observed in fig. 5, which shows the perfect switching activity with appreciable optical signal strength at the output ports. However, the analysis of the transfer function involves the computation refractive index change (Δn), which can be represented by the eq. (9) [25].

$$\Delta n = - \left[8.8 \times 10^{-22} \frac{\beta t_p^2}{2h\nu\sqrt{\pi}S^2} P_{avg}^2 + 8.5 \times 10^{-22} \left(\frac{\beta t_p^2}{2h\nu\sqrt{\pi}S^2} P_{avg}^2 \right)^{0.8} \right] \quad (9)$$

Equation (1) – (9) provides the mechanism to derive the appropriate blue shift phenomena at the suggested wavelength $\lambda = 1.55 \mu\text{m}$. Change in the phase shift of the optical signal at the specified wavelength within one circle of the ring, as refractive index changes. The phase is the function of Δn , and it can be represented as $\phi = \frac{2\pi}{\lambda} \Delta n L$.

Fig. 5 Transfer function of normalized output response at the through and drop port at the specified wavelengths 1550nm in the presence and absence of control pump signal

Fig. 6: Variation of Phase Shift with an average amount of pump power inside the ring resonator

The phase shift corresponding to different wavelengths can be observed using the MATLAB simulation result, represented in fig. 5. In fig. 6, the analysis of the phase shift with the average amount of controlled pump power has been analyzed. The analysis suggests that 2.552 mW amount of average pump power is enough and sufficient to create the π amount of phase shift.

However, to achieve optimum performance of the proposed 1×4 memory register, the performance parameters of the micro-ring resonator structure are analyzed and the appropriate values of some important parameters e. g. coupling co-efficient (k_1, k_2) and ring radius is obtained. The detailed analysis of parameters can be represented as follow.

The coupling coefficient k_1 and k_2 are key design parameters of a micro-ring resonator (MRR) for the proper functioning of an MRR as an optical switch. In a single ring resonator, if the control signal is not applied then, the input optical signal will appear at the drop port of MRR and in the presence of the control signal, the input signal will be directed towards through the port of MRR. In this way, the MRR is working as an optical switch and for obtaining the switching of MRR, the optimum values of k_1 and k_2 should be selected. Hence, to select the optimum values of k_1 and k_2 , simulation is performed for a different combination of these coupling coefficients and the obtained results are shown in fig. 7 and fig. 8, respectively.

Fig. 7: Intensity variation at the through the port and drop port with Coupling Coefficient k_1 , for different value of $k_2 \rightarrow 0.1 - 0.5$ in the absence of control signal

Fig. 8: Intensity variation at the through the port and drop port with Coupling Coefficient k_1 , for different value of $k_2 \rightarrow 0.1 - 0.5$ in the presence of optical control pump signal

Figure 7 show the variation of through port and drop intensities of the optical signal for the coupling coefficient k_1 and for different values of k_2 , in the absence of optical control pump signal. Similarly, fig. 8 shows the variation of through port and drop intensities of the optical signal for k_1 and for different values of k_2 in the presence of a control pump signal. It can be seen from the fig. 7 that, in the absence of a control pump signal, when the values of k_1 and k_2 are same then the through the port is showing the

minimum intensity and, at the same time drop port is showing the maximum intensity of the optical signal. Similarly, for the identical values of k_1 and k_2 and when the control signal is applied to the MRR, through the port is showing maximum value and drop port is showing the minimum value of the optical signal. Now, the corresponding values of through and drop port intensities from the fig. 7 & fig. 8 for all the identical values of k_1 and k_2 are represented in table 1.

Table 1

Coupling Coefficient		Normalized Intensity of Optical Signal at the through port and drop port without applying the Optical Control Pump Signal		Normalized Intensity of Optical Signal at the through port and drop port with the application of the Optical Control Pump Signal	
k_1	k_2	Through port (au)	Drop Port (au)	Through Port	Drop Port
0.1	0.1	0.347	0.934	0.999	0.0934
0.15	0.15	0.232	0.969	0.998	0.1433
0.20	0.20	0.170	0.983	0.997	0.1952
0.25	0.25	0.133	0.994	0.995	0.1489
0.30	0.30	0.107	0.992	0.983	0.3040
0.35	0.35	0.089	0.994	0.932	0.3604
0.40	0.40	0.075	0.996	0.908	0.4176
0.45	0.45	0.064	0.997	0.878	0.4752
0.50	0.50	0.054	0.997	0.846	0.5322

From table 1, it is visible that in the absence of a control signal, the lowest value of through port intensity is 0.054 and the highest value of drop port intensity is 0.997 at the values $k_1 = k_2 = 0.5$. But for these values of coupling coefficients, when the control pulse signal is applied to the MRR, the corresponding values of both the through port and drop port intensities are close to 1 i. e. 0.846 & 0.5322 and it is against the basic principle of MRR. So, we cannot consider the values of coupling coefficients $k_1 = k_2 = 0.5$ as the optimum value. Again, from table 1, we can see that for $k_1 = k_2 = 0.1$, and in the presence of control pulse signal, we are getting very good results i. e. highest value of through port intensity (0.999) and lowest value of drop port intensity (0.0934). But despite this, we cannot take $k_1 = k_2 = 0.1$ as an optimum value, because for the same values of k_1 and k_2

and in the absence of a control pump signal, the through port intensity is 0.347, which is very high. Similarly, by analyzing all the readings of table 1, we have selected the values of coupling coefficients $k_1 = k_2 = 0.25$ as an optimum value for the proper working of a micro-ring resonator as an optical switch.

The radius of the ring is also a very important parameter for the switching operation of an MRR. By using the suitable value of ring radius, the output signals can be optimized accordingly. The wave propagates within the system acquires phase shift, as it travels along the radius of curvature of the ring. The relative phase of the traveling wave determines whether the light interferes constructively or destructively with the input signals. This phenomenon directly influences the output signal of the system. To obtain the most suitable value of the radius, simulation is performed by considering all the other parameters of MRR as constant, and the radius of the ring is varied from 1 to 10 μm . The effects of the ring radius towards the through port and drop port intensities of MRR are presented in fig. 9 and fig. 10.

Fig 9: Variation of normalized optical signal intensity at the through port and drop port (in the absence of optical control pump signal)

Fig 10: Variation of normalized optical signal intensity at the through port and drop port (in the presence of optical control pump signal)

The fig. 9 shows the variation of through port and drop port intensity with the variation of radius R of a micro-ring resonator in the absence of a control pump signal while fig. 10 shows the variation of through port and drop port intensity for radius R of a micro-ring resonator in the Presence of the control pump signal.

Table 2

Radius (μm)	Normalized Intensity of Optical Signal at the through port and drop port without applying the Optical Control Pump Signal		Normalized Intensity of Optical Signal at the through port and drop port with the application of the Optical Control Pump Signal	
	Through port	Drop Port	Through Port	Drop Port
1.418	0.0028	0.9982	0.8783	0.5334
2.836	0.0042	0.9992	0.8779	0.5300
4.253	0.0025	0.9990	0.9587	0.4999
5.662	0.0772	0.9960	0.8509	0.4888
7.089	0.0751	0.9996	0.9082	0.4176
8.507	0.4671	0.8731	0.9588	0.2674
9.924	0.0021	0.9990	0.9663	0.2564

In the absence of a control pump signal, we are getting seven minima values of through port intensity at a different value of R and seven maxima values of drop port intensity of the optical signal for the respective values of R . All the values of through port minima and drop port maxima at their corresponding values of radius, are shown by the column 2 and column 1 of Table 2. Now in the presence of the control pump signal, from fig. 10, we are taking values of through port and Drop port intensity for the respective values of radius R as given by the first column of Table 2. These values of through port and Drop port intensity of the signal are noted in the third column of Table 2. As per the basic working principle of ring resonator as an optical switch, in the absence of control signal through port must be at the minimum intensity, and Drop port must be at the maximum intensity of input optical signal and vice versa in the presence of control signal. So, from the obtained data of table 5, it can be concluded that the best value for the ring radius of the system is at $R = 7.08 \mu\text{m}$.

Figure of Merits

The radius of the ring R and coupling coefficients (k_1 and k_2) of a ring resonator are very crucial parameters and from our analysis, we have chosen their optimum values as $k_1 = k_2 = 0.25$ & $R = 7.08 \mu\text{m}$. Now, we are going to calculate the values of different performance parameters of the ring resonator from the simulation result and also verify that, we are getting the optimum value of performance parameters at the mentioned values of coupling coefficients/radius of the ring. The performance of each ring resonator can be measured in terms of the free spectrum range (FSR), 3-dB bandwidth or full width at half maximum (FWHM), Finesse (F), Q factor, on-off ratio (OOR), extinction ratio (ER), contrast ratio (CR), amplitude modulation (AM) and switching speed. The output of the simulation result is shown in Fig. 11. It shows the variation of normalized output intensity of through port and drop port for the wavelength of the input optical signal in the presence and absence of optical control pump signal.

Fig. 11: Variation of through port and drop port intensity in the presence and absence of optical control pump signal

Free spectrum range (FSR): It is the frequency spacing between two resonance peaks of the drop port signal which is shown in fig. 6. For the calculation of FSR, let us consider k as the phase constant which corresponds to $\Phi = 2m\pi$ and $k+\Delta k$ as the phase constant which corresponds to $\Phi = (2+1)m\pi$ where m is an integer and Δk is the phase constant. The frequency and phase shifts are denoted by Δf and $\Delta\lambda$ and can be written as [26],

$$\Delta f = \frac{c}{2\pi} \Delta k \quad (10)$$

$$\Delta\lambda = -\left(\frac{\lambda^2}{2\pi}\right) \Delta k \quad (11)$$

Now the FSR in terms of frequency (f) and wavelength (λ) is expressed as: -

$$\Delta f = \frac{c}{n_{gr} \cdot L} \quad (12)$$

$$\Delta\lambda = \left| -\frac{\lambda^2}{n_{gr} \cdot L} \right| \quad (13)$$

Where n_{gr} is the group refractive index and it is defined as,

$$n_{gr} = n_{eff} - \lambda \frac{dn_{eff}}{d\lambda} \quad (14)$$

In fig 11, the FSR of the proposed MRR structure is computed as 43 nm.

The full width at half maximum (FWHM): -The bandwidth of the ring resonator is given by the full width at half maximum (FWHM) of the ring intensity resonance or its 3-dB bandwidth. It is a measure of the sharpness of the resonance [26]-[27]. The resonance bandwidth determines how fast the optical data can be processed by a ring resonator. The FWHM, in terms of frequency (f) and wavelength (λ) can be expressed as:

$$FWHM(f) = \frac{c}{F n_{gr} \cdot L} \quad (15)$$

$$FWHM(\lambda) = \frac{\lambda^2}{F n_{gr} \cdot L} \quad (16)$$

Where F denotes finesse of ring resonator. In the fig. 11, the computed value of FWHM is 2 nm.

Finesse: - The finesse, F of the resonator is defined as the ratio of the free spectral range (FSR) to the full width at half maximum (FWHM) of a micro-ring resonator.

$$F = \frac{FSR}{FWHM} \quad (17)$$

Now, computing the values of FSR and FWHM using the fig. 11, the value of Finesse is computed as 21.5.

Quality factor: - The quality factor or Q factor of an optical waveguide is due to its energy stored and the power lost per optical cycle. The Q factor is defined as:

$$Q = \omega \frac{\text{Stored energy}}{\text{Power lost}} \quad (18)$$

The Q factor of a ring resonator can be defined as

$$Q = \frac{f_0}{\delta f} = \frac{\lambda_0}{\delta \lambda} \quad (19)$$

The shape and bandwidth of the ring resonator output are determined by the Q factor. A high value of the Q factor is required for all-optical signal processing applications [26]. According to the suggested parameters of the proposed unit, the Q factor of the proposed unit is computed as 750.

On-off ratio (OOR): - The ON-OFF ratio for the throughput and drop port, which is the ratio of the on-resonance intensity to the off-resonance intensity, is given by [26]-[27]:

$$\text{On-off Ratio} = \frac{T_{\max(\text{through port})}}{T_{\min(\text{drop port})}} \quad (20)$$

A high value of the ON-OFF ratio is required for designing the high-performance micro ring resonator system and it should be more than 20 dB [28]. From fig. 11, the obtained value of the ON-OFF ratio is 41.0490 dB.

Extinction ratio (ER): - The extinction ratio is defined as, [26]- [27],

$$\text{ER(dB)} = 10 \cdot \log \left(\frac{P_{\min}^1}{P_{\max}^0} \right) \quad (21)$$

Where $P_{\min}^1$ and $P_{\max}^0$ are the minimum and maximum values of the peak intensity of high ('1') and low ('0') respectively. The high value of extinction ratio distinguishes the high level (1) from the low level (0) very clearly.

Fig. 12: Variation of Extinction Ratio with the different values of coupling coefficients

Fig. 13: Variation of Extinction Ratio with the different values of Radius.

The impact of the variation of coupling coefficient on ER is represented in fig. 12 and the impact of the variation of ring radius on ER is shown in fig. 13. From these two graphs, it can be seen that at coupling coefficient $k_1 = k_2 = 0.25$ and ring radius = $7.08 \mu\text{m}$, we are getting the maximum value of extinction ratio as 18.98 dB. Therefore, this result justifies that we have selected optimum values of coupling coefficient and ring radius.

Contrast ratio (CR): The output contrast ratio (CR) is defined as the ratio of the mean value of output intensity for '1' (P_{mean}^1) to the mean output intensity for '0' (P_{mean}^0) and given as [29],

$$\text{CR(dB)} = 10\log\left(\frac{P_{\text{mean}}^1}{P_{\text{mean}}^0}\right) \quad (22)$$

For optimum performance, the CR must be as high as possible so that the main fraction of input can exist at the output.

Fig. 14: Variation of Contrast Ratio with the different values of coupling coefficients

Fig. 15: Variation of Contrast Ratio with the different values of coupling coefficients

Variation of contrast ratio with the variation of coupling coefficient is given in fig. 14 and the variation of contrast ratio for the radius of the ring is given by fig. 10. In fig. 14 and 15, we are getting the highest value of CR as 19.54 dB at coupling coefficients = 0.25 and ring radius = 7.08 μm , respectively.

Amplitude modulation (AM): - The amplitude modulation of the ring resonator can be defined as, [30]-[31],

$$AM(dB) = 10\log\left(\frac{P_{\max}^1}{P_{\min}^1}\right) \quad (23)$$

Where $P_{\max}^1$ and $P_{\min}^1$ are the maximum and minimum values of intensity at a high (1) level. As we know that, the typical value of AM must be less than 1dB [32].

Fig. 16: Variation of Amplitude Modulation parameter with the different values of coupling coefficients

Fig. 17: Variation of Amplitude Modulation parameter with the different values of Radius.

The simulation results for determining the optimum value of amplitude modulation (AM) are shown graphically in fig. 16 and fig. 17. The effect of the variation of coupling coefficients on AM is shown in fig. 16 and from the figure it can be observed that the lowest value of AM is 0.0165 dB and it is obtained at 0.25 of coupling coefficient. Hence, the result shows that we have selected the most suitable value of the coupling coefficient. Figure 17 shows the impact of the variation of radius of the ring (R) on amplitude modulation (AM). We can observe from fig. 17 that, the lowest value of AM (0.0166 dB) is obtained at $R = 7.08 \mu\text{m}$.

Switching speed: - In a micro-ring resonator, the output optical signal is switched on and off by the application of continuous optical input signal and control pump signal. As a result of this ultra-fast rising and falling edges can be observed. When the input signal is applied across the ring resonator in the presence of the control pump signal, the output signal starts to rise and in the absence of the control signal, the output signal falls to a low level. The rise and falling time of the micro ring resonator is shown below in fig.18 (a) & 18 (b).

Fig. 18: Representation of Switching Time (a) Rise Time (b) Fall Time

From the fig. 18 (a), the switching speed for rise time is taken as the time required to reach the output optical signal from 10% to 90% of its magnitude. Similarly, from the fig.18 (b), the switching speed for fall time is taken as the time required to reach the output optical signal from 90% to 10% of its magnitude. Hence, the obtained values of rise time and fall time are 2.531ps and 2.52ps, respectively. Based on the investigated parameter, the proposed 1×4 memory register is simulated, and suitable results are obtained. The final result is represented using tables (4)-(6). Hence, the above analysis shows the suitability of the selected parameters for the proposed all-optical memory registers. Based on the parameter analysis, we have suggested some optimum device

parameters as shown in table 1. The optimum parameters are used to design the proposed unit and the optimum result can be observed as shown in the fig. (26)-(28).

Table: 3 Parameters of Micro-ring resonator structures

Materials have taken for the MRR	GaAs-AlGaAs
Coupling Coefficient k_1 and k_2	0.25
Wavelength	$1.55 \mu\text{m}$
Attenuation Co-efficient	$\alpha = 0.0005 \mu\text{m}^{-1}$
Insertion loss	$\gamma = 5\%$.
Effective Radius	$7.08 \mu\text{m}$
β	$7.9 \times 10^{-10} \text{cm/W}$
τ (pulse width at half power peak)	100fs
t_p (photon lifetime)	12.5 ns
$h\nu$	$49.725 \times 10^{-20} \text{J}$
S (Average Cross Sectional area)	$0.25 \mu\text{m}^2$
n_2	$4 \times 10^{-18} \text{m}^2/\text{W}$

Fig. 19 All-optical clocked D flip-flop using the feedback assisted micro-ring resonator structure

In figure 19, the design of the optical clocked D flip-flop using the micro-ring resonator structure is discussed. The proposed Optical clocked D flip-flop can be used to store the optical data up to the desired duration of time-based on an optically controlled pump signal [22]. The layout consists of feedback assisted micro-ring resonator structure. The main objective of feedback is to maintain the previous state of the flip-flop in the absence of the controlled pump signals. The suitability of the layout can be verified by the MATLAB simulation result as shown in fig. 20. Figure 20 shows the proper working of clocked assisted all-optical clocked D flip-flop. The first row indicates the presence of data bits in the form of the presence and absence of the optical signal.

Fig. 20: MATLAB simulation result of the optical clocked D flip-flop.

The second row indicates the optically controlled pump signals. Similarly, the third row describes the characteristics of a feedback-assisted optical clocked D flip-flop. It indicates that the proposed unit behaves as a transparent unit in the presence of a clock signal, whereas the unit maintains the previous output at the through port of the unit, in the presence of an optical clock signal.

Fig. 21: All-optical active low tri-state buffer logic using two MRR structure

Figure 21 describes the functionality of one of the sub-modules used in the construction of the optical memory register. The unit shown in fig. 21 provides the controlling mechanism to implement the READ/WRITE operation [23]. The layout of active low tri-state buffer logic comprises two micro-ring resonators (MRR) structures. The first MRR is responsible for the presence of the optical signal at the input port of the second MRR. The switching of the first MRR can be controlled using the vertically applied optical signal EN. In the absence of EN, the optical signal can be observed at the drop port of the first MRR, which is directly connected to the input port of the second MRR. Hence, in the absence of EN, the optical signal can be observed at the input port of the second MRR structure. The second MRR can be controlled by the optical control pump signal 'IN'. Hence, the presence of an optical signal at the through port of the second MRR depends upon the status of the input signal. Similarly, if the EN acquires the high value the

optical signal switches to through port of the first MRR. Hence, the status of IN signal will not change the status of the through the port of the second MRR.

Fig. 22: MATLAB simulation result of the proposed optical active low tri-state buffer

The MATLAB simulation result of the all-optical tri-state buffer is represented as shown in fig. 22. The first row of the simulation result represents the status of the first MRR control signal EN. The second and third-row describes the status of the Input signal and Output signal, respectively. The Output signal can be observed at the through-port of the second MRR. The MATLAB simulation result is obtained using the eq. (1) – (8). Figure 22 represents that, in the absence of signal EN, the second MRR simply transfers the input optical signal to the through port whereas, if the EN signal is made high the output signal can be observed as low, irrespective of any status of the control signal 'IN' i.e. input signal.

(CLK). In the presence of the clock signal, the optical data bits D_0 , D_1 , D_2 and D_3 can be observed at the respective output ports in the form of Q_0 , Q_1 , Q_2 and Q_3 , respectively. In the absence of a clock signal, it maintains the previous output through the feedback path for a small duration. The fourth column of the proposed layout ensures the controlled READ operation. The switching activity in each MRR of the fourth column (MRR13-MRR16) can be controlled by the common vertically applied optical RD signal. For the low value of RD signal, the optical signals Q_0 , Q_1 , Q_2 and Q_3 can be observed at the corresponding drop port of the respective MRR in the form of D_{OUT_0} , D_{OUT_1} , D_{OUT_2} and D_{OUT_3} . The simultaneous application of optical control pump signal is very important in the proposed unit. In the proposed unit, an all-optical control pump signal is applied in the form of a green laser from the top of the ring. The control pump signal (2.552mW) enables the switching from the drop port to the through-port under the process of blue shift phenomena. However, the simultaneous application of control pump signals e.g. WR, $D_{in0} - D_{in1}$, CLK and RD signal can be applied using the approach of diffractive beam splitter techniques. The unit involves the splitting of the laser into multiple beams and simultaneously focusing on multiple points by combining lenses or focusing lenses. It can be used with multi-mode and single-mode lasers. It provides the facility of easy alignment and in this technique, splitting characteristics remain independent of beam incidence position.

Fig. 24: Diffractive Beam Splitter

Fig. 24 shows the basic arrangement in the diffractive beam splitter technique, which consists diffractive beam splitter and focusing lens. Spot pitch is proportional to the focal length. The working principle can be represented using fig. 25.

Fig 25: Schematic view of Set up of Diffractive Optical Element

The collimated laser beam is allowed to pass through the beam splitter with the pre-specified separation angle. The well-focused spots can be achieved with precise and certain distance by adding a focusing lens after the diffractive beam splitter. The selection of lens can be performed on the basis eq. (24)

$$d = \tan(\theta_s) \times \text{EFL} \quad (24)$$

The minimum input beam size can be decided by the fact, that it should be at least 3 times the size of the period in the DOE. The period is given by the grating equation (25).

$$\Lambda = \frac{m\lambda}{\sin\theta_s} \quad \text{where} \quad \begin{array}{l} \Lambda: \text{Period of DOE} \\ m: \text{Diffraction Order} \\ \lambda: \text{Wavelength} \end{array} \quad (25)$$

θ_s : Separation angle between two beams

The system modeling and simulation process of the proposed unit can be divided into four groups. The first group (MRR1-MRR4) is associated with the WRITE operation, which enables the write operation based on the status of the optical control pump signal (WR). Figure 23 suggests that, if the status of (WR) is '0', which means $\overline{\text{WR}} = 1$, optical input signal can be observed at the drop port of the MRR1-MRR4. The mathematical expression of the output signal intensity at the drop port of MRR1-MRR4 can be represented using the equation (26).

$$\left. \begin{aligned} \text{EdMRR1} &= \frac{-D\sqrt{k_1 k_2} x \exp(j\phi_{\text{MRR1}})}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2} x^2 \exp^2(j\phi_{\text{MRR1}})} (x_0) \\ \text{EdMRR2} &= \frac{-D\sqrt{k_1 k_2} x \exp(j\phi_{\text{MRR2}})}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2} x^2 \exp^2(j\phi_{\text{MRR2}})} (x_0) \\ \text{EdMRR3} &= \frac{-D\sqrt{k_1 k_2} x \exp(j\phi_{\text{MRR3}})}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2} x^2 \exp^2(j\phi_{\text{MRR3}})} (x_0) \\ \text{EdMRR4} &= \frac{-D\sqrt{k_1 k_2} x \exp(j\phi_{\text{MRR4}})}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2} x^2 \exp^2(j\phi_{\text{MRR4}})} (x_0) \end{aligned} \right\} \quad (26)$$

Where, the parameters D, k_1, k_2, x are having the usual meaning as described in the equation (1) – (8), in the segment of mathematical analysis of a single MRR structure. The expression for $\phi_{\text{MRR1}} - \phi_{\text{MRR4}}$ can be represented using the equation (27).

$$\left. \begin{aligned} \phi_{\text{MRR1}} &= \frac{2\pi}{\lambda} n_{\text{eff(MRR1)}} \\ \phi_{\text{MRR2}} &= \frac{2\pi}{\lambda} n_{\text{eff(MRR2)}} \\ \phi_{\text{MRR3}} &= \frac{2\pi}{\lambda} n_{\text{eff(MRR3)}} \\ \phi_{\text{MRR4}} &= \frac{2\pi}{\lambda} n_{\text{eff(MRR4)}} \end{aligned} \right\} \text{ where, } \left. \begin{aligned} n_{\text{eff(MRR1)}} \\ n_{\text{eff(MRR2)}} \\ n_{\text{eff(MRR3)}} \\ n_{\text{eff(MRR4)}} \end{aligned} \right\} = n_0 + n_2 \cdot I_{\text{WR}} = n_0 + \frac{n_2}{A_{\text{eff}}} P_{\text{WR}} \quad (27)$$

Where, I_{WR} and P_{WR} is the intensity and power associated with the optical control pump signal WR. The second stage (MRR5-MRR8) provides the optical signals ($D_0 - D_3$) based on the status of the optical control pump signal ($D_{\text{in0}} - D_{\text{in3}}$). In the presence of optical data bits ($D_{\text{in0}} - D_{\text{in3}}$) the output signal can be observed in the form of ($D_0 - D_3$) at the through ports of MRR5-MRR8, respectively. Hence, in this process, we can observe the input data bits ($D_{\text{in0}} - D_{\text{in3}}$) in the form of the optical input signal, which is represented as ($D_0 - D_3$). The mathematical expression of ($D_0 - D_3$) can be represented using the eq. (28).

$$\left. \begin{aligned} D_0 &= \left[\frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR5}})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR5}})} \right] \text{EdMRR1} \\ D_1 &= \left[\frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR6}})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR6}})} \right] \text{EdMRR2} \\ D_2 &= \left[\frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR7}})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR7}})} \right] \text{EdMRR3} \\ D_3 &= \left[\frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR8}})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR8}})} \right] \text{EdMRR4} \end{aligned} \right\} \quad (28)$$

The mathematical expression can be represented by putting the values of EdMRR1-EdMRR4 from eq. (26) to eq. (28), as shown in the eq. (29)

$$\left. \begin{aligned} D_0 &= \left[\frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR5}})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR5}})} \right] \left[\frac{-D\sqrt{k_1 k_2}x \exp(j\phi_{\text{MRR1}})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR1}})} (x_0) \right] \\ D_1 &= \left[\frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR6}})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR6}})} \right] \left[\frac{-D\sqrt{k_1 k_2}x \exp(j\phi_{\text{MRR2}})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR2}})} (x_0) \right] \\ D_2 &= \left[\frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR7}})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR7}})} \right] \left[\frac{-D\sqrt{k_1 k_2}x \exp(j\phi_{\text{MRR3}})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR3}})} (x_0) \right] \\ D_3 &= \left[\frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR8}})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR8}})} \right] \left[\frac{-D\sqrt{k_1 k_2}x \exp(j\phi_{\text{MRR4}})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{\text{MRR4}})} (x_0) \right] \end{aligned} \right\} \quad (29)$$

Whereas

$$\left. \begin{aligned} \phi_{MRR5} &= \frac{2\pi}{\lambda} n_{eff(MRR5)} \\ \phi_{MRR6} &= \frac{2\pi}{\lambda} n_{eff(MRR6)} \\ \phi_{MRR7} &= \frac{2\pi}{\lambda} n_{eff(MRR7)} \\ \phi_{MRR8} &= \frac{2\pi}{\lambda} n_{eff(MRR8)} \end{aligned} \right\} \text{ where, } \left. \begin{aligned} n_{eff(MRR5)} &= n_0 + n_2 \cdot I_{D_{IN0}} = n_0 + \frac{n_2}{A_{eff}} P_{D_{IN0}} \\ n_{eff(MRR6)} &= n_0 + n_2 \cdot I_{D_{IN1}} = n_0 + \frac{n_2}{A_{eff}} P_{D_{IN1}} \\ n_{eff(MRR7)} &= n_0 + n_2 \cdot I_{D_{IN2}} = n_0 + \frac{n_2}{A_{eff}} P_{D_{IN2}} \\ n_{eff(MRR8)} &= n_0 + n_2 \cdot I_{D_{IN3}} = n_0 + \frac{n_2}{A_{eff}} P_{D_{IN3}} \end{aligned} \right\} \quad (30)$$

In equation (30), $(I_{D_{IN0}} - I_{D_{IN3}})$ and $(P_{D_{IN0}} - P_{D_{IN3}})$ are the intensities and powers associated with the data input signals $(D_{in0} - D_{in3})$. In the third stage (MRR9-MRR12), we have shown the application of MRR as a feedback-assisted optical clocked D flip-flop. The section includes an optical delay unit, which provides the status of the previous output $(Q_{prev0} - Q_{prev3})$. The unit MRR9-MRR12 provides the output $(Q_0 - Q_3)$ at the through port of corresponding MRRs depending upon the status of optical control pump CLK signal. The mathematical expression of $(Q_0 - Q_3)$ can be represented as shown in the eq. (31),

$$\left. \begin{aligned} Q_0 &= \left[\frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}x^2 \exp^2(j\phi_{MRR9})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{MRR9})} \right] D_0 + \left[\frac{-D\sqrt{k_1 k_2}x \exp(j\phi_{MRR9})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{MRR9})} \right] Q_{prev0} \\ Q_1 &= \left[\frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}x^2 \exp^2(j\phi_{MRR10})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{MRR10})} \right] D_1 + \left[\frac{-D\sqrt{k_1 k_2}x \exp(j\phi_{MRR10})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{MRR10})} \right] Q_{prev1} \\ Q_2 &= \left[\frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}x^2 \exp^2(j\phi_{MRR11})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{MRR11})} \right] D_2 + \left[\frac{-D\sqrt{k_1 k_2}x \exp(j\phi_{MRR11})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{MRR11})} \right] Q_{prev2} \\ Q_3 &= \left[\frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}x^2 \exp^2(j\phi_{MRR12})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{MRR12})} \right] D_3 + \left[\frac{-D\sqrt{k_1 k_2}x \exp(j\phi_{MRR12})}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2 \exp^2(j\phi_{MRR12})} \right] Q_{prev3} \end{aligned} \right\} \quad (31)$$

In equation (31), the value of $(D_0 - D_3)$ can be taken from the eq. (29). The values of $(\phi_{MRR9} - \phi_{MRR12})$ can be represented by the eq. (32)

$$\left. \begin{aligned} \phi_{MRR9} &= \frac{2\pi}{\lambda} n_{eff(MRR9)} \\ \phi_{MRR10} &= \frac{2\pi}{\lambda} n_{eff(MRR10)} \\ \phi_{MRR11} &= \frac{2\pi}{\lambda} n_{eff(MRR11)} \\ \phi_{MRR12} &= \frac{2\pi}{\lambda} n_{eff(MRR12)} \end{aligned} \right\} \text{ where, } \left. \begin{aligned} n_{eff(MRR9)} \\ n_{eff(MRR10)} \\ n_{eff(MRR11)} \\ n_{eff(MRR12)} \end{aligned} \right\} = n_0 + n_2 \cdot I_{CLK} = n_0 + \frac{n_2}{A_{eff}} P_{CLK} \quad (32)$$

Where, I_{CLK} and P_{CLK} is the intensity and power associated with the optical control pump signal CLK . The final and fourth stage shows the READ operation of the proposed 1×4 memory register. The MRR13-MRR16 switches the optical input signal $(Q_0 - Q_3)$ to specified output ports $(D_{out0} - D_{out3})$ based on the status of the control pump signal RD. In fig. 23, it is visible that, the absence of control pump signal RD ($RD=0$ or $\overline{RD} = 1$) switches the optical signal $(Q_0 - Q_3)$ to the specified output port of $(D_{out0} - D_{out3})$. Finally, the mathematical expression for the status of the output port $(D_{out0} - D_{out3})$ can be represented using the equation (33).

$$\left. \begin{aligned} D_{out0} &= \frac{-D\sqrt{k_1 k_2} \exp(j\phi_{MRR13})}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2} x^2 \exp^2(j\phi_{MRR13})} (Q_0) \\ D_{out1} &= \frac{-D\sqrt{k_1 k_2} \exp(j\phi_{MRR14})}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2} x^2 \exp^2(j\phi_{MRR14})} (Q_1) \\ D_{out2} &= \frac{-D\sqrt{k_1 k_2} \exp(j\phi_{MRR15})}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2} x^2 \exp^2(j\phi_{MRR15})} (Q_2) \\ D_{out3} &= \frac{-D\sqrt{k_1 k_2} \exp(j\phi_{MRR16})}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2} x^2 \exp^2(j\phi_{MRR16})} (Q_3) \end{aligned} \right\} \quad (33)$$

In equation (33), the values $(Q_0 - Q_3)$ can be taken from the eq. (31). The values of $(\phi_{MRR13} - \phi_{MRR16})$ present in the eq. (33), can be represented by the equation (34).

$$\left. \begin{aligned} \phi_{MRR13} &= \frac{2\pi}{\lambda} n_{eff}(MRR13) \\ \phi_{MRR14} &= \frac{2\pi}{\lambda} n_{eff}(MRR14) \\ \phi_{MRR15} &= \frac{2\pi}{\lambda} n_{eff}(MRR15) \\ \phi_{MRR16} &= \frac{2\pi}{\lambda} n_{eff}(MRR16) \end{aligned} \right\} \text{ where, } \left. \begin{aligned} n_{eff}(MRR13) \\ n_{eff}(MRR14) \\ n_{eff}(MRR15) \\ n_{eff}(MRR16) \end{aligned} \right\} = n_0 + n_2 \cdot I_{RD} = n_0 + \frac{n_2}{A_{eff}} P_{RD} \quad (34)$$

In equation (34), I_{RD} and P_{RD} is the intensity and power of the optical control pump signal (RD). The equation (26)-(34) is analyzed and simulated using the MATLAB software to implement the MRR switching activity-based 1×4 memory register. Based on the eq. (26) – (34), the MATLAB simulation of the proposed layout, represented in fig. 26-28. In fig 26, the first row represents the status of WR. The status of the optical data bits can be observed in the second row. The 3rd and 4th row show the previous and present status of the output signals, respectively. Similarly, the 5th and 6th row shows the status of the control signal RD and output signals (D_{OUT_0} , D_{OUT_1} , D_{OUT_2} and D_{OUT_3}), respectively. It can be observed that, in fig. 26, as the status of the WR signal is low, the status of 2nd row ($D_{IN_0} D_{IN_1} D_{IN_2} D_{IN_3} \rightarrow 0110$) is written to the 4th row (through-port of each feedback-assisted optical clocked D flip-flop). As for the simulation, we have made the clock signal high, hence the through ports of (MRR9-MRR12) ($Q_0 Q_1 Q_2 Q_3 \rightarrow 0000$) is completely independent of the previous state of the output at the D-flip flop (Q_{prev0} , Q_{prev1} , Q_{prev2} and Q_{prev3}). In the fourth row, the RD is made high, hence at the output port D_{OUT_0} , D_{OUT_1} , D_{OUT_2} and D_{OUT_3} the READ operation cannot be observed. Basically, in fig. 26, the write operation has been performed.

Fig. 26 MATLAB simulation result of 1×4 optical memory representing the WRITE operation ($RD = 1$ and $WR = 0$) for the high level of the clock signal

Table 4: Tabular representation of the output describing the WRITE operation ($RD = 1$ and $WR = 0$) of the proposed 1×4 Memory Registers

Input, Output and Control Signals of 1×4 Memory Registers		Normalized Intensity (au)	Logic
Input WRITE Control Signal	(WR)	0	0
Input Data Signals	D_{in0}	0	0
	D_{in1}	1	1
	D_{in2}	1	1
	D_{in3}	0	0
Previous Output Signal	Q_{prev0}	0	0
	Q_{prev1}	0	0
	Q_{prev2}	0	0
	Q_{prev3}	0	0
	Q_0	0.139	0

Status of the Present Output Set	Q_1	0.9828	1
	Q_2	0.9828	1
	Q_3	0.139	0
Input READ Control Signal	RD	1	1
Status of the Optical Signal at the Specified port of the proposed unit	D_{out0}	0.0612	0
	D_{out1}	0.2967	0
	D_{out2}	0.2967	0
	D_{out3}	0.0612	0

Table 4 shows the tabular validation of WRITE operation of the all-optical memory register, where the data provided in the form of $D_{in0} - D_{in3}$ can be written at the through- port of optically clocked D flip flop, which can be observed as $Q_0 - Q_3$.

Fig. 27: MATLAB simulation result of 1×4 optical memory representing the READ operation ($RD = 0$ and $WR = 1$) for the low level of the clock signal

Similarly, fig. 27 represents all-optical READ operation. The first row shows the WR signal is high, which ensures that the write operation is disabled. In fig. 27, although the second row is loaded with the optical data $D_{IN_0} D_{IN_1} D_{IN_2} D_{IN_3} \rightarrow 0111$, but in the absence of a clock signal the device maintains the previous optical data $Q_{prev0}, Q_{prev1}, Q_{prev2}$ and $Q_{prev3} \rightarrow 0110$ at the output of each optical clocked D flip-flop $Q_0 Q_1 Q_2 Q_3 \rightarrow 0110$. In the 4th row of fig. 27, as the RD signal is maintained at the low, hence at the output port of the proposed device is observed as the $D_{OUT_0} D_{OUT_1} D_{OUT_2} D_{OUT_3} \rightarrow 0110$, which clearly shows the optical READ operation.

Table 5: Tabular representation of the output describing the READ operation (RD = 0 and WR= 1) of the proposed 1×4 Memory Registers

Input, Output and Control Signals of 1×4 Memory Registers		Normalized Intensity (au)	Logic
Input WRITE Control Signal	(WR)	1	1
Input Data Signals	Din ₀	0	0
	Din ₁	1	1
	Din ₂	1	1
	Din ₃	1	1
Previous Output Signal	Q _{prev0}	0	0
	Q _{prev1}	0.9709	1
	Q _{prev2}	0.9709	1
	Q _{prev3}	0	0
Status of the Present Output Set	Q ₀	0	0
	Q ₁	0.9706	1
	Q ₂	0.9706	1
	Q ₃	0.0612	0
Input READ Control Signal	RD	0	0
Status of the Optical Signal at the Specified port of the proposed unit	D _{out0}	0.0137	0
	D _{out1}	0.9565	1
	D _{out2}	0.9565	1
	D _{out3}	0.0612	0

The tabular representation of the READ operation can be verified using table 5. The table shows the validity of the proposed unit, with the selected value operating parameter as shown in table 3, which is obtained by the parameter analysis. Figure 28 shows, we have made the READ and WRITE operation disabled.

Fig. 28: MATLAB simulation result of 1×4 optical memory representing the $RD = 1$ and $WR = 1$ operation for the low level of clock signals

The MATLAB simulation clearly shows the memory-mode of the unit, where both WR and RD are maintained at the logic high. In this case, although the optical data bits are given as $D_{IN_0} D_{IN_1} D_{IN_2} D_{IN_3} \rightarrow 1001$ but the output ports is associated with $Q_0 Q_1 Q_2 Q_3 \rightarrow 0111$, which is the same as the previous data $Q_{prev0}, Q_{prev1}, Q_{prev2}$ and $Q_{prev3} \rightarrow 0111$. Since we have disabled the READ operation by making RD signal as logic high, hence we are not observing the output at the output terminals. Figure 28 shows the memory-mode of the 4-bit all-optical memory register.

Table 6: Tabular representation of the output describing the MEMORY operation ($RD = 1$ and $WR = 1$) of the proposed 1×4 Memory Registers

Input, Output and Control Signals of 1×4 Memory Registers		Normalized Intensity (au)	Logic
Input WRITE Control Signal	WR	1	1
Input Data Signals	D_{in_0}	1	1
	D_{in_1}	0	0
	D_{in_2}	0	0
	D_{in_3}	1	1
Previous Output Signal	Q_{prev0}	0.9889	1
	Q_{prev1}	0.9887	1

	Q_{prev2}	0.9800	1
	Q_{prev3}	0	0
Status of the Present Output Set	Q_0	0.9888	1
	Q_1	0.9886	1
	Q_2	0.9799	1
	Q_3	0	0
Input READ Control Signal	RD	1	1
Status of the Optical Signal at the Specified port of the proposed unit	D_{out0}	0.1252	0
	D_{out1}	0.1252	0
	D_{out2}	0.1252	0
	D_{out3}	0.0401	0

The tabular representation of memory mode can be represented using table 6, where we can find the previous output at the through-port of optically clocked D flip-flop, with some power loss. The loss analysis for the three different modes i.e. READ, WRITE, and MEMORY mode of the proposed memory register are as follows. The loss factor for the cascaded Micro-ring resonator can be represented using the eq. (35) [27],

$$\text{Loss Factor} = 20 \log \left(\frac{\text{Output Intensity}}{\text{Input Intensity}} \right) \quad (35)$$

Based on the eq. (35) the loss factor is computed for the proposed unit, which can be represented as follow,

Fig. 29: Average Loss factor for the cascaded Micro-ring resonator structure

Fig. 29 suggests the average loss factor of all the four output data ports in the state of READ, WRITE, and MEMORY mode for 1 clock duration. The analysis shows that the average loss factor is -3.487dB, -2.901dB, and -2.703dB for the READ, WRITE, and MEMORY modes.

2. Conclusion

In this paper, we have described one of the applications of the switching activity of the micro-ring resonator structure. The paper shows the efficient application of appropriate numbers of MRR structures to implement the all-optical 1x4 memory register. The different segment of the proposed unit is described. The paper shows the complete mathematical description of the switching activity of the micro-ring resonator structure. The paper describes the requirement of the average amount of controlled power to perform the appropriate switching activity at the wavelength of 1550nm. In this paper, we have performed the complete parameter analysis to optimize the performance effecting parameter of the proposed memory register. The important device parameter of the switching unit e.g. coupling coefficients and radius of MMR structures are investigated to optimize various performance effecting parameters e.g. extinction ratio, on-off ratio, contrast ratio, amplitude modulation, and switching time. The different segments used to implement the proposed unit e.g. optical clocked D flip-flop, all-optical active low tri-state buffers are discussed and the corresponding MATLAB simulation result is described. Finally, 16 identical MRR assisted complete 1×4 memory register layout is described completely with the detailed mathematical modeling and simulation process. The proposed unit is verified using the appropriate MATLAB simulation result, where READ and WRITE, and MEMORY mode of operations are represented.

References

- [1]. Edmond J. Murphy, Thomas F. Adda, William J. Minford, Robert W. Irwin, Edward I. Ackerman, Stephen B. Adam, "Guided-Wave optical time delay network" IEEE Photonics Technology Letters, Vol. 8, No. 4, pp. 545 – 547, (1996).
- [2]. Edison A. Camargo, Harold M. H. Chong, Richard M. De La Rue, "2D Photonic crystal thermo-optic switch based on AlGaAs/GaAs epitaxial structure" Optic Express (OSA), Vol. 12, No. 4, pp. 588-592, (2004).
- [3]. Ajay Kumar, Sanjeev Kumar Raghuwanshi, "Implementation of optical gray code converter and even parity checker using the electro-optic effect in the Mach-Zehnder interferometer" Optical and Quantum Electronics (Springer), Vol. 47, pp. 2117-2140, (2015).
- [4]. Ajay Kumar, Santosh Kumar, S. K Raghuwanshi, "Implementation of Full-adder and Full-subtractor based on Electro-optic Effect in Mach-Zehnder Interferometers, "Optics Communication (Elsevier), Vol. 324, pp. 93 – 107, (2014).
- [5]. Ajay Kumar, Santosh Kumar, Sanjeev Kumar Raghuwanshi, "Implementation of XOR/XNOR and AND Logic Gates using Mach-Zehnder interferometers," Optik (Elsevier), Vol. 125, no. 19, pp. 5764-5767, (2014).
- [6]. Sanjeev Kumar Raghuwanshi, Ajay Kumar, Nan K Chen, "Implementation of Sequential logic circuits using the Mach-Zehnder interferometer based on Electro-optic effect," Optics Communications (Elsevier), Vol. 333, pp. 193-208, (2014).
- [7]. Kristian E. Stubkjaer, "Semiconductor optical amplifier-based all-optical gates for high-speed optical processing", IEEE Journal on selected topics in quantum electronics, Vol. 6, No. 6, pp. 1428 – 1435, (2000).

- [8]. Shaozhen Ma, Zhe Chen, Hongzhi Sun, Niloy K. Dutta, "High speed all optical logic gates based on quantum dot semiconductor optical amplifiers," *Optics Express*, Vol. 18, No. 7, pp. 6417 – 6422, (2010).
- [9]. Evangelia Dimitriadou, Kyriakos E. Zoiros, "All optical XOR gate using single quantum-dot SOA and optical filter," *Journal of Lightwave Technology (OSA)*, Vol. 31, No. 23, pp. 3813-3831, (2013).
- [10]. Amer Kotb, Chunlei Guo, "Two-photon absorption in quantum dot semiconductor optical amplifier-based all optical XOR gate at 2 Tb/s," *Optical and Quantum Electronics (Springer Nature)*, Vol. 58, pp. 51-58, (2019).
- [11]. E. G. Anagha, R. K. Jeyachitra, "An investigation on the cascaded operation of photonic crystal based all optical logic gates and verification of De-Morgan's law," *Optical and Quantum Electronics (Springer Nature)*, Vol. 52, pp: 293-319, (2020).
- [12]. Rui-hua Yuan, Chen Wang, Zhi-yuan Li, "Design of on-chip optical logic gate in 2D silicon photonic crystal slab," *Optical Review (Springer)*, Vol. 27, pp. 277-282, (2020).
- [13]. Gaurav Kumar Bharti, Jayanta Kumar Rakshit, "Design of all-optical JK, SR and T flip-flops using micro-ring resonator-based optical switch," *Photonic Network Communications (Springer)*, Vol. 35, pp: 381-391, (2018).
- [14]. Kangmei Li, Hong-Fu Ting, Mark A. Foster and Amy C. Foster, "High-speed all-optical NAND/AND logic gates using four-wave mixing Bragg scattering," *Optics Letters*, Vol. 41, No. 14, pp: 3320:3323, (2016).
- [15]. S. N. Andrianov, A. A. kalchev, O. P. Shindyaev, A. V. Shkalilkov, "A quantum –controlled NOT gate based on four wave mixing in a cavity for polarization photonic qubits," *Bulletin of the Russian Academy of Science: Physics*, Vol. 83, No. 3, pp: 381-383, (2019).
- [16]. F. K. Law, M. Rakib Uddin, Hasnul Hashim, Zainidi Hamid, "Simulation and demonstration of electro-optic digital logic gates based on a single microring resonator," *Optical and Quantum Electronics*, Vol. 49, pp: 413-429, (2017).
- [17]. Law Foo Kui, M. Rakib Uddin, "Photonic microring resonator resonance response analysis," *Optical and Quantum Electronics (Springer)*, Vol. 49, pp: 275-286, (2017).
- [18]. Foo Kui Law, M. Rakib Uddin, Angie Teo Chen Chen, Bikash Nakkarmi, "Positive edge-triggered JK flip-flop using silicon based micro-ring resonator," Vol. 52, pp: 314-326, (2020).
- [19]. Foo Kui Law, M. Rakib Uddin, Hasnul Hashim, "Photonic D-type flip flop based on micro-ring resonator," *Optical and Quantum Electronics (Springer)*, Vol. 50, pp. 119-129, (2018).
- [20]. Ajay Kumar, "Application of micro-ring resonator as high speed optical gray code converter," *Optical and Quantum Electronics (Springer)*, Vol. 48, pp: 460- 474, (2016).
- [21]. Ajay Kumar, "Implementation of All - Optical NAND Logic Gate and Half-Adder Using the Micro-Ring Resonator Structures," *Optical and Quantum Electronics (Springer)* Vol. 48, pp: 477-489, (2016).
- [22]. Ajay Kumar, Sanjeev Kumar Raghuwanshi, "Implementation of some high speed combinational and sequential logic gates using micro-ring resonator," *Optik - International Journal for Light and Electron Optics*, Vol. 127, No. 20, pp. 8751-8759, (2016).
- [23]. Ajay Kumar, Manish Kumar, Sumit Kumar Jindal, Sanjeev Kumar Raghuwanshi, "Implementation of All-Optical Active low/high Tri-state Buffer logic using the Micro-Ring Resonator Structures," *Optical and Quantum Electronics (Springer Nature)*, Vol. 51, pp: 191-208, (2019)

- [24]. Jayanta Kumar Rakshit, Jitendra Nath Roy, "Micro-ring Resonator based all-optical reconfigurable Logic Operations," *Optics Communications* (Elsevier), Vol. 321, pp: 38-46, (2014).
- [25]. Gaurav Kumar Bharti, Jayant Kumar Rakshit, "Design and Performance analysis of High Speed Optical Binary Code Converter using Micro ring Resonator," *Fiber and Integrated Optics* (Taylor & Francis), Vol. 37, No. 2, pp: 103-121, (2018).
- [26]. S. B. I. N. Daud, *Simulation of Optical Soliton Control in Ring Resonator Systems* Universiti Teknologi Malaysia.
- [27]. J. K. Rakshit, T. Chattopadhyay, and J. N. Roy, "Design of ring resonator based all optical switch for logicand arithmetic operations - A theoretical study," *Optik.*, vol. 124, no. 23, pp. 6048–6057, (2013).
- [28]. P. Saeung and P. P. Yupapin, "Generalized analysis of multiple ring resonator filters: Modeling by using graphical approach," *Optik.*, vol. 119, no. 10, pp. 465–472, 2008, doi: 10.1016/j.ijleo.2006.12.017.
- [29]. 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* (Elsevier), Vol. 124, No. 23, pp: 6048-6057, (2013).
- [30]. K. E. Zoiros, G. Papadopoulos, T. Houbavlis, and G. T. Kanellos, "Theoretical analysis and performance investigation of ultrafast all-optical Boolean XOR gate with semiconductor optical amplifier-assisted Sagnac interferometer," *Opt. Commun.*, vol. 258, no. 2, pp. 114–134, 2006, doi: 10.1016/j.optcom.2005.07.059.
- [31]. J. K. Rakshit and J. N. Roy, "All-optical ultrafast switching in a silicon microring resonator and its application to design multiplexer/demultiplexer, adder/subtractor and comparator circuit," *Opt. Appl.*, vol. 46, no. 4, pp. 517–539, 2016, doi: 10.5277/oa160402.
- [32]. K. E. Zoiros, "Performance investigation of all-optical clock recovery circuit based on Fabry-Pérot filter and semiconductor optical amplifier assisted Sagnac switch," *Opt. Eng.*, Vol. 46, no. 8, p. 085005, (2007).

Figures

Figure 1

Two Active low tri-state buffers and one clocked D flip-flop assisted single bit memory register

Figure 2

Layout diagram of 4-bit memory register unit using 8 active low tri-state buffer logic and 4 clocked D flip-flop

Figure 3

Layout of the micro-ring resonator structure

Figure 4

Switching activity of Micro-ring resonator structure

Figure 5

Transfer function of normalized output response at the through and drop port at the specified wavelengths 1550nm in the presence and absence of control pump signal

Figure 6

Variation of Phase Shift with an average amount of pump power inside the ring resonator

Figure 7

Intensity variation at the through the port and drop port with Coupling Coefficient k_1 , for different value of $k_2 \in 0.1 - 0.5$ in the absence of control signal

Figure 8

Intensity variation at the through the port and drop port with Coupling Coefficient k_1 , for different value of $k_2 \in 0.1 - 0.5$ in the presence of optical control pump signal

Figure 9

Variation of normalized optical signal intensity at the through port and drop port (in the absence of optical control pump signal)

Figure 10

Variation of normalized optical signal intensity at the through port and drop port (in the presence of optical control pump signal)

Figure 11

Variation of through port and drop port intensity in the presence and absence of optical control pump signal

Figure 12

Variation of Extinction Ratio with the different values of coupling coefficients

Figure 13

Variation of Extinction Ratio with the different values of Radius.

Figure 14

Variation of Contrast Ratio with the different values of coupling coefficients

Figure 15

Variation of Contrast Ratio with the different values of coupling coefficients

Figure 16

Variation of Amplitude Modulation parameter with the different values of coupling coefficients

Figure 17

Variation of Amplitude Modulation parameter with the different values of Radius.

Figure 18

Figure 19

All-optical clocked D flip-flop using the feedback assisted micro-ring resonator structure

Figure 20

MATLAB simulation result of the optical clocked D flip-flop.

Figure 21

All-optical active low tri-state buffer logic using two MRR structure

Figure 22

MATLAB simulation result of the proposed optical active low tri-state buffer

Figure 23

All-optical 4-bit memory registers using the micro-ring resonator structures

Figure 24

Diffractive Beam Splitter

EFL: Effective Focal Length
m: order of the multi-spot
 θ_s : Separation angle between two spot
 d : Separation between two focal spot
 θ_f : Full Angle
 D : Length of the Spot array

Figure 25

Schematic view of Set up of Diffractive Optical Element

Figure 26

MATLAB simulation result of 1 x 4 optical memory representing the WRITE operation ($RD = 1$ and $WR = 0$) for the high level of the clock signal

Figure 27

MATLAB simulation result of 1 x 4 optical memory representing the READ operation ($RD = 0$ and $WR = 1$) for the low level of the clock signal

Figure 28

MATLAB simulation result of 1 x 4 optical memory representing the RD = 1 and WR = 1 operation for the low level of clock signals

Figure 29

Average Loss factor for the cascaded Micro-ring resonator structure