PES UNIVERSITY

Karnataka, Bengaluru – 560080

Department of Electronics and Communications

Course Name: Chip Level Photonics

Course Code: UE22EC342AB4

ESA REPORT

Project Title:

"Design and Modeling of Polarization-Conversion Based all-Optical NOT Logic Gate using a Single Silicon Ring Resonator"

Project by:

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Abstract:

The demonstration of all-optical basic logic gates using single silicon micro-ring resonator is presented in the paper. Based on the nature of the pump signal rather than its intensity, the polarization-conversion in ring resonator occurs with the response time of 0.2 ps. To validate the proposed model, the finite-difference time domain (FDTD) simulation results are included in this report. The Q-factor and operational speed are also calculated to justify its utility. The ring parameters are optimized through numerical simulation to obtain the conversion of polarization in the ring resonator. The nature of the pump and source signal is responsible to obtain polarization conversion based all-optical switch and all-optical logic gates in the ring resonator. The design in this paper is simple and stable.

Introduction:

In today's high-speed communication systems, optical technologies have become essential for faster and more efficient data transmission. All-optical logic gates, which eliminate the need for optical-to-electrical conversion, play a critical role in reducing delays, minimizing power consumption, and enhancing processing speeds.

Silicon-based micro-ring resonators (MRRs) are at the forefront of these technologies due to their compact size, high efficiency, and compatibility with silicon-on-insulator (SOI) platforms. A novel method for implementing optical logic gates involves **polarization conversion**, where logical operations are performed by manipulating the polarization states of light (quasi-TE and quasi-TM modes). Unlike traditional intensity-based methods, polarization conversion relies on the nature of the pump signal, ensuring improved reliability and stability.

This work focuses on the design of a **polarization-conversion-based NOT gate** using a single silicon ring resonator. Optimized using finite-difference time-domain (FDTD) simulations, the proposed design achieves ultra-fast response times, high Q-factors, and seamless integration into modern photonic circuits.

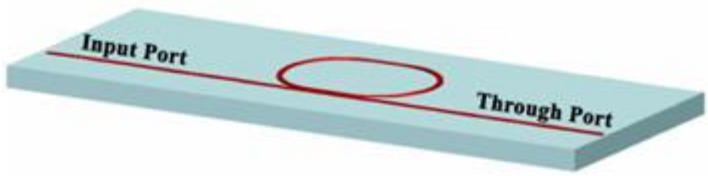


Fig 1: Diagram of ring resonator

Implementation:

The Ansys Lumerical's tools enable the design of photonic components, circuits, and systems. FDTD is a simulator within Lumerical's DEVICE Multiphysics Simulation Suite, the world's first Multiphysics suite purpose-built for photonics designer.

The polarization conversion-based ring resonator works by selectively converting light polarization states to implement a **NOT gate**. TE (Transverse Electric) polarization corresponds to **Logic 1**, and TM (Transverse Magnetic) polarization represents **Logic 0**. At resonance, the optical signal undergoes **polarization conversion** due to nonlinear effects in the material, transforming TE-polarized light (Logic 1) into TM-polarized light (Logic 0). If the input signal is already TM-polarized (Logic 0), it remains unchanged. This selective behavior enables logical inversion, making the design compact, ultra-fast, and reliable for all-optical logical operations.

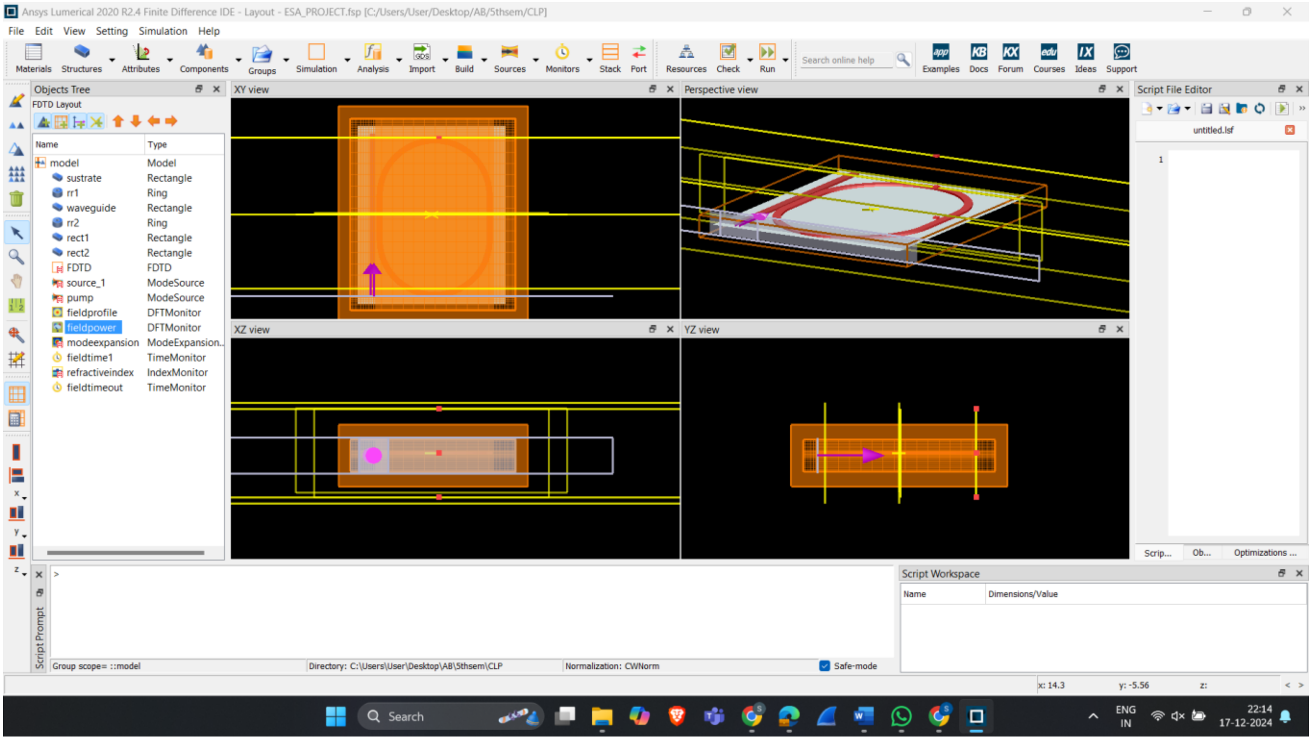


Fig 2: Representative Image of Lumerical FDTD

Steps:

- Design the race-track ring resonator with optimized geometry parameters.
- Define material properties for silicon waveguide and silicon dioxide substrate.
- Set input source as quasi-TE polarized light and configure pump signals.
- Place field and time monitors at input and output ports.
- Run FDTD simulation to analyse light propagation through the resonator.
- Observe polarization conversion from quasi-TE to quasi-TM or vice versa at output.
- Extract transmission spectrum and identify resonant and non-resonant wavelengths.
- Validate the output results with the NOT gate truth table for functionality

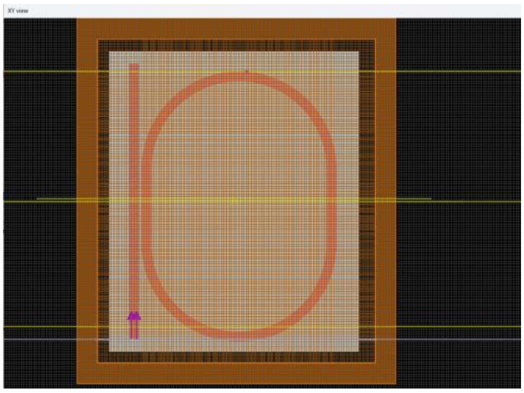


Fig 3: XY-view of designed Building block for NOT gate logic

Design Parameters:

S. No.	Parameters	Description
1	RR waveguide	Silicon (Si)
2	Material used for SOI platform	Silicon Dioxide (SiO_2, Glass)
3	Effective cross-sectional area	450 × 415 nm^2
4	Refractive index of Si	3.455
5	Bending radius of ring	5 µm
6	Height and width of waveguide	0.22 µm (height), 0.4 µm (width)
7	Gap between ring and waveguide	0.1 µm
8	Refractive index of SiO_2	1.445
9	Coupling length (Lc)	3 µm
10	Coupling coefficients (r, t)	r = 0.837, t = 0.547
11	TPA coefficient (β_2)	7.9×10^{-10} cm/W
12	Pulse width (τ) of pump pulse	100 fs

Table 1: Dimensions of structures used in design

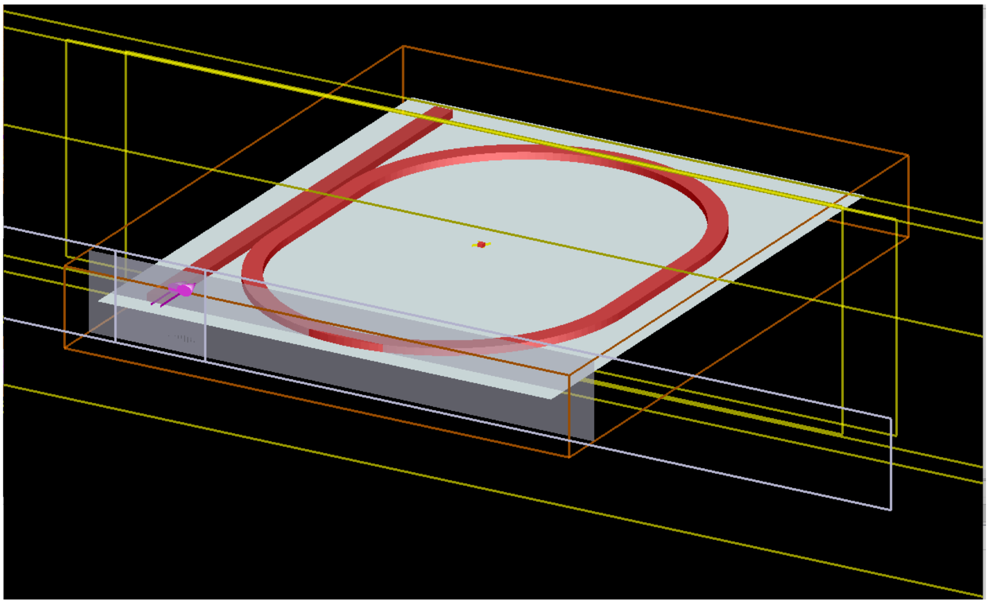


Fig 4: Perspective View of designed Building blocks for ring resonator.

Results:

1. DFT Monitor showing NOT gate logic

CASE 1: "Logic 1" obtained at output when input is "logic 0".

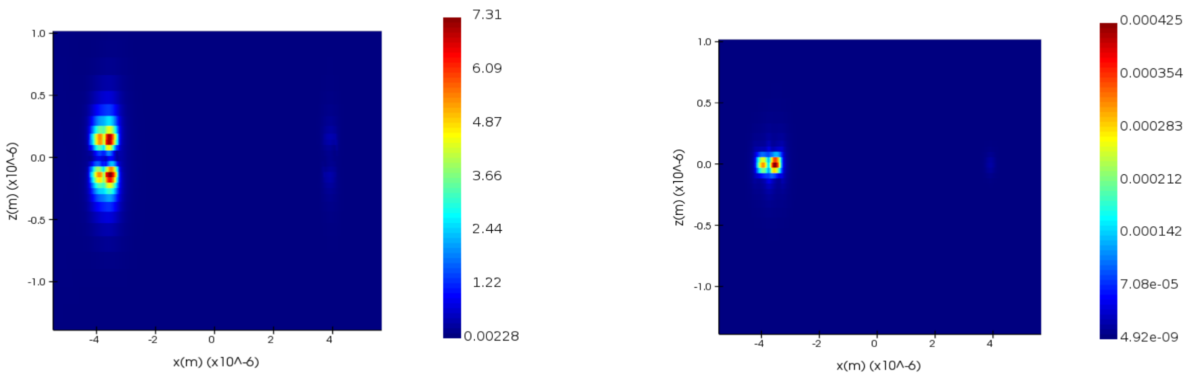


Fig 5: **(a)** E-Field of quasi-TE polarized light **(b)** H-Field of quasi-TM polarized light

CASE 2: “Logic 0” obtained at output when input is “logic 1”.

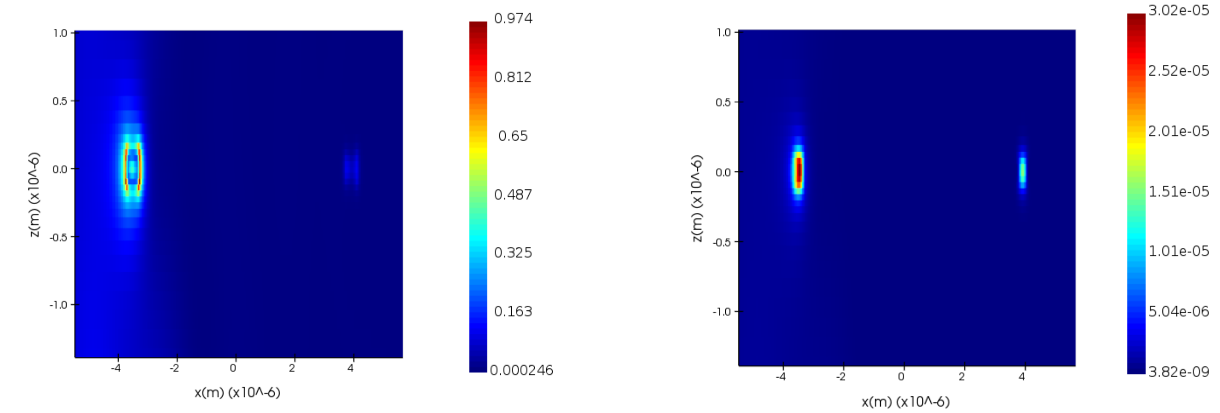


Fig 6: **(a)** E-Field of quasi-TM polarized light **(b)** H-Field of quasi-TE polarized light

2. Signal Spectrum obtained from TimeMonitor

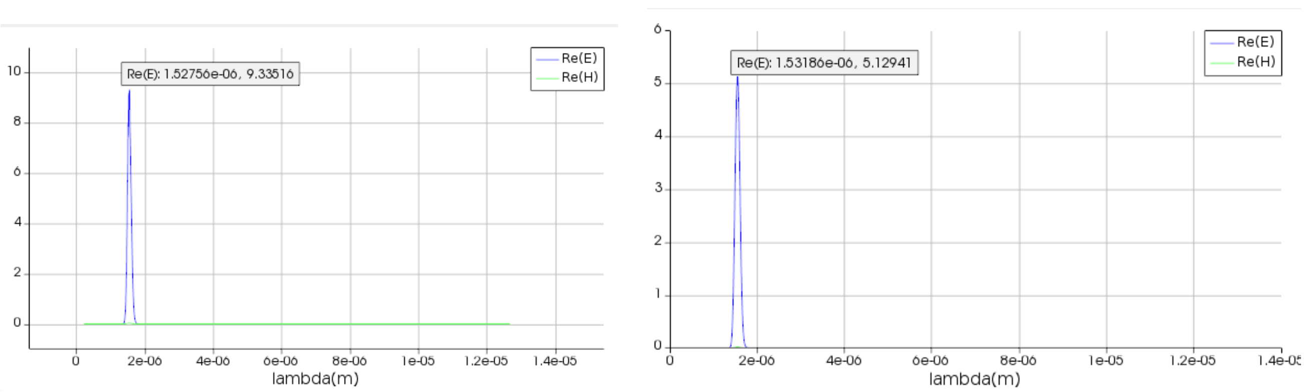
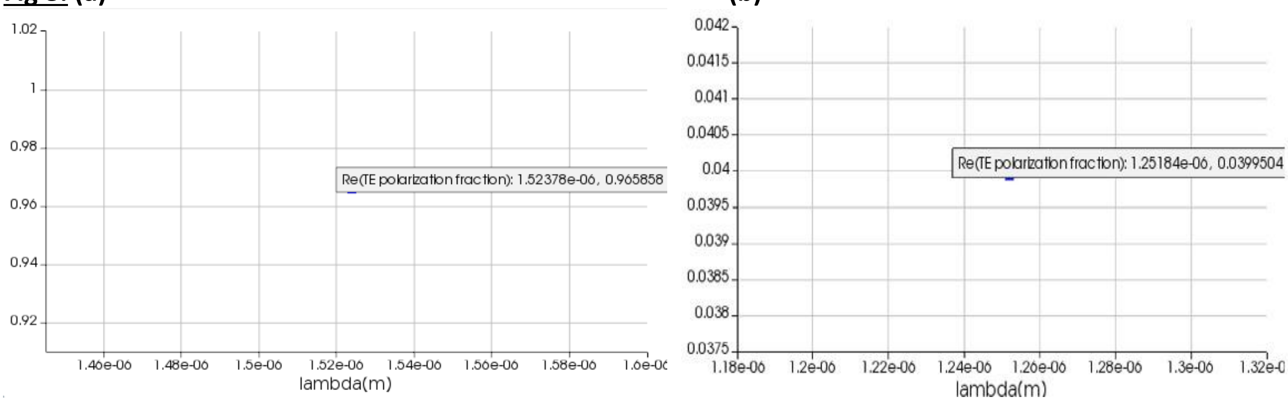


Fig 7: (a) spectrum when output is logic1 (amplitude is 9.3 corresponds to logic1) (b) signal spectrum when output is logic 0 (amplitude is 5.1 corresponds to logic0)

3. Polarization fraction obtained from Mode expansion Monitor

Fig 8: (a) **(b)**



(a) The TE polarization fraction observed for this case was 0.965858 (96.58%), this suggest that the output is quasi-TE (1).

(b) The TE polarization fraction observed for this case was 0.0399504(3.99%), this suggest that the output is quasi-TM (0).

Analysis with Theoretical and Mathematical Background:

1.Polarization Conversion Mechanism in the Single-Ring Resonator-Based NOT Gate :

Polarization conversion plays a crucial role in the operation of the NOT gate in a single-ring resonator. When the **input signal, initially in the quasi-TE polarization** (representing Logic 1), interacts with a **quasi-TE pump signal**, the resonator **induces polarization conversion**, switching the **output to quasi-TM polarization (Logic 0).** On the other hand, when the **pump signal is in the quasi-TM state**, it does **not trigger polarization conversion** due to the **polarization mismatch** with the input. As a result, the **output remains in the quasi-TE state**, corresponding to Logic 1. This polarization conversion mechanism ensures reliable logical inversion and supports efficient all-optical logic processing in the system.

2.Coupled-Mode Theory (CMT): The dynamics of light in a micro-ring resonator are modeled using coupled-mode theory (CMT). This framework describes the transfer of optical power between the input waveguide and the ring resonator. The evolution of optical fields is represented through mathematical equations, capturing the coupling process effectively.

$$\frac{da(z)}{dz} = -i\beta_1 a(z) - iK_1 b(z)$$

$$\frac{db(z)}{dz} = -i\beta_2 a(z) - iK_2 b(z)$$

Where

- a(z) and b(z) are the field amplitudes
- β1 and β2 are propagation constants of TE and TM modes
- K is the coupling coefficient

Nature of input source (Fixed state)	Nature of pump P1 (Varying state)	Output state (field intensity)
(quasi-TE)	1 (quasi-TE)	0 (quasi-TM)
(quasi-TE)	0 (quasi-TM)	1 (quasi-TE)

Table 2: Logical operation of the all-optical NOT gate

Conclusion: The proposed design successfully demonstrates the realization of an all-optical NOT gate using a single silicon ring resonator. The polarization-dependent mode conversion achieves logical inversion with high speed and efficiency. The design's simplicity, compactness, and compatibility with silicon-on-insulator platforms make it highly viable for integration into photonic integrated circuits. This work validates the potential of polarization conversion for all-optical logic operations and opens Opportunities for further development of optical computing systems.

References:

[1] G. K. Bharti, M. P. Singh, and J. K. Rakshit, "Design and Modeming of Polarization-Conversion Based All-Optical Basic Logic Gates in a Single Silicon Ring Resonator," *Silicon*, vol. 12, no. 6, pp. 1279–1288, Sep. 2019, Doi: 10.1007/s12633-019-00204-7.

[2] A. Kumar, S. Kumar, and S. K. Raghuvanshi, "Implementation of XOR/XNOR and AND logic gates by using Mach-Zehnder interferometers," *Optik - International Journal for Light and Electron Optics*, vol. 125, no. 19, pp. 5764–5767, Oct. 2014.

[3] J. K. Rakshit and J. N. Roy, "Micro ring resonator-based all-optical reconfigurable logic operations," *Optics Communications*, vol. 321, pp. 38–46, May 2014.

[4] P. Bianucci, C. R. Fietz, J. W. Robertson, G. Shvets, and C. K. Shih, "Polarization conversion in a silica microsphere," *Optics Express*, vol. 15, no. 11, pp. 7000–7005, May 2007.

APPENDIX:

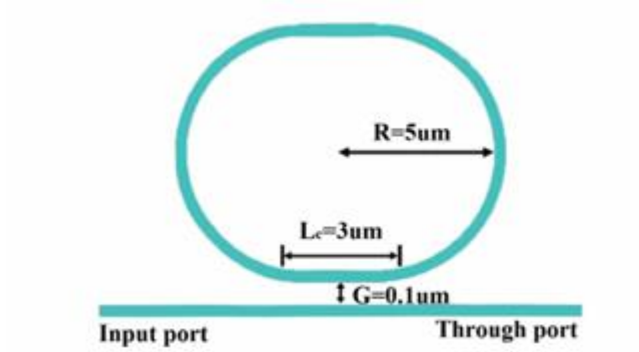


Fig 9 : Proposed design of ring resonator

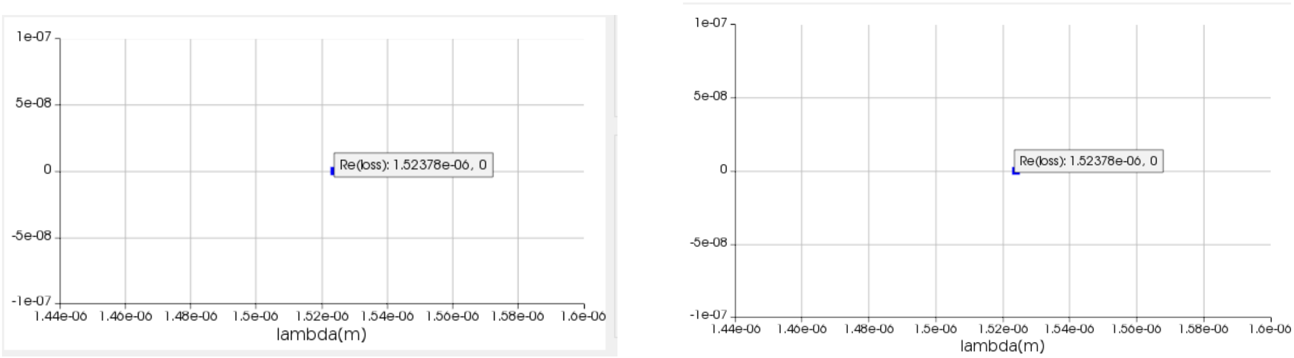


Fig 10: (a)loss fraction graph for TE polarized light **(b)** loss fraction graph for TM polarized light

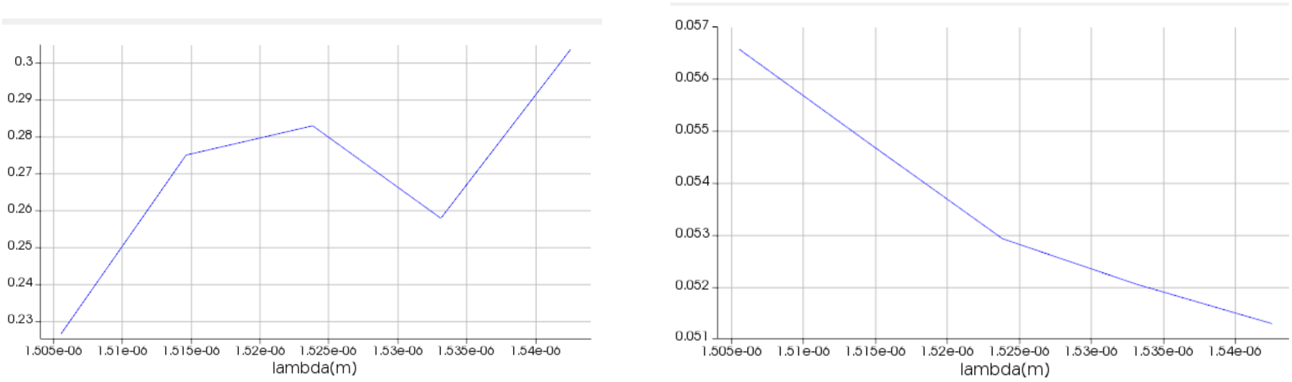


Fig 11:(a) Transmission graph for TE polarized light **(b)** Transmission graph for TM polarized light

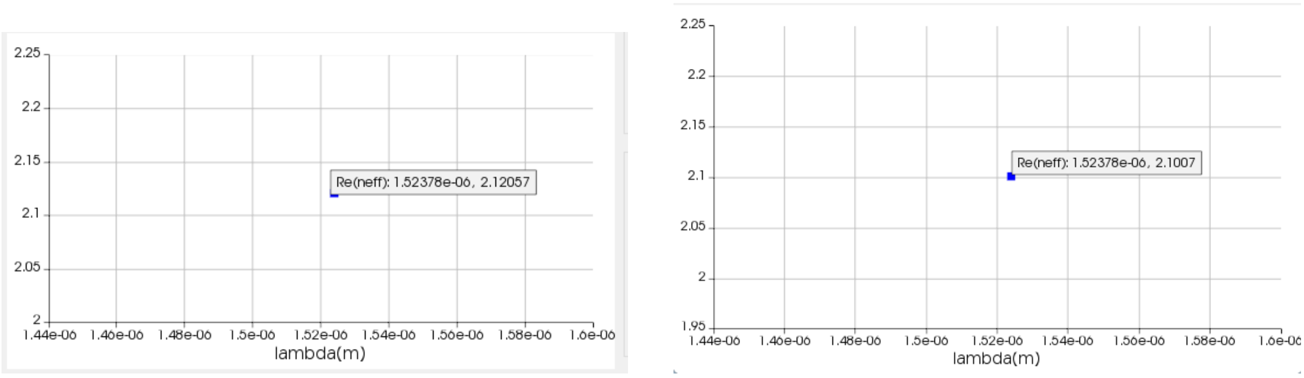


Fig 12:(a) effective refractive index graph for TE polarized light

(b) effective refractive index graph for TM polarized light

Mathematical analysis :

1.TE-TE (Hee) and TM-TM (Hmm) Transfer Functions:

This equation describes the transfer function for modes that do **not undergo polarization conversion**. It applies to signals that retain their original polarization, such as TE → TE or TM → TM

$$H_{ee/mm} = \frac{rz^{-2} - (1-r^2)z^{-1}\cos\phi - iRt^2z^{-1}\sin\phi + r}{1 + r^2z^{-2} - 2rz^{-1}\cos\phi}$$

Parameters:

- r: Coupling coefficient (reflection term).
- z: Propagation constant $z=e^{-i\beta LR}$ is the average propagation constant, and L_R is the resonator length.
- ϕ: Phase shift in the ring resonator.
- R: Coefficient related to the phase mismatch or birefringence in the ring resonator.
- t: Coupling coefficient (transmission term).

This function determines how much of the light in the original polarization state (TE or TM) exits in the resonator without converting to another polarization state.

2. TM-TE (Hem) and TE-TM (Hme) Transfer Functions:

This equation models the polarization conversion process inside the resonator, describing how a TE input mode converts to a TM output mode (TE → TM), or vice versa (TM → TE).

$$H_{em/me} = \frac{iSt^2z^{-1}\sin\phi}{1 + r^2z^{-2} - 2rz^{-1}\cos\phi}$$

S: Parameter related to the strength of the polarization conversion (nonlinear effects in the resonator).

The numerator includes the term Ssinϕ, showing that polarization conversion depends on the phase conditions in the ring resonator. The denominator $1+r^2 z^{-2}-2rz^{-1}\cos\phi$ ensures that the resonator's resonance effects are considered.