Implementation of all-optical 1 × 4 memory register unit using the micro-ring resonator structures

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Abstract

Implementation of switching activity in the all-optical domain is an essential aspect 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. 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 read (RD) and write (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 efficiently select device parameters. Finally, it 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
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 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 (Murphy et al. 1996). 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 (Camargo et al. 2004). 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 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 (Kumar and Raghuwanshi 2015; Kumar and Kumar 2014; Kumar et al. 2014; Sanjeev Kumar Raghuwanshi 2014). 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 cross-gain modulation and four-wave mixing to the integrated interferometric gates using cross-phase modulation is described (Stubkjaer 2000). Scheme to realize all-optical Boolean logic functions AND, XOR, and NOT using semiconductor optical amplifiers with quantum-dot active layers is studied where non-linear 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 Boolean logic functions (Ma et al. 2010). The implementation of an all-optical XOR gate for 160 Gb/s return to zero data signal using a single quantum dot semiconductor optical amplifier is discussed and analysed (Dimitriadou and Zoiros 2013). The scheme involves the detuning optical amplifier, which shows its importance in all-optical signal processing and its application. The non-linear 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 (Kotb and Guo 2019). 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 configuration set is proposed to implement simple and highly compact photonic crystal-based all-optical logic AND and OR gates (Anagha and Jeyachitra 2020). The design of two types of on-chip logic gates in 2D silicon photonic crystal slab is investigated, and the relevant result associated with AND and XOR logic gate function at different frequencies is verified (Yuan et al. 2020). 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) (Gaurav Kumar Bharti
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 non-linear fiber (Li et al. 2016). 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 (Andrianov et al. 2019). 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 an efficient technique. 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 (Law et al. 2017). A novel analysis of a micro-ring resonator structure is presented, including the mathematical and simulation analysis of the modulated signals in Kui and Rakib Uddin (2017). In the analysis of Kui and Rakib Uddin (2017), 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 Kui and Uddin (2020). In this scheme, the basic single micro-ring resonator structure uses free-carrier plasma dispersion electro-optic effect properties in its ring waveguide, 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 is investigated. It was observed that carrier injection forward-biased PIN waveguide resonance phenomena could generate the logic of D flip-flops (Law et al. 2018). 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 (Kumar 2016a), NAND logic gate, Half-adders (Kumar 2016b), and some well-known combinational and sequential circuits (Kumar 2016c). 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 Sect. 1, the relevant introduction associated with the modern optical switching schemes and related technology is discussed. Section 2 represents the basic idea of 1 bit and 4 bits memory registers, including the specific arrangement of clocked D flip-flop and active low tri-state buffers. In this section, we have shown the implementation of a 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 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 (k₁,k₂) and radius of MRR. The basic idea of optically clocked D flip-flop and all-optical active low tri-state buffer is described based on the parameter analysis. Finally, the layout of the proposed MRR switching-based all-optical 1 × 4 memory registers is discussed. In Sect. 2, it is observed that the selected device parameters provide the relevant result, and it is verified using the appropriate MATLAB simulation result and proper mathematical modelling. 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 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 (Kumar and Kumar 2019). 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.

The input bits can be read-only if the output buffer is enabled; otherwise, the output Q and output terminal \( D_{\text{out}} \) 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, Fig. 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 \( 1 \times 4 \) bit memory register, which consists of 4 I/O lines and two control line RD and WR. Figure 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.

However, this paper has represented an ideal technique to implement the all-optical \( 1 \times 4 \) 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, closely coupled with one or two straight 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 the minimum at the through 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, introducing the change in the effective index of the ring resonator section.

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 $k_2$ are the coupling coefficient between the ring structure and the straight waveguide section. The effective index of the ring structure can be represented as $n_{\text{eff}} = n_0 + n_2.I = n_0 + \frac{n_2.A_{\text{eff}}}{\lambda}$, where $n_0$ 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 Fig. 3, symbols \( E_{i1} \) and \( E_{i2} \) are the inputs 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 (Jayanta Kumar Rakshit 2014; Kumar et al. 2021):

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

(1)

\[
E_{rb} = E_{ra}\exp(-\alpha L/4)\exp(jk_nL/2)
\]

(2)

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

(3)

\[
E_{rd} = E_{rc}\exp(-\alpha L/4)\exp(jk_nL/2)
\]

(4)

The field at the through port is given by

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

(5)

The field at the drop port is given by

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

(6)

For the simplification, let us consider,

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

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

\[
E_t = \frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}x^2\exp^2(j\phi)}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2\exp^2(j\phi)}E_{i1} + \frac{-D\sqrt{k_1k_2}x\exp(j\phi)}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2\exp^2(j\phi)}E_{i2}
\]

(7)

\[
E_d = \frac{-D\sqrt{k_1k_2}x\exp(j\phi)}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2\exp^2(j\phi)}E_{i1} + \frac{D\sqrt{1-k_2} - D\sqrt{1-k_1}x^2\exp^2(j\phi)}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2\exp^2(j\phi)}E_{i2}
\]

(8)

In the Eqs. (1)–(8), \( \gamma \) and \( \alpha \) 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 \( \lambda \) is the resonant wavelength of the ring. Equations (7)–(8) can be used to show the implementation of the ring resonator structure as a perfect all-optical switch (Kumar et al. 2021).

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, as shown in Table 3. 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 the 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...
Implementation of all-optical 1 × 4 memory register unit using…

Table 1 The through port and drop port intensities of MRR with and without the control pump signal concerning different identical values of k1 and k2

| 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 |
|----------------------|--------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
|                      | Through port (au) | Drop port (au) | Through port | Drop port |
| k1       | k2 | 0.147 | 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 |

Fig. 4 Switching activity of Micro-ring resonator structure

from the drop port to the through 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 1550 nm. Figure 5 describes the temporary blue shift of the micro-ring resonator wavelength (Kumar et al. 2021). Some important parameters are assigned for the occurrence of appropriate blue shift phenomena. The design parameters of MRR structure can be represented in Table 3. Based on the specified parameters, the MATLAB
The 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 transfer function analysis involves the computation of refractive index change ($\Delta n$), which can be represented by the Eq. (9) (Gaurav Kumar Bharti 2018b).

**Table 2**  The through port and drop port intensities of MRR with and without the control pump signal concerning different values of ring radius R

| 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     |

**Fig. 5**  Transfer function of normalized output response at the through and drop port at the specified wavelengths 1550 nm in the presence and absence of control pump signal
Equations (1)–(9) provides the mechanism to derive the appropriate blue shift phenomena at the suggested wavelength $\lambda = 1.55 \mu m$. 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 $\Delta n$, and it can be represented as $\phi = \frac{2\pi}{\lambda} \Delta n L$.

The phase shift corresponding to different wavelengths can be observed using the MATLAB simulation result, represented in Fig. 5. In Fig. 6, the phase shift analysis with the average amount of controlled pump power has been analyzed. The analysis suggests that a 2.552 mW amount of average pump power is enough to create the $\pi$ amount of phase shift (Kumar et al. 2021).

$$\Delta n = -\left[ 8.8 \times 10^{-22} \frac{\beta t_p^2}{2h\nu \sqrt{\pi S^2}} P_{avg}^2 + 8.5 \times 10^{-22} \left( \frac{\beta t_p^2}{2h\nu \sqrt{\pi S^2}} P_{avg}^2 \right)^{0.8} \right]$$  \hspace{1cm} (9)
However, to achieve optimum performance of the proposed $1 \times 4$ memory register, the performance parameters of the micro-ring resonator structure are analysed, and the appropriate values of some crucial 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 the 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, the input optical signal will appear at the drop port of MRR. In the presence of the control signal, the input signal will be directed towards through 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 choose 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 Figs. 7 and 8, respectively.

Figure 7 shows 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, for the identical values of $k_1$ and $k_2$ and in the absence of control pump signal, the through port is showing the minimum intensity, whereas drop port is at the maximum intensity of the optical signal. In contrast, with the application of a control signal on MRR and for identical values of $k_1$ and $k_2$, the through port is having the maximum intensity while the drop port exhibits the minimum intensity of the optical signal. Now, the corresponding values of through and drop port intensities from the Figs. 7 and 8 for all the identical values of $k_1$ and $k_2$ are represented in Table 1.

![Variation of Optical Intensity at the through port in the absence of Optical Control Pump Signal](image)

**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
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 $k_1 = k_2 = 0.5$. The values of coupling coefficients at $k_1 = k_2 = 0.5$ is not considered as the optimum value, because in the presence of a control pump signal, values of both the through port and drop port intensities are approximately close to 1, i.e. 0.846 & 0.5322, which is against the basic principle of MRR. Again, from Table 1, we can see that for $k_1 = k_2 = 0.1$, and in the presence of control pulse signal, we get excellent results, i.e., the 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 significant 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 travelling 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 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 Figs. 9 and 10.

Figure 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. Similarly, 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.

From Fig. 9, we obtained seven minima of through port intensity at seven different points of radius R and seven maxima of drop port intensity for the same points of radius R. All the seven values of through port minima and drop port maxima at their corresponding
values of radius, are represented by the column 2, column 3 and column 1 of Table 2. 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 represented in the fourth and fifth columns 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 while Drop port must be at the maximum intensity of input optical signal and the condition is reversed in the presence of control signal. So, from the obtained data in Table 2, it can be concluded that the best value for the ring radius of the system is at \( R = 7.08 \, \mu m \).

### 2.3 Figure of merits

The radius of the ring \( R \) and coupling coefficients \( (k_1, k_2) \) of a ring resonator are very crucial parameters, and from our analysis, we have chosen their optimum values as \( k_1 = k_2 = 0.25 \) and \( R = 7.08 \, \mu m \). Now, we will calculate the values of different performance parameters of the ring resonator from the simulation result and 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.

**Free spectrum range (FSR):** The frequency spacing between two resonance peaks of the drop port signal is defined as FSR, 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 \( \Delta k \) is the.
phase constant. The frequency and phase shifts are denoted by $\Delta f$ and $\Delta \lambda$ and can be written as (Daud et al. 2015),

$$\Delta f = \frac{c}{2\pi} \Delta k$$  \hspace{1cm} (10)

$$\Delta \lambda = -\left(\frac{\lambda^2}{2\pi}\right) \Delta k$$  \hspace{1cm} (11)

Now the FSR in terms of frequency ($f$) and wavelength ($\lambda$) is expressed as:

$$\Delta f = \frac{c}{n_{gr} L}$$  \hspace{1cm} (12)

$$\Delta \lambda = -\left|\frac{\lambda^2}{n_{gr} L}\right|$$  \hspace{1cm} (13)

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

$$n_{gr} = n_{eff} - \lambda \frac{dn_{eff}}{d\lambda}$$  \hspace{1cm} (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 expressed 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 (Daud et al. 2015; Rakshit et al. 2013). The resonance bandwidth determines how fast a ring resonator can process the optical data. The FWHM, in terms of frequency ($f$) and wavelength ($\lambda$) can be expressed as:

$$\text{FWHM}(f) = \frac{c}{F n_{gr} L}$$  \hspace{1cm} (15)

$$\text{FWHM}(\lambda) = \frac{\lambda^2}{F n_{gr} L}$$  \hspace{1cm} (16)

where $F$ refers to the finesse of the 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.

$$F = \frac{\text{FSR}}{\text{FWHM}}$$ \hspace{1cm} (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:
The Q factor of a ring resonator can be defined as

$$Q = \frac{f_0}{\delta f} = \frac{\lambda_0}{\delta \lambda}$$  \hspace{1cm} (19)$$

The Q factor determines the shape and bandwidth of the ring resonator output. A high value of the Q factor is required for all-optical signal processing applications (Daud et al. 2015). 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 (Daud et al. 2015; Rakshit et al. 2013):

$$\text{On–off Ratio} = \frac{T_{\text{max(through port)}}}{T_{\text{min(drop port)}}}$$  \hspace{1cm} (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 (Saeung and Yupapin 2008). From Fig. 11, the obtained value of the ON–OFF ratio is 41.0490 dB.

**Extinction ratio (ER):** The extinction ratio is defined as, (Daud et al. 2015; Rakshit et al. 2013),

$$\text{ER(dB)} = 10 \log \left( \frac{P_{\text{min}}}{P_{\text{max}}} \right)$$  \hspace{1cm} (21)$$

where $P_{\text{min}}$ and $P_{\text{max}}$ 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.

Figure 12 represents the variation of extinction ratio (ER) with respect to coupling coefficients. The variation of ER w.r.t ring radius R can be observe in Fig. 13. From these two graphs, it can be seen that at the value of coupling coefficients $k_1 = k_2 = 0.25$ and ring radius = 7.08 µm, we are getting the maximum value of extinction ratio as 18.98 dB. Therefore, this result also 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’ ($P_{\text{mean}}^1$) to the mean output intensity for ‘0’ ($P_{\text{mean}}^0$) and given as (Rakshit et al. 2013),

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

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

The variation of contrast ratio with the variation of coupling coefficient can be observed in Fig. 14. The variation of contrast ratio with different values of radius of the ring is observed in Fig. 15. In Figs. 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.
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

**Amplitude modulation (AM):** The amplitude modulation of the ring resonator can be defined as (Zoiros et al. 2006; Rakshit and Roy 2016a),

$$\text{AM}(\text{dB}) = 10 \log \left( \frac{P_\text{max}^1}{P_\text{min}^1} \right)$$  \hspace{1cm} (23)
where $P_{1_{\text{max}}}$ and $P_{1_{\text{min}}}$ are the maximum and minimum values of intensity at a high (1) level. The typical value of AM must be less than 1 dB (Zoiros 2007).

The simulation results for determining the optimum amplitude modulation (AM) value are shown graphically in Figs. 16 and 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

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

Fig. 15 Variation of Contrast Ratio with the different values of ring radius
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 µm.

**Switching speed:** In a micro-ring resonator, the output optical signal is switched on and off by applying a 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 and b).

From Fig. 18a, the switching speed for the 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, 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 the rise time and fall time are 2.531 and 2.52 ps, 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 5, 6, and 7. 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 Figs. (26, 27, and 28).

**Data Rate:** The data rate or operational speed of the micro-ring resonator circuit can be calculated by using the relation given in Eq. (24) (Tanushi and Yokoyama 2006; Rakshit and Roy 2016b)

\[
T = \frac{Y^2}{1 + X^2 - 2X\cos\phi}
\]

(24)

where \(X = \cos^2(k)\exp(-\alpha\pi R)\), \(Y = \sin^2(k)\exp(-\alpha\pi R/2)\), and \(\phi = n_{\text{eff}}\frac{4\pi R^2}{\lambda}\). The data rate of the proposed model is estimated as 100 Gbps.

The performance comparison of the various optical switching techniques is shown in Table 4. Here MRR, the proposed structure stands for Micro-Ring Resonator, MZI stands for Mach–Zehnder Interferometer, TODA stands for Terahertz Optical Asymmetric De-multiplexer PPLN stands for Periodically Poled Lithium Niobate, HNLF stands for Highly Nonlinear Fiber, and MEMS stands for Micro-electromechanical systems. In Table 4, we have compared the three very important performance parameters of all-optical micro-ring resonator switching, namely data rate, extinction ratio, and switching time, with some other optical switching techniques. The values of data rate and extinction ratio should be very high, and switching time should be significantly less for the implementation of high-speed optical computational systems. MRR based
Table 4  Performance comparison of the various optical switching techniques

| Parameter                        | Proposed structure | Other technologies (Sasikala and Chitra 2018) |
|----------------------------------|--------------------|-----------------------------------------------|
| Switching method adopted         | MRR                | MZI, TODA, PPLN, Silicon nanowire, HNLF       |
| Data rate                        | 100 Gbps and can be extended upto 250 Gbps | 10–80 Gbps, 10 Gbps, 20 Gbps, 40 Gbps, 10–40 Gbps |
| Extinction ratio                 | 18.98 dB           | 11–15.5 dB, 11 dB, 14 dB, 20 dB, 14–25 dB     |
| Parameter                        | Proposed structure | Other Technologies (Singh and Sanjeev 2015)    |
| Different devices                | MRR                | MEMS, Electro-optic, Thermo-optic, Liquid Crystal, Acousto-optic |
| Rise and Fall time/switching time| 2.52 ps            | 12 ms, 5 ns, 3 ms, 5 ms, 3 µs                  |
optical switching may show the value of data rate is 100 Gbps (can be extended up to 250 Gbps) as per Table 4. It is the highest value compared to other optical switching techniques like MZI, TODA, PPLN, silicon nanowire, and HNLF based optical switching. Similarly, the calculated value of extinction ratio for MRR is 18.98 dB which is also quite appreciable. It can also be seen from Table 4 that the MRR based switching is having the lowest value switching time, i.e., 2.52 picoseconds compared to all other mentioned optical switching techniques.

In Fig. 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 store the optical data up to the desired duration of time-based on an optically controlled pump signal (Kumar 2016c). 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.
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.

Figure 21 describes the functionality of one of the sub-modules used in constructing the optical memory register. The unit shown in Fig. 21 provides the controlling mechanism to implement the READ/WRITE operation (Kumar and Kumar 2019). 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 IN signal status will not change the status of the through port of the second MRR.
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 Eqs. (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.

The layout of the 4-bit memory register consists of 16 identical micro-ring resonator structures. Figure 23 shows that the first and second columns of identical MRR structures of the layout can be used to perform the write operation of the 4-bit optical memory register. The CW optical input signal $(x_0)$ is applied at the input port of each MRR (MRR1-MRR4) in the first column, whereas the switching of the optical signal can be controlled by applying a vertically applied optical control pump signal WR. It can be observed that, in the absence of a WR signal, the optical signal switches to the drop port of each MRR of the first column. The drop port of each MRR (MRR1-MRR4) is connected to the input ports of respective MRRs (MRR5-MRR8) present in the second column. Hence, in the absence of the WR signal, the optical signal is available at the input port of each MRR of the second column. It can be observed that MRRs of the second column are controlled by 4-bit optical input data $D_{IN0}$, $D_{IN1}$, $D_{IN2}$, and $D_{IN3}$. Now, we can observe the optical signal at the output ports of each MRR (MRR5-MRR8) present in the second column of MRRs, based on the status of control signal.

Fig. 23 All-optical 4-bit memory registers using the micro-ring resonator structures
data bits $D_{IN1}$, $D_{IN2}$, $D_{IN3}$, and $D_{IN4}$. The third column of the proposed layout can be used as the feedback-assisted optical clocked D flip-flop (MRR10-MRR12). The optical data bits obtained from the through port of each MRR (MRR5-MRR8) of the 2nd column ($D_0$, $D_1$, $D_2$, and $D_3$) are connected to the input port of respective MRRs (MRR9-MRR12) of the third column, as shown in Fig. 23. The switching activity in the third column is controlled by the optical clock 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 $D_{OUT0}$, $D_{OUT1}$, $D_{OUT2}$, and $D_{OUT3}$. The simultaneous application of the 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 splitting 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.

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

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 specific distance by adding a focusing lens after the diffractive beam splitter. The selection of lens can be performed based on Eq. (25)

\[ d = \tan(\theta_s) \times \text{EFL} \]  

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 Eq. (26).

\[ \Lambda = \frac{m\lambda}{\sin \theta_s} \]

where:

- \( \Lambda \): Period of DOE
- \( m \): Diffraction Order
- \( \lambda \): Wavelength
- \( \theta_s \): Separation angle between two beams

The system modelling 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 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 Eq. (27).

\[
\begin{align*}
\text{EdMRR1} &= \frac{-D\sqrt{k_1k_2x}\exp{(j\phi_{\text{MRR1}})}}{1 - \sqrt{1 - k_1}\sqrt{1 - k_2x^2}\exp{2(j\phi_{\text{MRR1}})}}(x_0) \\
\text{EdMRR2} &= \frac{-D\sqrt{k_1k_2x}\exp{(j\phi_{\text{MRR2}})}}{1 - \sqrt{1 - k_1}\sqrt{1 - k_2x^2}\exp{2(j\phi_{\text{MRR2}})}}(x_0) \\
\text{EdMRR3} &= \frac{-D\sqrt{k_1k_2x}\exp{(j\phi_{\text{MRR3}})}}{1 - \sqrt{1 - k_1}\sqrt{1 - k_2x^2}\exp{2(j\phi_{\text{MRR3}})}}(x_0) \\
\text{EdMRR4} &= \frac{-D\sqrt{k_1k_2x}\exp{(j\phi_{\text{MRR4}})}}{1 - \sqrt{1 - k_1}\sqrt{1 - k_2x^2}\exp{2(j\phi_{\text{MRR4}})}}(x_0)
\end{align*}
\]

The mathematical analysis of a single MRR structure the parameters like D, k1, k2, x are having the usual meaning as described in the Eqs. (1)–(8). The expression for \( \phi_{\text{MRR1}} - \phi_{\text{MRR4}} \) can be represented using the Eq. (28).
\[ \phi_{\text{MRR}1} = \frac{2\pi}{\lambda} n_{\text{eff(MRR1)}} \]
\[ \phi_{\text{MRR}2} = \frac{2\pi}{\lambda} n_{\text{eff(MRR2)}} \]
\[ \phi_{\text{MRR}3} = \frac{2\pi}{\lambda} n_{\text{eff(MRR3)}} \]
\[ \phi_{\text{MRR}4} = \frac{2\pi}{\lambda} n_{\text{eff(MRR4)}} \]

where, \( D_{\text{in0}} \) and \( P_{\text{WR}} \) is the intensity and power associated with the optical control pump signal \( \text{WR} \). 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. (29).

\[
\begin{align*}
D_0 & = \left[ \frac{D\sqrt{1 - k_1} - D\sqrt{1 - k_2x^2\exp^2(j\phi_{\text{MRR5}})}}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2x^2\exp^2(j\phi_{\text{MRR5}})}} \right]_{\text{EdMRR1}} \\
D_1 & = \left[ \frac{D\sqrt{1 - k_1} - D\sqrt{1 - k_2x^2\exp^2(j\phi_{\text{MRR6}})}}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2x^2\exp^2(j\phi_{\text{MRR6}})}} \right]_{\text{EdMRR2}} \\
D_2 & = \left[ \frac{D\sqrt{1 - k_1} - D\sqrt{1 - k_2x^2\exp^2(j\phi_{\text{MRR7}})}}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2x^2\exp^2(j\phi_{\text{MRR7}})}} \right]_{\text{EdMRR3}} \\
D_3 & = \left[ \frac{D\sqrt{1 - k_1} - D\sqrt{1 - k_2x^2\exp^2(j\phi_{\text{MRR8}})}}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2x^2\exp^2(j\phi_{\text{MRR8}})}} \right]_{\text{EdMRR4}}
\end{align*}
\]

The mathematical expression can be represented by putting the values of EdMRR1-EdMRR4 from Eq. (27) to Eq. (29), as shown in the Eq. (30)

\[
\begin{align*}
D_0 & = \left[ \frac{D\sqrt{1 - k_1} - D\sqrt{1 - k_2x^2\exp^2(j\phi_{\text{MRR5}})}}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2x^2\exp^2(j\phi_{\text{MRR5}})}} \right]_{(x_0)} \\
D_1 & = \left[ \frac{-D\sqrt{k_1k_2x \exp(j\phi_{\text{MRR1}})}}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2x^2\exp^2(j\phi_{\text{MRR5}})}} \right]_{(x_0)} \\
D_2 & = \left[ \frac{-D\sqrt{k_1k_2x \exp(j\phi_{\text{MRR2}})}}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2x^2\exp^2(j\phi_{\text{MRR5}})}} \right]_{(x_0)} \\
D_3 & = \left[ \frac{-D\sqrt{k_1k_2x \exp(j\phi_{\text{MRR3}})}}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2x^2\exp^2(j\phi_{\text{MRR5}})}} \right]_{(x_0)} \\
D_4 & = \left[ \frac{-D\sqrt{k_1k_2x \exp(j\phi_{\text{MRR4}})}}{1 - \sqrt{1 - k_1} \sqrt{1 - k_2x^2\exp^2(j\phi_{\text{MRR5}})}} \right]_{(x_0)}
\end{align*}
\]
\[
\begin{align*}
\phi_{\text{MRR5}} &= \frac{2\pi}{\lambda} n_{\text{eff(MRR5)}} \\
\phi_{\text{MRR6}} &= \frac{2\pi}{\lambda} n_{\text{eff(MRR6)}} \\
\phi_{\text{MRR7}} &= \frac{2\pi}{\lambda} n_{\text{eff(MRR7)}} \\
\phi_{\text{MRR8}} &= \frac{2\pi}{\lambda} n_{\text{eff(MRR8)}} \\
\end{align*}
\]

whereas

In Eq. (31), \((I_{D_{\text{in}}} - I_{D_{\text{in}}})\) and \((P_{D_{\text{in}}} - P_{D_{\text{in}}})\) are the intensities and powers associated with the data input signals \((D_{\text{in0}} - D_{\text{in3}})\). 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 \((Q_{\text{prev0}} - Q_{\text{prev3}})\). The unit MRR9-MRR12 provides the output \((Q_0 - Q_3)\) at the through port of corresponding MRRs depending upon the status of the optical control pump CLK signal. The mathematical expression of \((Q_0 - Q_3)\) can be represented as shown in the Eq. (32),

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

In Eq. (32), the value of \((D_0 - D_3)\) can be taken from the Eq. (30). The values of \((\phi_{\text{MRR9}} - \phi_{\text{MRR12}})\) can be represented by the Eq. (33)

\[
\begin{align*}
\phi_{\text{MRR9}} &= \frac{2\pi}{\lambda} n_{\text{eff(MRR9)}} \\
\phi_{\text{MRR10}} &= \frac{2\pi}{\lambda} n_{\text{eff(MRR10)}} \\
\phi_{\text{MRR11}} &= \frac{2\pi}{\lambda} n_{\text{eff(MRR11)}} \\
\phi_{\text{MRR12}} &= \frac{2\pi}{\lambda} n_{\text{eff(MRR12)}} \\
\end{align*}
\]

where, \(I_{\text{CLK}}\) and \(P_{\text{CLK}}\) are the intensity and power associated with the optical control pump signal \(\text{CLK}\). 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 \((D_{\text{out0}} - D_{\text{out3}})\) based on the status of the control pump signal \(\text{RD}\). In Fig. 23, it is visible that the absence of control pump signal \(\text{RD} = 0\) or \(\text{RD} = 1\) switches the optical signal \((Q_0 - Q_3)\) to the specified output port of \((D_{\text{out0}} - D_{\text{out3}})\). Finally, the mathematical expression for the status of the output port \((D_{\text{out0}} - D_{\text{out3}})\) can be represented using the Eq. (34).
\[
D_{\text{out}0} = \frac{-D\sqrt{k_1k_2x\exp(j\phi_{\text{MRR13}})}\sqrt{1 - k_1\sqrt{1 - k_2x^2}\exp^2(j\phi_{\text{MRR13}})}}{1 - \sqrt{1 - k_1\sqrt{1 - k_2x^2}\exp^2(j\phi_{\text{MRR13}})}} (Q_0) \]
\[
D_{\text{out}1} = \frac{-D\sqrt{k_1k_2x\exp(j\phi_{\text{MRR14}})}\sqrt{1 - k_1\sqrt{1 - k_2x^2}\exp^2(j\phi_{\text{MRR14}})}}{1 - \sqrt{1 - k_1\sqrt{1 - k_2x^2}\exp^2(j\phi_{\text{MRR14}})}} (Q_1) \]
\[
D_{\text{out}2} = \frac{-D\sqrt{k_1k_2x\exp(j\phi_{\text{MRR15}})}\sqrt{1 - k_1\sqrt{1 - k_2x^2}\exp^2(j\phi_{\text{MRR15}})}}{1 - \sqrt{1 - k_1\sqrt{1 - k_2x^2}\exp^2(j\phi_{\text{MRR15}})}} (Q_2) \]
\[
D_{\text{out}3} = \frac{-D\sqrt{k_1k_2x\exp(j\phi_{\text{MRR16}})}\sqrt{1 - k_1\sqrt{1 - k_2x^2}\exp^2(j\phi_{\text{MRR16}})}}{1 - \sqrt{1 - k_1\sqrt{1 - k_2x^2}\exp^2(j\phi_{\text{MRR16}})}} (Q_3) \] (34)

In Eq. (34), the values \((Q_0 - Q_3)\) can be taken from the Eq. (32). The values of \((\phi_{\text{MRR13}} - \phi_{\text{MRR16}})\) present in the Eq. (34) can be represented by the Eq. (35).

\[
\phi_{\text{MRR13}} = \frac{2\pi}{\lambda} n_{\text{eff(MRR13)}} \]
\[
\phi_{\text{MRR14}} = \frac{2\pi}{\lambda} n_{\text{eff(MRR14)}} \]
\[
\phi_{\text{MRR15}} = \frac{2\pi}{\lambda} n_{\text{eff(MRR15)}} \]
\[
\phi_{\text{MRR16}} = \frac{2\pi}{\lambda} n_{\text{eff(MRR16)}} \]
\[
\left\{ \begin{array}{l}
\phi_{\text{MRR13}} = \frac{2\pi}{\lambda} n_{\text{eff(MRR13)}} \\
\phi_{\text{MRR14}} = \frac{2\pi}{\lambda} n_{\text{eff(MRR14)}} \\
\phi_{\text{MRR15}} = \frac{2\pi}{\lambda} n_{\text{eff(MRR15)}} \\
\phi_{\text{MRR16}} = \frac{2\pi}{\lambda} n_{\text{eff(MRR16)}} \\
\end{array} \right. \] (35)

In Eq. (35), \(I_{RD}\) and \(P_{RD}\) are the intensity and power of the optical control pump signal (RD). The Eqs. (27)–(35) is analysed and simulated using the MATLAB software to implement the MRR switching activity-based \(1 \times 4\) memory register represented in Figs. 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 show the status of the control signal RD and output signals \((D_{\text{OUT}0}, D_{\text{OUT}1}, D_{\text{OUT}2},\ \text{and} \ D_{\text{OUT}3})\) respectively. It can be observed that, in Fig. 26, as the status of the WR signal is low, the status of 2nd row \((D_{\text{IN}0}, D_{\text{IN}1}, D_{\text{IN}2}, D_{\text{IN}3} \rightarrow 0110)\) 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 \((\text{MRR9-MRR12})(Q_0, Q_1, Q_2, Q_3 \rightarrow 0000)\) are entirely independent of the previous state of the output at the D-flip flop \((Q_{\text{prev0}}, Q_{\text{prev1}}, Q_{\text{prev2}},Q_{\text{prev3}})\). In the fourth row, the RD is made high hence at the output port \(D_{\text{OUT}0}, D_{\text{OUT}1}, D_{\text{OUT}2}\) and \(D_{\text{OUT}3}\) the READ operation cannot be observed. Basically, in Fig. 26, the write operation has been performed.

Table 5 shows the tabular validation of WRITE operation of the all-optical memory register, where the data provided in the form of \(D_{\text{IN}0} - D_{\text{IN}3}\) can be written at the through port of optically clocked D flip flop, which can be observed as \(Q_0 - Q_3\).

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 \(D_{\text{IN}0}, D_{\text{IN}1}, D_{\text{IN}2}, D_{\text{IN}3} \rightarrow 0111\), in the absence of a clock signal, the device maintains the previous optical data \(Q_{\text{prev0}}, Q_{\text{prev1}}, Q_{\text{prev2}}\) and \(Q_{\text{prev3}} \rightarrow 0110\) 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.

The tabular representation of the READ operation can be verified using Table 6. 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.

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 are 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.

The tabular representation of memory mode can be represented using Table 7, 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

Fig. 26 MATLAB simulation result of $1 \times 4$ optical memory representing the WRITE operation ($RD = 1$ and $WR = 0$) for the high level of the clock signal
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. (36) (Rakshit et al. 2013),

\[
\text{Local factor} = 20 \log \left( \frac{\text{Output Intensity}}{\text{Input Intensity}} \right)
\]  \hspace{1cm} (36)

Based on the Eq. (36) the loss factor is computed for the proposed unit, which can be represented as follow.

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.

### 3 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 1 × 4 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 1550 nm. 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

| 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     |
| Status of the present output set                           | $Q_0$                     | 0.139 | 0     |
|                                                           | $Q_1$                     | 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 5: Tabular representation of the output describing the WRITE operation ($RD = 1$ and $WR = 0$) of the proposed 1 × 4 Memory Registers
switching unit, e.g., coupling coefficients and radius of MMR structures, are investigated to optimize various performance affecting 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 $1 \times 4$ memory register layout is described completely with the detailed mathematical modelling 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.

Fig. 27 MATLAB simulation result of $1 \times 4$ optical memory representing the READ operation ($RD = 0$ and $WR = 1$) for the low level of the clock signal
Table 6  Tabular representation of the output describing the READ operation (RD = 0 and WR = 1) of the proposed 1 × 4 Memory Registers

| Input WRITE control signal | Normalized intensity (au) | Logic |
|---------------------------|---------------------------|-------|
| (WR)                      | 1                         | 1     |

Input data signals

| Din0 | 0 | 0 |
| Din1 | 1 | 1 |
| Din2 | 1 | 1 |
| Din3 | 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

| Q0 | 0 | 0 |
| Q1 | 0.9706 | 1 |
| Q2 | 0.9706 | 1 |
| Q3 | 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 |

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
Table 7  Tabular representation of the output describing the MEMORY operation ($RD = 1$ and $WR = 1$) of the proposed $1 \times 4$ Memory Registers

| Input WRITE control signal | WR | 1 | 1 |
|----------------------------|----|---|---|
| Input data signals         | Din\(_0\) | 1 | 1 |
|                            | Din\(_1\) | 0 | 0 |
|                            | Din\(_2\) | 0 | 0 |
|                            | Din\(_3\) | 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 |

![Fig. 29 Average Loss factor for the cascaded Micro-ring resonator structure](image)

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