

Implementation of All-optical Reversible New Gate Using Silicon Micro-ring Resonator Based All-optical Switch

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Abstract: The irreversible logic gates disperse energy into the environment due to loss of every bit and that is why, the concept of reversible logic gates evolve in recent times. The reversible logic gates have some favourable advantages. One of the key advantages is that it reduces heat dissipation. In the present communication, all optical reversible New Gate is implemented with the help of all-optical silicon micro-ring resonator (MRR) that is simulated in MATLAB. Different binary logic functions can be implemented using New Gate. The optimized performance parameters of this design are calculated through numerical simulation that could help to implement the design practically.

Keywords: All-optical Switch, Optical Micro-ring Resonator, Reversible Logic gate, New gate.

1. Introduction

According to Landauer¹, if one bit information is lost, then it dissipates energy $kT \ln 2$ joules where, k is denoted as the Boltzmann constant and T is the absolute temperature of the operation being performed. According to Bennett², no energy will be dissipated if the reversible logic is employed for computation. For this reason, the reversible logic design step towards an emerging solution to the drawback of the conventional logic design. This can be employed in many applications of nano-technology such as optical computing, quantum- computing, quantum-dot cellular automata etc^{3,4}. In case of reversible logic design, there is one by one mapping between input and output vector. The reversible logic has several advantages such as it uses minimum counts of reversible logic gates, less constant inputs, minimizes the garbage output (GO) as well as quantum cost (QC). For new

computation, we cannot use GO as the inputs. The QC means the cost of each reversible gate. Some popular reversible logic gates are Fredkin gate, Toffoli gate⁵, Feynman gate⁶ and Peres gate⁷.

In modern life, all-optical technology has been adopted for different high-speed operations like switching, routing and processing of data and a large number of information travels nearly at the speed of light as the carriers of information is photon. It can be utilized to design different logic circuits by employing different techniques like Mach Zehnder interferometer (MZI)⁸, semiconductor optical-amplifier (SOA)⁹, quantum-dot SOA (QD-SOA)¹⁰, terahertz-optical asymmetric de-multiplexers (TOAD)¹¹, non-linear material (NLM)¹², ultra-fast nonlinear interferometer (UNI)¹³ and micro-ring resonator (MRR)¹⁴, etc.

All-optical employment of New Gate (NG) using SOA based MZI has been done in¹⁵. This design requires 6 MZI switch, 3 beam-combiners (BC), 8 beam-splitters (BS) and 6 erbium doped fiber amplifier (EDFA). This technique is capable of implementing different Boolean logic functions. In this paper, the NG is proposed based on all-optical MRR with less hardware complexity as compared to previous work with inherent advantages of MRR such as high quality factor, ultrafast switching, compact size, improved bandwidth, low power consumption, ease in fabrication^{16,17}.

2. Working Procedure of MRR Based All-Optical-Switch (AOS)

A silicon MRR composed of a circular-shaped waveguide, one input waveguide, one output waveguide, one input coupler and one output coupler. This is a four ports structure and that is presented in Fig.1¹⁸. If the optical path-length difference (OPD) of a circular trip is an integer multiple of the resonant wavelength, the MRR is said to be at resonance due to interference, the drop port (DP) acquires maximum output and the through port (TP) will get no light. The refractive index (RI) of non-linear material can be changed by high intensity optical pump. The intense beam provides the carriers in the ring resonator and the effective RI of the material is altered. This is because of two-photon absorption (TPA). The effective RI can be manifested as:

$$(2.1) \quad n_{eff} = n_0 + n_2 \cdot I_n = n_0 + n_2 \cdot \frac{P_p}{A_{eff}} .$$

where, n_2 and n_0 are non-linear and linear RIs of the material sequentially. I_n , P_p are intensity and pump power. The area of cross-section of ring is A_{eff} . When π phase-shift occurs because of optical pump source, the input signal goes from DP to the TP of the MRR. The DP has minimum transmittance and TP has maximum transmission at this time. The TP and the DP output electric fields can be recorded¹⁸,

$$(2.2) \quad E_t = \frac{M\sqrt{1-k_1} - M\sqrt{1-k_2}x^2\exp^2(j\phi)}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2\exp^2(j\phi)} E_{i1} \\ + \frac{-M\sqrt{k_1}\sqrt{k_2}x\exp(j\phi)}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2\exp^2(j\phi)} E_{i2}.$$

$$(2.3) \quad E_d = \frac{-M\sqrt{k_1}\sqrt{k_2}x\exp(j\phi)}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2\exp^2(j\phi)} E_{i1} \\ + \frac{M\sqrt{1-k_2} - M\sqrt{1-k_1}x^2\exp^2(j\phi)}{1 - \sqrt{1-k_1}\sqrt{1-k_2}x^2\exp^2(j\phi)} E_{i2}.$$

where $M = (1-\delta)^{1/2}$, $x = M\exp\left(-\frac{YL}{4}\right)$, $\phi = \frac{k_n L}{2}$, k_1 and k_2 are the input-output coupling coefficient (CC) of the ring, wave propagation constant is k_n , where $k_n = \frac{2\pi}{\lambda} \cdot n_{eff}$, the resonant wavelength is λ , intensity attenuation and loss-coefficient are Y and δ respectively, the length of the ring is L , E_{i1} and E_{i2} are the input and add port electric fields respectively.

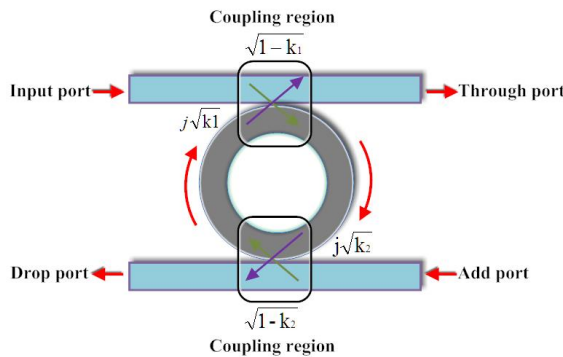


Figure 1. Two-waveguide coupled ring resonator

The control pump beam changes the phase shift of the optical signal and refractive index of the waveguide material. This phase shift and change of refractive index can be calculated using the following equations¹⁹. The pulsed laser can be used as pump beam which affects the silicon material by TPA effect. Phase shift,

$$(2.4) \quad \varphi = \frac{2\pi}{\lambda} \Delta n L ,$$

where,

$$(2.5) \quad \Delta n = -8.8 \times 10^{-22} \frac{\beta t_p^2}{2h\nu\sqrt{\pi}\tau S^2} P_{avg}^2 + 8.5 \times 10^{-22} \left(\frac{\beta t_p^2}{2h\nu\sqrt{\pi}\tau S^2} P_{avg}^2 \right)^{0.8} .$$

L is the ring length, P_{avg} is the average power, where t_p is pulse separation, pulse width is τ , $h\nu$ is photon energy, and β is TPA coefficient. The relation of the phase shift with pump power is depicted in Fig.2. We can calculate the required pump power for a π -phase shift and it is 1.47 mW only.

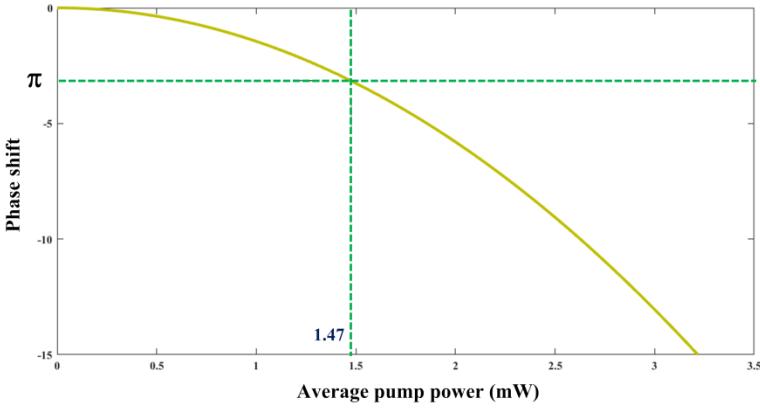


Figure 2. Change of phase shift versus pump power

3. MRR Based NG

A. Logic architecture of New Gate: The New Gate is a three by three reversible logic gate. The outputs P, Q, R for corresponding inputs A, B and C of NG satisfies the following relations¹⁵:

(3.1)
$$\begin{cases} P = A \\ Q = AB \oplus C \\ R = \bar{A}.\bar{C} + \bar{B} \end{cases}$$

Using Eq. (3.1), the logic table of this design is presented in Table 1. An illustrative diagram of the NG is shown in the Fig.3.

Table 1. Logical table of the NG

Sl No.	Inputs			Outputs		
	A	B	C	P	Q	R
1	'0'	'0'	'0'	'0'	'0'	'0'
2	'0'	'0'	'1'	'0'	'1'	'1'
3	'0'	'1'	'0'	'0'	'0'	'1'
4	'0'	'1'	'1'	'0'	'1'	'0'
5	'1'	'0'	'0'	'1'	'0'	'1'
6	'1'	'0'	'1'	'1'	'1'	'1'
7	'1'	'1'	'0'	'1'	'1'	'0'
8	'1'	'1'	'1'	'1'	'0'	'0'

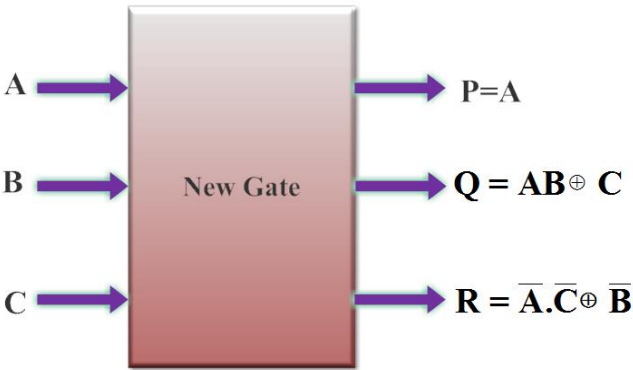


Figure 3. Schematic diagram of NG

B. Working principle of MRR based XOR Gate:The XOR gate is one of the important digital logic gates which is essential for the implementation of the proposed design. The output will be logic '0', if there is all logic '0' inputs or even number of logic '1' inputs. The output will be logic '1', if there is odd number of logic '1' inputs. The working principle of two input

all-optical silicon MRR based XOR gate is thoroughly described in the paper¹⁹ and depicted in the Fig.4. The logical table of XOR gate is shown in the Table 2.

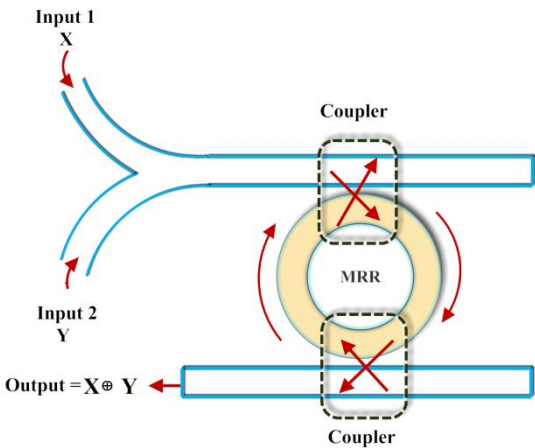


Figure 4. All-optical Ex-OR gate using MRR

Table 2. Logical Truth table of the MRR-based XOR gate

Input 1 X	Input 2 Y	Output at DP ($X \oplus Y$)
0	0	0
0	1	1
1	0	1
1	1	0

C. Working principle of proposed all-optical MRR based NG: Implementation of NG circuit using six all-optical silicon MRRs, 1-BS and 4-EDFA is depicted in the Fig.5. The working principle of all the MRRs is explained in the following section one by one.

MRR1: A continuous wave (CW) optical signal has been applied to the input port of the MRR1. Optical pump signal ‘A’ is enforced from the top of the ring. Logic ‘0’ is denoted when pump signal is off and logic ‘1’ is denoted by high intensity pump signal. According to the principle of MRR, we will get logical state of A i.e. either logic ‘0’ or logic ‘1’ at the TP and logical $\bar{A}$ at the DP of MRR1. The beam splitter BS1 has been used to extract $P=A$ and the same signal goes to the input of MRR2 through an EDFA1 that is used for sufficient power of the input signal of MRR2 as BS1 degrades the power of the signal.

MRR2: Due to the same principle, we will get logical output AB at the TP of the MRR2 which has been used as one of the input to the MRR3.

MRR3: The two inputs of MRR3 are AB which is logical output of MRR2 and C . So the DP output of MRR3 will be logical $(AB \oplus C)$ that has already been shown in section 3.B and this is the expected output Q of NG.

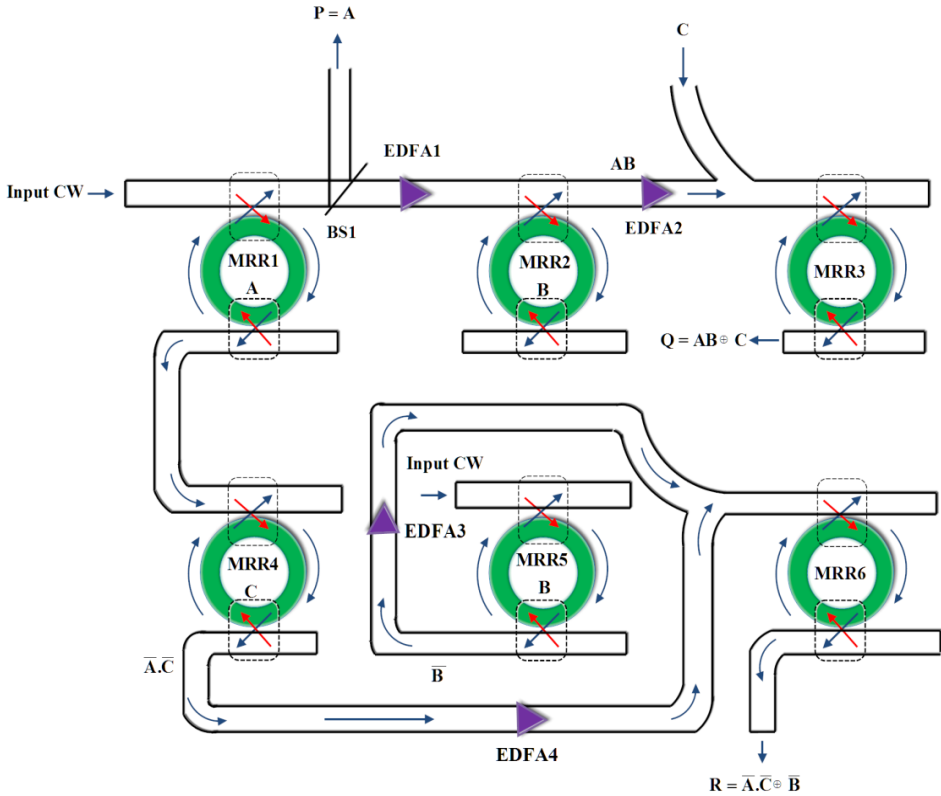


Figure 5. All-optical 3×3 reversible NG

MRR4: The DP output will be $\bar{A}.\bar{C}$ of MRR4 that is transmitted to one of the input of MRR6 through an EDFA4.

MRR5: The DP output of the MRR5 is logical $\bar{B}$ that acts as an input to the MRR6. The EDFA3 has been inserted between the DP of MRR5 and input of MRR6 to enhance the optical power to the desired level for the same reason mentioned above.

MRR6: Finally, we will get logical output $(\bar{A}.\bar{C} \oplus \bar{B})$ from the DP of the MRR6 that is the desired logical output R required for the NG.

4. Simulation Results

The proposed MRR-based New Gate was numerically simulated using MATLAB at operating speed of 260 Gb/s. The radius of the ring is considered as $7.16 \mu\text{m}$, coupling coefficients are 0.2, effective area of cross-section is $0.25 \mu\text{m}^2$ and the other optimized parameters are same²⁰. The time-domain simulation outcomes of NG are given in the Fig.6 that satisfies the Eq. (3.1) as well as the Table 1.

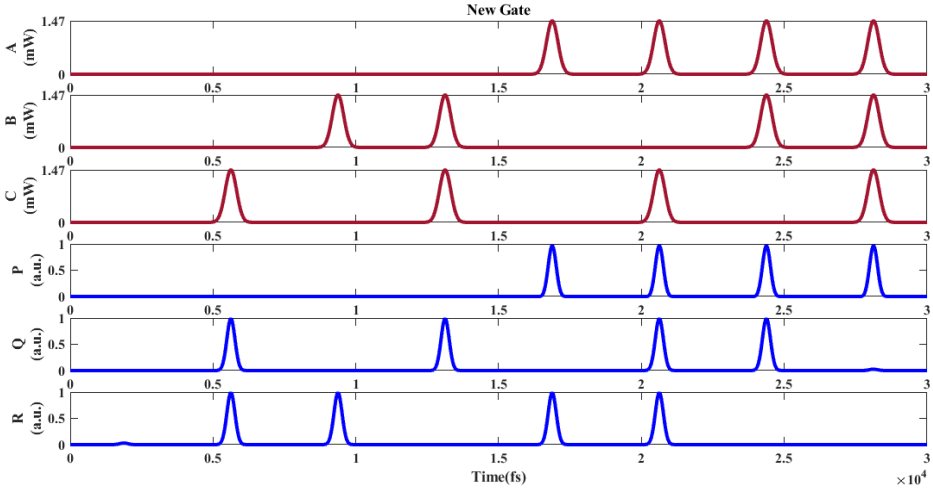


Figure 6. Simulation result of the NG

5. Discussion

The different performance parameters termed as “figure of merits” (FOM) of design indicates the performance of the proposed NG. Here, extinction ratio (ER), contrast ratio (CR), rise time (RT), fall time (FT), on-off ratio (OOR) have been studied from the simulation results. The quality of the output optical signal depends on the assessment of ER and CR for a specific design. The assessment of ER and CR should be as high as possible. The high value of ER discriminates between logic ‘1’ and logic ‘0’ level clearly; ER (dB) is shown²¹

$$(5.1) \quad ER \text{ (dB)} = 10 \log \left(\frac{P_{min}^1}{P_{max}^0} \right),$$

where, the minimum amounts of the intensity for the peak of logic ‘1’ is P_{min}^1 and the maximum amounts of the intensity for the peak of logic ‘0’ is

P_{max}^0 . Firstly, the ER is calculated against the radius of the ring, for a fixed value of the CC and which is exhibited in the Fig.7(a). Secondly, it is plotted against different CCs keeping the ring radius constant and the plot is exhibited in the Fig.7(b). It is noticed from the plot that the ER is 14.73 dB at the optimized values of the ring parameters.

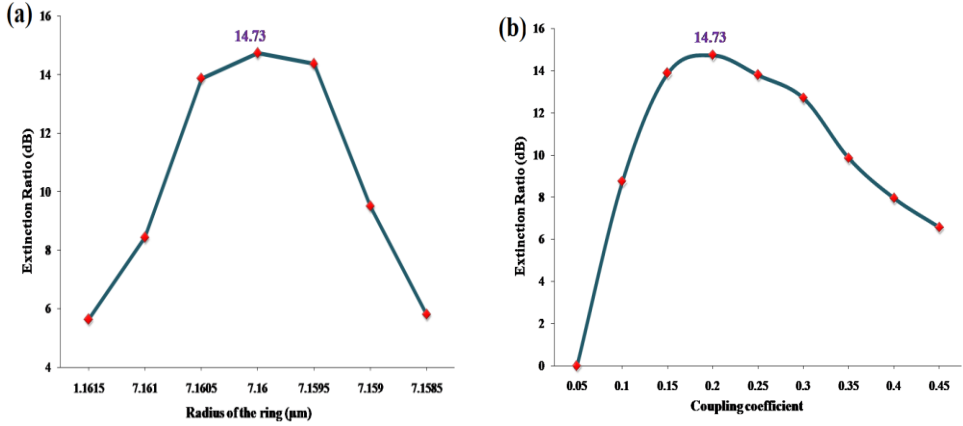


Figure 7. ER against (a) ring radius (b) CC

The CR is presented as the ratio of the average intensity for logic ‘1’ output (P_{avg}^1) to the average intensity for logic ‘0’ output (P_{avg}^0) and is expressed in dB²¹

$$(5.2) \quad CR \text{ (dB)} = 10 \log \left(\frac{P_{avg}^1}{P_{avg}^0} \right).$$

Similarly, CR is plotted and depicted in Fig.8. It is seen from the graph that the CR is 22.71 dB for the parameters used in the design.

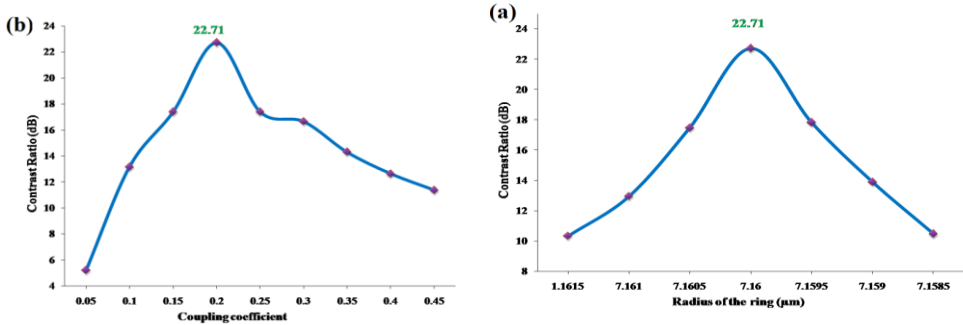


Figure 8. CR against (a) ring radius (b) CC

Beside the above parameters, we have shown the on-off ratio (OOR) and speed of the circuit in the forms of rise time (RT) and fall time (FT). The on-off ratio is also a vital parameter of the MRR based design and it can be manifested as the ratio of the intensities of ‘ON’ resonance to the ‘OFF’ resonance²² and is shown in Fig.9.

(5.3)
$$\text{on-off ratio} = \frac{T_{\text{max(dropport)}}}{T_{\text{min(throughport)}}$$

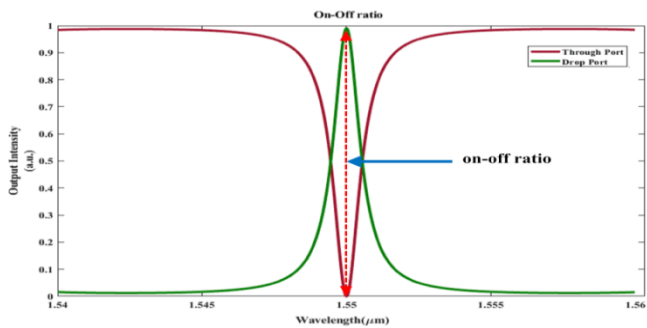


Figure 9. On-off ratio

For a high performance circuit, the value of OOR is greater than 20 dB. The achieved value of OOR is nearly 38.2 dB. The RT and FT of this design is represented in Fig.10(a) and Fig.10(b) respectively. The achieved rise time is 27 fs and fall time is 27 fs for this design.

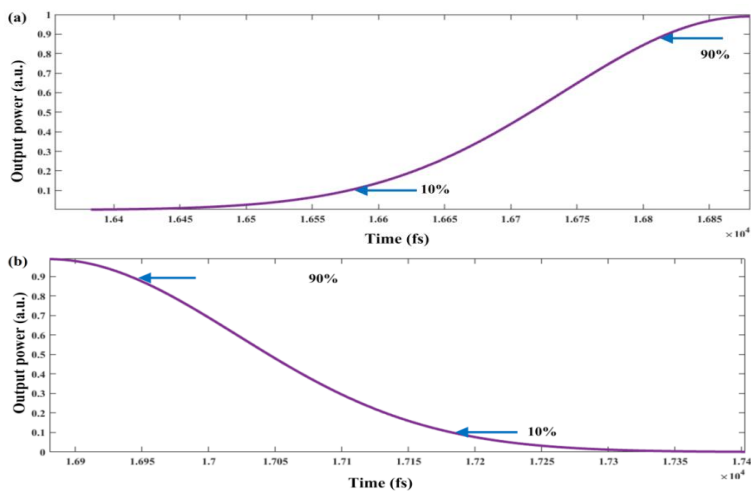


Figure 10. Switching time of the circuit (a) rise time (b) fall time

6. Conclusion

In conclusion, all-optical silicon MRR based NG is designed with less number of optical components as compared to the earlier design. The simulation results of the designed NG circuit are verified by comparing to its truth table numerically. The proposed design is capable of implementing different Boolean logic functions with two variables in radix-2 numbering system. Different performance parameters or “figure of merits” of the proposed design have been calculated against optimized MRR parameters. The high value of ER and CR is achieved for silicon MRR and the values are 14.73 dB and 22.71 dB respectively at a very low pump power of 1.47 mW and at very high data rate of 260 Gbps.

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