PES UNIVERSITY

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Course: Chip Level Photonics

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Project on:

Micro-ring resonator based all optical reversible logic gates and its applications

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Abstract: This project design of reversible logic gate Micro-ring resonator Silicon based Micro-ring resonator and analysis of the structure under critical coupling using ANSYS Lumerical 2020 R2.4 and the FDTD electromagnetic simulator. Further a short note of the reversible gates and how they are used to implement a half adder and full adder with a study on tolerance of critical coupling between waveguide and its effect on the output is included.

Introduction:

A. Principle of operation of Micro-ring Resonator-

Micro-ring resonator is the basic component of silicon photonic integrated circuits. It is an element used for silicon photonic modulators, photonic logic design for computation circuitry and photonic WDM system for chip-to-chip communications. The wavelength resonance is the basic principle of the micro-ring resonator. The resonant wavelength should be stable during any system operation. The resonance of the ring resonator is a physical phenomenon so that it must be affected by the device materials and structure dimensions(including Radius of ring, cross section of waveguide and gap between ring and bus waveguide) [2]. A basic ring resonator consists of optical waveguide which looped back on itself and a coupling mechanism to access the loop unidirectional couplers with coupling coefficients κ1 and κ2 (coupling can be described by means of two constants κ and t and a unitary scattering matrix as given in equation 1) between a ring cavity and input-output bus waveguides(fig 1). When the waves in the loop build up a round trip phase shift that equals an integer times 2, the waves interfere constructively and the cavity is in resonance.

$$\begin{vmatrix} b_1 \\ b_2 \end{vmatrix} = \begin{vmatrix} t & \kappa \\ \kappa^* & -t^* \end{vmatrix} \begin{vmatrix} a_1 \\ a_2 \end{vmatrix} \qquad (1)$$

Unitary matrix representing coupling

A constructive interference will take place when the optical path-length of a round trip is integer multiple of the effective wavelength and the OMRR will be 'ON' resonance. At 'ON' resonant, OMRR transmit the input port signal through the drop port and hence drop port shows high transmission and through port shows low transmission. Pumping induces the free carriers in the waveguide which change the refractive index of the material [1]. So when the pump pulse is applied to the ring, the resonance wavelength of OMRR will be shifted due to the change in refractive index, which shows high transmission at the through-port and low transmission at the drop-port(fig 2). The change in refractive index can be given as:

$$n_{eff} = n_0 + n_2 \qquad (2)$$

Coupling is the interaction of light with the waveguide. The performance of a ring resonator is determined by two coefficients: the self-coupling coefficient t, which specifies the fraction of the amplitude transmitted on each pass of light through the coupler; and the loss coefficient α, which specifies the fraction of the amplitude transmitted per pass around the ring. In optimizing the design of a ring resonator, it is important to extract and distinguish these coefficients, as they are governed by different factors in design and fabrication.

In this report we will be using MRR's as non-linear switches and utilizes Two Photon Absorption. Mainly there are 3 types of coupling observed in an MRR namely

1. Under coupling-caused due to large gap or weak coupling coefficient where not enough light is transferred into the resonator(dip at transmission in through port)
2. Critical coupling-resonator perfectly traps light at resonance wavelength(complete dip at through port).
3. Over coupling-too much light trapped in the resonator due to small gap (partial dip in resonator).

To achieve critical coupling we will be changing the gap of the MRR wrt to the ring and bus waveguides to achieve maximum transmission of light through the logic circuit.

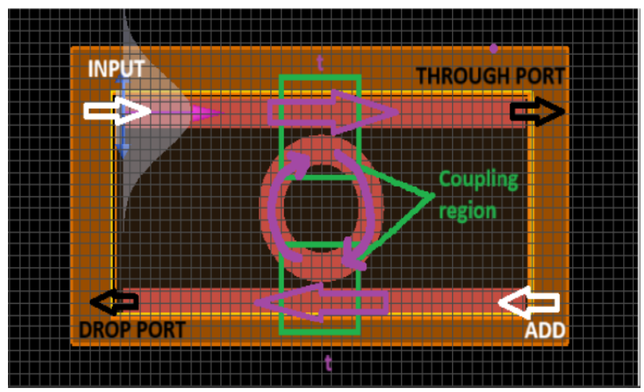


Fig 1. Representation of micro-ring oscillator with ports and coupling region

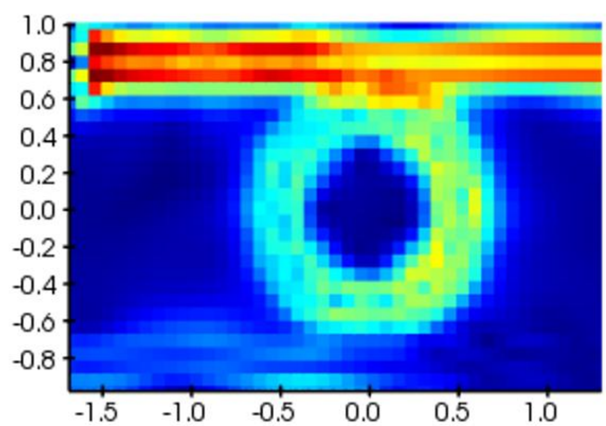


Fig 2. Simulation of MRR with TPA and high transmission at through port and low transmission at drop port

B. Reversible Logic Gates

A Reversible Logic gate can generate a unique output vector from multiple input vectors, that is it has a one-to-one mapping between inputs and outputs. It has various applications in nanotechnologies such as quantum computing, quantum dot cellular automata, optical computing, etc[1]. The main objective of design and synthesis of reversible logic is to reduce garbage values (refer to the unutilized outputs that are not used as primary outputs and which cannot be used as inputs for new computation) and quantum cost (The quantum cost of a reversible gate is the number of 2×2 Reversible gates or quantum logic gates required in designing the circuit).

There are significant differences in in synthesis techniques of reversible techniques:

1. Each output can be used only once.
2. Feedback is not permitted.
3. Use minimum no of garbage outputs
4. Use minimum circuit level
5. Une minimum no of gates

A set of reversible gates are required to synthesize reversible logic. Majorly Peres gate, Tofolli Gate, Fredkin Gate and T-R Gate.

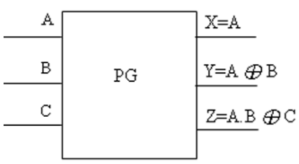
PERES GATE:

It is a 3 input(A,B and C), 3 output(X,Y and Z) with the relation:

X = A

Y = A $\oplus$ B

Z = A.B $\oplus$C



Inputs			outputs		
A	B	C	X	Y	Z
0	0	0	0	0	0
0	0	1	0	0	1
0	1	0	0	1	0
0	1	1	0	1	1
1	0	0	1	1	0
1	0	1	1	1	1
1	1	0	1	0	1
1	1	1	1	0	0

Fig 3.Block diargam and Truth table of Peres gate

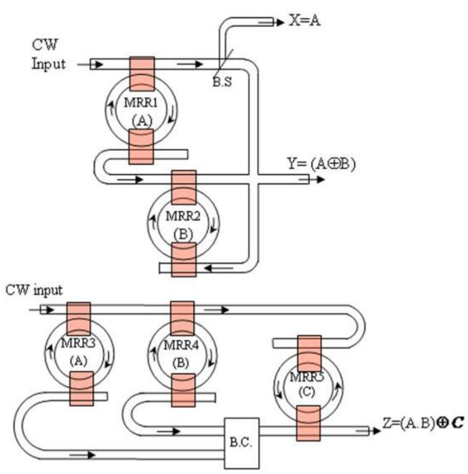


Fig 4. Schematic structure of all optical Peres gate

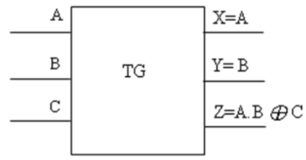
TOFOLLI GATE

It is a 3 input(A,B and C), 3 output(X,Y and Z) with the relation:

X = A

Y = B

Z = A.B $\oplus$C



Inputs			outputs		
A	B	C	X	Y	Z
0	0	0	0	0	0
0	0	1	0	0	1
0	1	0	0	1	0
0	1	1	0	1	1
1	0	0	1	0	0
1	0	1	1	0	1
1	1	0	1	1	1
1	1	1	1	1	0

Fig 5. Block diagram and truth table of Tofolli gate

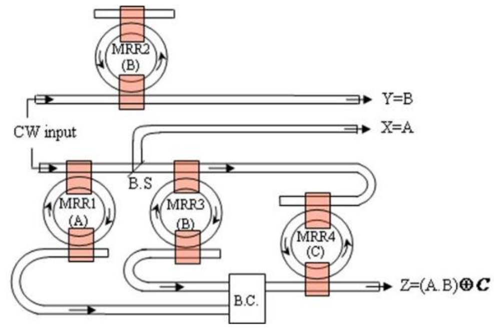


Fig 6. Schematic of all optical Tofolli gate

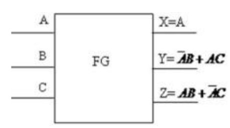
FREDKIN GATE

It is a 3 input(A,B and C), 3 output(X,Y and Z) with the relation:

X = A

Y = AB + AC

Z = AB + A’C



Inputs			outputs		
A	B	C	X	Y	Z
0	0	0	0	0	0
0	0	1	0	0	1
0	1	0	0	1	0
0	1	1	0	1	1
1	0	0	1	0	0
1	0	1	1	1	0
1	1	0	1	0	1
1	1	1	1	1	1

Fig 7. Block diagram and truth table of Fredkin gate

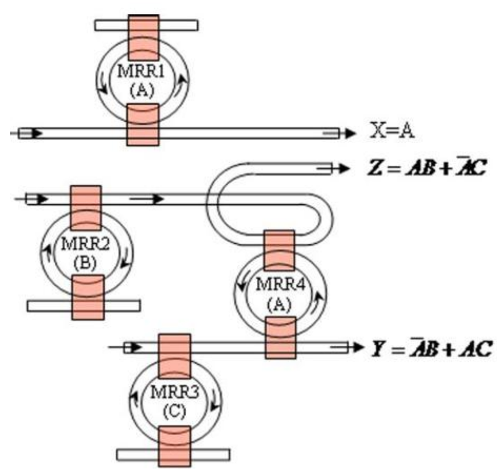


Fig 8. Schematic of all optical Fredkin gate

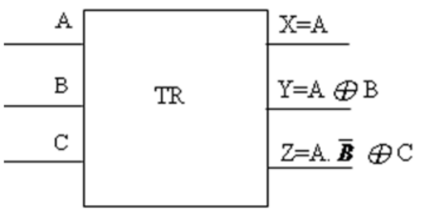
TR GATE

It is a 3 input(A,B and C), 3 output(X,Y and Z) with the relation:

X = A

Y = A ⊕ B

Z = A.B' ⊕C



INPUTS			OUTPUTS		
A	B	C	X	Y	Z
0	0	0	0	0	0
0	0	1	0	0	1
0	1	0	0	1	0
0	1	1	0	1	1
1	0	0	1	1	1
1	0	1	1	1	0
1	1	0	1	0	0
1	1	1	1	0	1

Fig 9. Block diagram and truth table of T-R gate

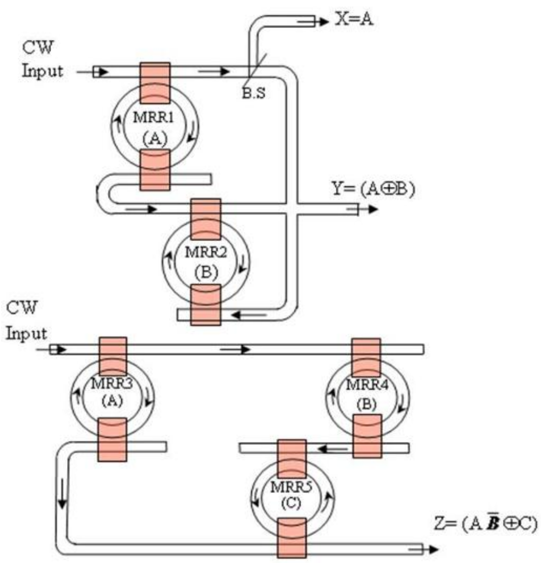


Fig10. Schematic of all optical T-R gate

Design and Simulation:

The reversible gates are used to design and implement a half adder and full adder with critical coupling and observe and verify the output of the half/full adder.

It can be broken down into 3 steps:

A. *Simulation of optical waveguide under critical coupling-*

i)Structure as shown in fig is made using straight and bent waveguides.

ii)The following design parameters are used:

Parameter	Value
Beam pump wavelength (β)	7.9 x 10^{-10}
Pulse width(t)	100fs
Radius of ringI	3050 nm
Cross section of waveguide(S)	450 x 250 nm^2
Non-linear refractive index of d=medium(n_2)	As that of Si
Coupling coefficient(κ)	0.22
gap	400nm

iii)Gaussian source with wavelength (λ) of 1551nm is used as incident light source and DFT power monitor is used to visualize the result.

iv)The gap is adjusted to find the critical coupling. The substructure is made and renamed to micro-ring resonator.

B. Simulation of Reversible gates-

i)The MRR's are used in combination with straight and bent waveguides to design the Peres, Tofolli, Fredrick and TR gate as shown in fig

ii)SiO_2(glass) is used as substrate.

iii)Gaussian source of 1551nm is used and visualized via DFT power monitor.

C. Simulation of Half/Full Adder

i)Corresponding reversible gates are used to design the half adder as shown in fig 11a and full adder as shown in fig 11b.

ii) Gaussian source of 1551nm is used and visualized via DFT power monitor.

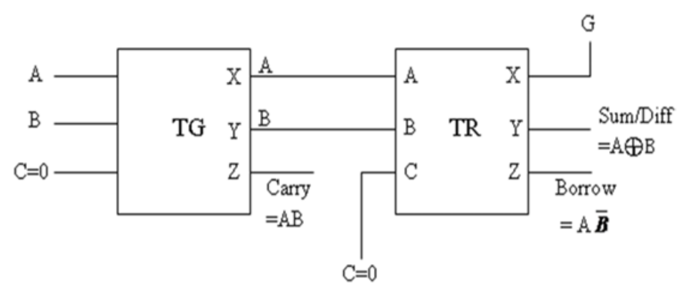


Fig 11a. Reversible Half adder

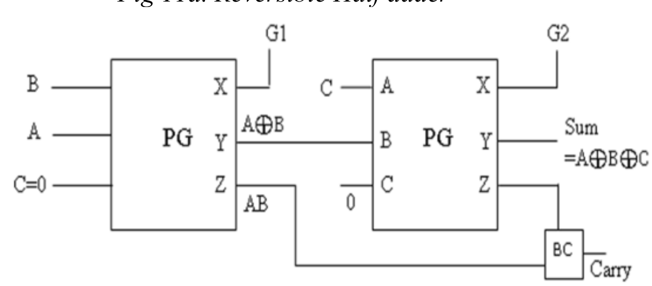


Fig 11b. Reversible Full adder

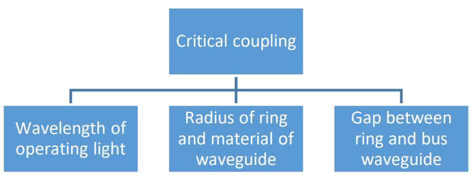
Result and Analysis:

A. Critical coupling and its effect on MRR

Normalised transmission in a MRR can be switched from unity to zero by critical coupling, which can be expressed as

$$\alpha=|\tau| \qquad (3)$$

Tuning of couplers involves playing with the gaps between ring and bus waveguide in reference to [3] we have selected a gap of which has given the best simuation result for transmission of waveguide for 1551 nm wavelength. A comparison can be established as to as gap reduces coupling increases while as gap increases coupling reduces (provided there is optimized radius to reduce bending losses). The intensity of propagated beam at critical coupling (fig 13a.) observed from fig 13b. is seen to couple and propagate much better as compared to that of Fig 12b. which shows over coupling (fig 12a.) which resulted in loss and leakage of beam.



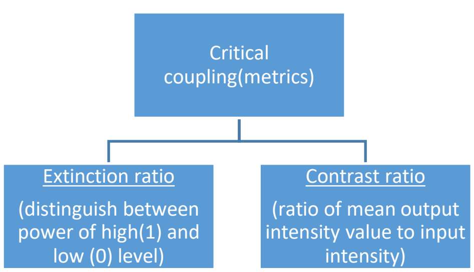
The effect of critical coupling on reversible logic can summarized from the simulation as:

a)Maximum energy transfer in logic gate design

b)Low error rate

c)Low power losses

In ref to [1] and [2], there are 2 other metrics which can relate to critical coupling conditions. They are:



$$\text{ER (dB)} = 10\log\left(\frac{P^{1}_{\min}}{P^{0}_{\max}}\right) \qquad \text{CR (dB)} = 10\log\left(\frac{P^{1}_{mean}}{P^{0}_{mean}}\right)$$

So higher ER and CR values which can be measured at input and output ports of reversible gates can also support to critical coupling as shown in fig 16.

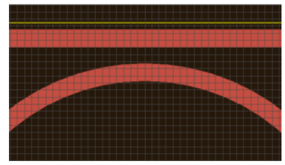


Fig 12a.

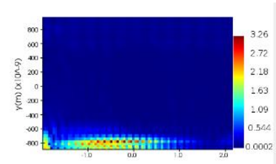


Fig 12b.

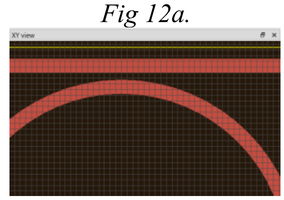


Fig 13a.

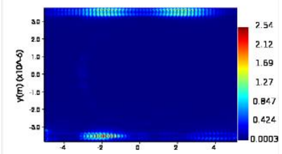


Fig 13b.

B. Reversible half and full adder using reversible logic gates

The half adder is built in reference to fig 11a. as shown in fig 14a.

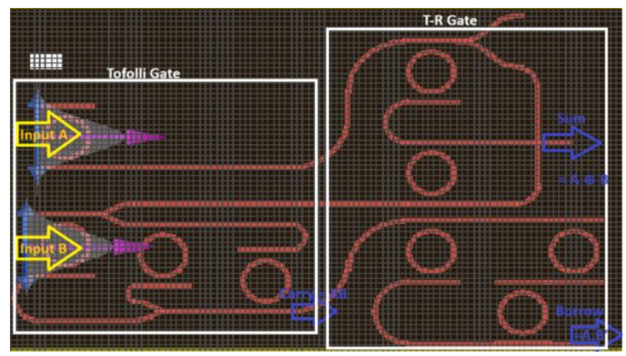


Fig 14 a. Schematic and input/output ports of reversible half adder

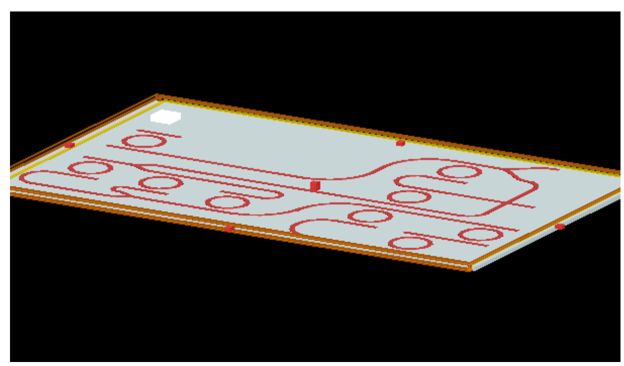


Fig 14 b. Perspective view of reversible half adder

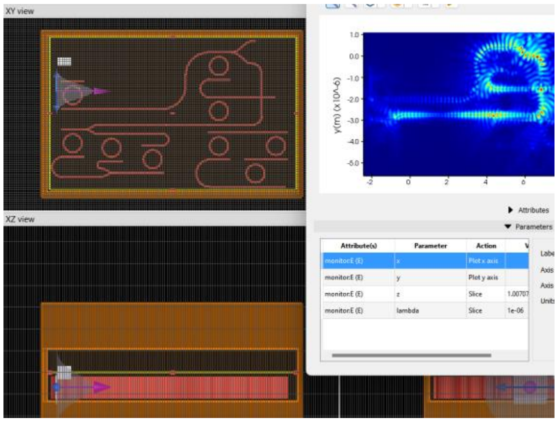


Fig 14 c. implementation and result of simulation of reversible half adder

Fig 14a. shows the inputs and output ports for the reversible half adder while fig 14b. gives the perspective view of the half adder. The simulation result was implemented for A=1, B=0, C=0 and the corresponding output was verified from fig 14c. showing Sum=1, carry=0 and borrow=0. Coupling was weak due to large gap as the following simulation was done wrt under coupling.

The full adder with critical coupling(by changing gap and wavelength is given in fig 15a.

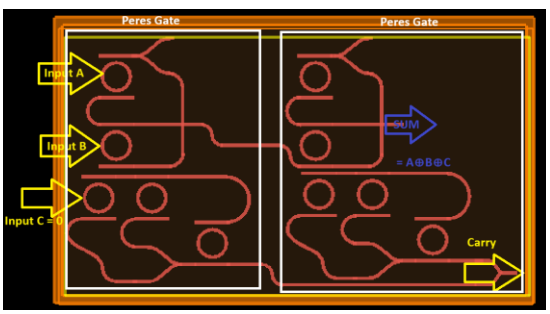


Fig 15 a. Schematic and input/output ports of reversible full adder

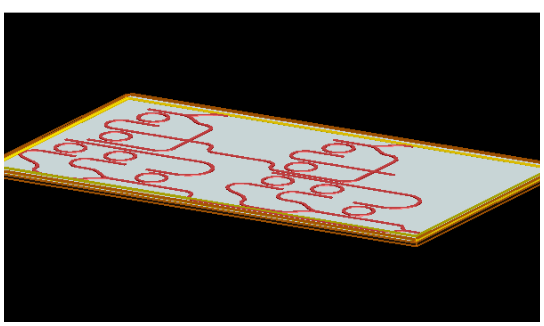


Fig 15 b. Perspective view of reversible full adder

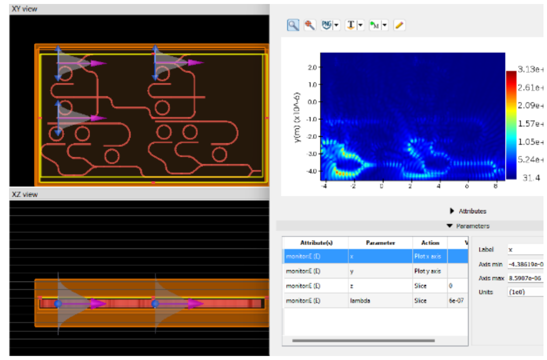
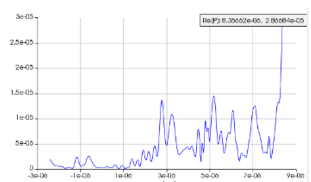


Fig 15 c. implementation and result of simulation of reversible full adder

Fig 15a. shows the inputs and output ports for the reversible full adder while fig 15b. gives the perspective view of the half adder. The simulation result was implemented for A=1, B=1, C=0 and the corresponding output was verified from fig 15c.showing Sum=0 and carry=1. Coupling was optimum due to perfect gap as the following simulation was done wrt critical coupling (better sim result in appendix.

A comparison of Output power graph is given in fig 16. It can be seen that under/ over coupling from half adder has large losses and distorted curve (fig a) while that compared to the one shown in the critical coupling graph from the full adder (fig b). The transmission of beam is affected as there is lesser resonance and more leakage in undercoupled ring resonator as compared to the critically coupled waveguides.



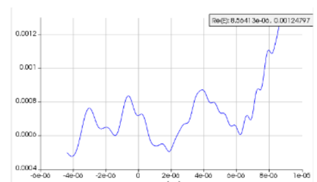


Fig 16 a. Fig 16 b.

(There is a distorted graph for undercoupling fig 16a. due to larger gap the MRR of half adder, the peak power observed at the output is lesser as well compared to that in fig 16b. The graph for critical coupling is more smooth, defined and more output power is observed at output ports)

Additionally the schematics for the Peres gate, Tofolli gate, Fredkin gate and the T-R gate are given in figure 17a, 17b, 17c and 17d respectively.

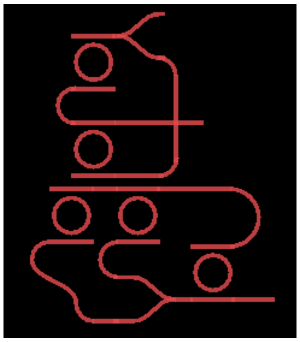


Fig 17 a.

Fig 17 b.

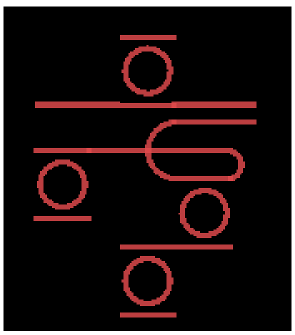


Fig 17 c.

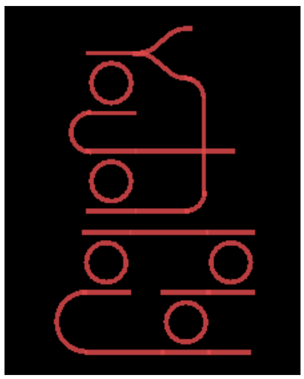


Fig 17 d.

Conclusion:

This project successfully demonstrated the design and analysis micro-ring resonator (MRR) structures for implementing reversible logic gates. Critical coupling was achieved through precise adjustments of the gap between the ring and bus waveguides.

Simulation results of half and full adder highlight the significance of critical coupling in improving the output power and reducing error rates, compared to undercoupling and overcoupling scenarios. The reversible gates, including Peres, Toffoli, Fredkin, and T-R gates, showcased efficient logic operations with minimized garbage outputs and quantum costs, essential for advanced nanophotonic applications like quantum computing and optical data processing.

References

[1] G. K. Bharti and J. K. Rakshit, "Micro-ring resonator based all optical reversible logic gates and its applications," *Optoelectronics and Advanced Materials - Rapid Communications*, vol. 13, no. 3-4, pp. 169-175, Feb. 2019.

[2] W. R. McKinnon, D.-X. Xu, C. Storey, E. Post, A. Densmore, A. Delâge, P. Waldron, J. H. Schmid, and S. Janz, "Extracting coupling and loss coefficients from a ring resonator," *Institute for Microstructural Sciences, National Research Council of Canada*, 1200 Montreal Road, Ottawa, Ontario, Canada, K1A 0R6.

[3] T.-T. Le and D.-T. Le, "High FSR and Critical Coupling Control of Microring Resonator Based on Graphene-Silicon Multimode Waveguides," *IntechOpen*, Jun. 2020.

Other references-

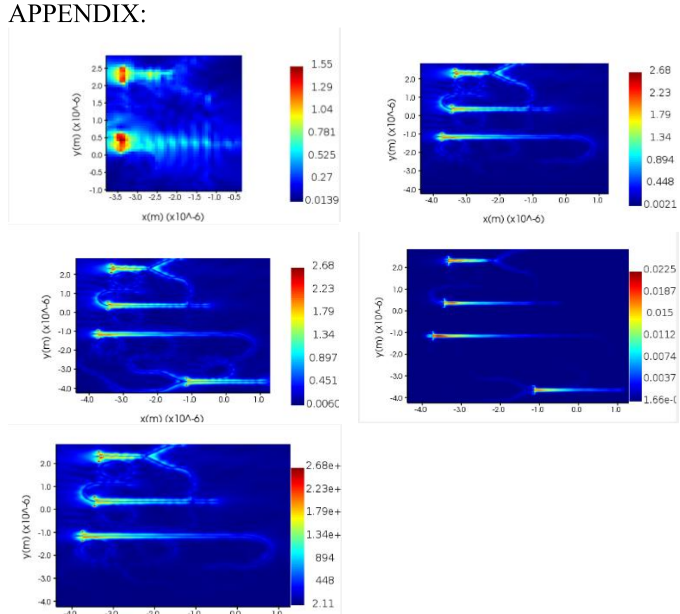
[4] course material- PES1UG22EC342AB4

[5]https://optics.ansys.com/hc/en-us/articles/11277217507603-Troubleshooting-diverging-simulations-in-FDTD

[6] https://www.youtube.com/watch?v=uPkr7MCApxY

[7]https://www.youtube.com/watch?v=w9P0swi0M2s&list=PL2JDS7U1Ih9yFbCWfS8luJyxtXk0BJ1xI&index=8

APPENDIX:



Full adder gate simulations to find critical coupling.