Design and Implementation of All-Optical XOR and XNOR Logic Gates using Photonic Crystals by combining T and Y-shaped Waveguides

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Abstract: In this paper, all-optical XOR (exclusive OR) and XNOR (exclusive NOR) logic gates are implemented using two-dimensional photonic crystal waveguides. It uses a square lattice structure with silicon dielectric rods in an air background, as well as both Y and T-shaped waveguide structures. In this, the light beam operates at a 1550nm wavelength. The proposed design is based on the principle of the beam interference phenomenon. The contrast ratio of the XOR gate and XNOR gate is 8.27dB and 13.71dB. Both designs are operated at the refractive index of 3.42 by giving the best output values. By using the plane wave expansion and the Finite Difference Time Domain (FDTD), the designed logic gates are analysed and simulated.

KEYWORDS: Photonic Crystal Waveguides, All-Optical logic gates, Beam Interference Principle, FDTD Method, T and Y-shaped waveguides.

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INTRODUCTION

The semiconductor technology was used to implement all of these devices in the past; however, they had several limitations, such as high-power dissipation, high input power requirements, and slow switching speeds. All-optical devices, with properties like fast switching, low power consumption, and large bandwidth, are therefore used to overcome these disadvantages. The signal degradation in photonic circuits is less as compared to the electronic circuit. The design of these logic gates involves several techniques, such as Photonic Crystal Ring Resonators (PCRRs) [1-3], Self-Collimation [4-5], Plasmonic Waves, Mach-Zehnder interferometers (MZIs) [6-7], Semiconductor Optical Amplifiers (SOAs)] [8-9], metal photonic crystal (MPC) with parabola-like dispersion, planar photonic crystal waveguides (PPCWGs), and others. However, they have some deficiencies, such as large size and lack of complexity. That is why many uses photonic crystals, which use beam interference techniques [10-16] as they also have advantages like compact in size, and having strong confinement of light, and less power dissipation.

Photonic crystals are a periodic nanostructure arrangement of the materials having many different refractive indices. Photonic Band Gap (PBG) crystals are structures that manipulate light like semiconductors manipulate electric current. The Photonic crystals occur in nature in the form of animal reflectors and structural coloration. This light is controlled by line and point defects. These materials show different colours due to their structure which can selectively reflect a certain band of wavelength. The photonic crystals can be manufactured in one, two, or three dimensions. In this case, we designed it as a two-dimensional lattice.

Many works have been done to design XOR [17-18] and XNOR gates either by using Y-shaped or T-shaped waveguides. This design results in the combination of T-shaped and Y-shaped waveguides. In this structure, the refractive index (RI) and silicon rod radius are optimized to reduce back reflection; as a result, power lost is less. The size of the XOR and XNOR gates are 9μm×9μm and 9μm×7.8μm. Based on the input signal phase angle and path traversed by signals, constructive or destructive interference occur in the waveguides. With odd integral multiples of the path difference or phase difference of 180°, destructive interference occurs, while constructive interference occurs with even integral multiples of the path difference and phase difference of 0°.

PAPER STRUCTURE

In this paper, we present our proposed design for XOR and XNOR logic gates that combine T and Y-shaped waveguides. FDTD is used to analyse and optimize this. The organization is outlined under Section 1, Introduction. Section 2, describes both logic gates and how they work. Section 3, provides the simulation results. Section 4, we conclude the proposed design.

DESIGN AND WORKING OF ALL-OPTICAL XOR, XNOR LOGIC GATES

A.XOR DESIGN:

The proposed structure is a two-dimensional Photonic Crystals using the combination of T-shaped and Y-shaped waveguides consist of arrays of silica dielectric rods with air substrate. An XOR gate using beam interference is implemented here. Silicon rods with a radius of 0.17a are used, where 'a' is the lattice constant (the distance between two dielectric rods) of value 0.6 μm, and the refractive index of the silicon rods is 3.42.

This structure operates with a wavelength of 1.55 μm. The junction rods or refractive rods are manipulated in this design to be able to transmit the high power at the output port with a minimum of back reflections. This design has an array size of 15a × 15a (9 μm × 9 μm) with one Y and T-shaped waveguides. In addition, a glass rod of 0.2a radius and 1.92 refractive indices are used at the output junction to decrease the back reflection. The proposed XOR gate has a contrast ratio of 8.27.

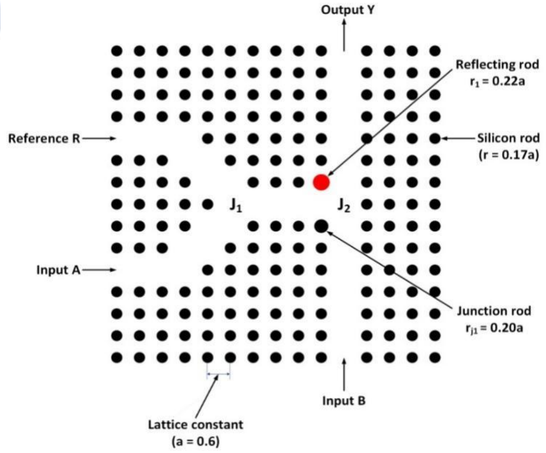

Figure 1: Layout of proposed all-optical XOR logic gate

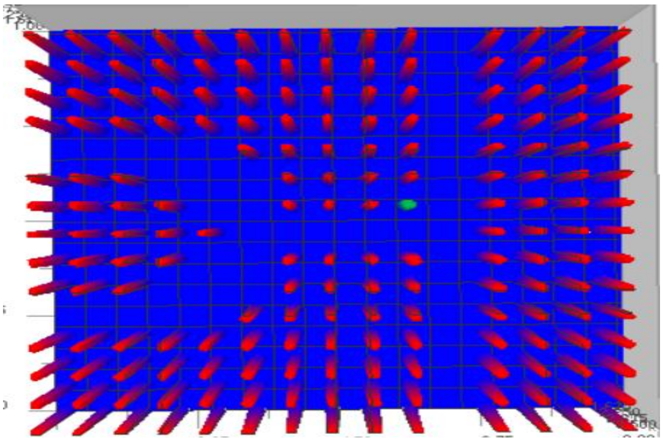

Figure 1: 2-D Refractive Index of all-optical XOR Logic Gate

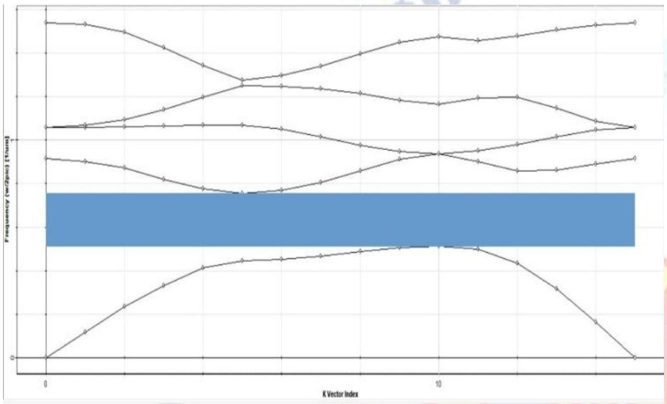

Figure 2: FDTD photonic band gap diagram for XOR gate

The Band gap of XOR is shown in the above figure. This can be determined by using the Planar Wave Expansion (PWE). There is a photonic band gap similar to the electronic band gap that exists between the conduction band and the valence band. The spectral ranges of XOR are (0.514, 0.754) and the total photonic band gap is 0.2. "a/lambda" is the wavelength through which light can't propagate, where lambda is the continuous wavelength. As a result, XOR has determined wavelengths (1.163, 0.795).

XNOR DESIGN:

Silicon rods with a radius of 0.17a (0.102) are used, and the refractive index of the silicon rods is 3.42. This structure operates with a wavelength of 1.55 μm. The junction rods or refractive rods are manipulated in this design to be able to transmit the high power at the output port with a minimum of back reflections. This design has an array size of 15a × 13a (9 μm × 7.8 μm) with one Y and T-shaped waveguides.

There are two junctions in this design, the input junction referred to as J1 and the output junction referred to as j2. Three silicon rods are manipulated at the J1. One silicon rod radius is changed to 0.317a (0.19) to reduce back reflections, while two more rods are replaced with a glass rod radius of 0.17a (0.102), which allows a stronger signal to be sent towards the output. At the J2 junction, two rods are manipulated, one is the left junction rod, which is changed to 0.217a (0.13), and the right junction rod is changed to a glass rod with a 1.92 refractive index 0.17a (0.102), resulting in high power output and reducing back reflection.

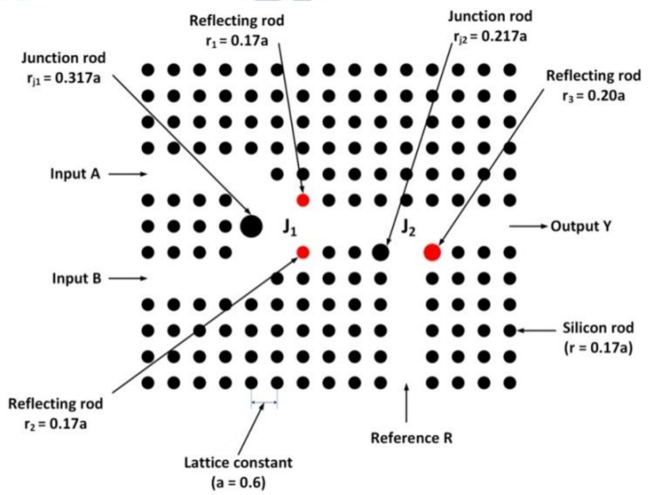

Figure 3: Layout of proposed all-optical XNOR logic Gate

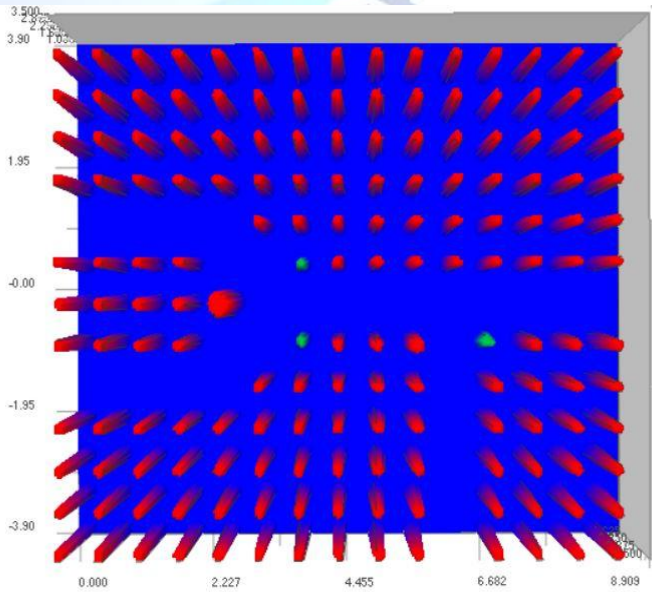

Fig 4:2-D Refractive Index of all-optical XNOR Logic Gate

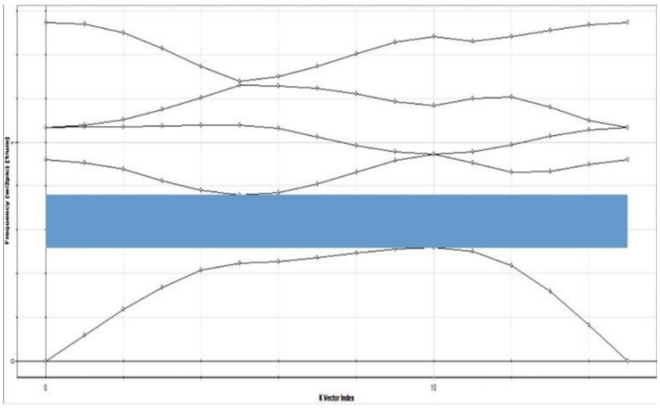

Figure 3: FDTD photonic band gap diagram for XNOR gate

In the following figure, we can see the Band gap of XNOR. You can determine this when you use the Planar Wave Expansion (PWE). In a similar way to the electronic band gap, there exists a photonic band gap between the conduction band and valence band. A total photonic band gap is 0.2 and XNOR's spectral ranges are (0.5199, 0.756). "a/lambda" is the wavelength through which light can't propagate, where lambda is the continuous wavelength. This results in wavelengths (1.156, 0.793).

SIMULATION RESULTS AND DISCUSSION

3.1 XOR Simulation Results

3.1.1 Case 1: (Input port A is '0', B is '0'; LOGIC '00')

In this input condition, both input planes exhibit an inactive signal, and reference is always high. In this input condition, both input planes exhibit an inactive signal, and reference is always high. The signal at the output can be observed due to the presence of a high reference since A is low and B is low with a phase of zero. This condition satisfied the truth table of the XOR gate we designed.

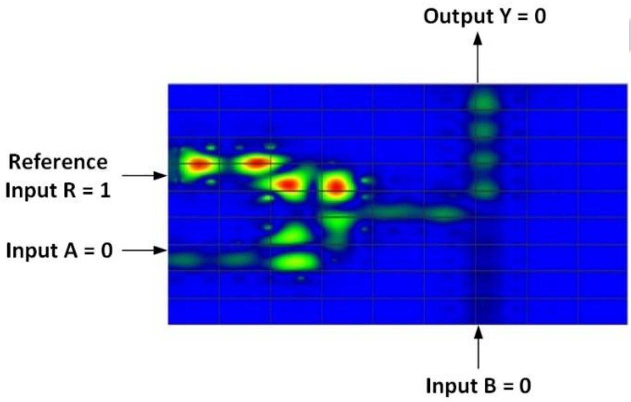

Fig 5: XOR- '00' Condition

3.1.2 Case 2: (Input port A is '0', B is '1'; LOGIC '01')

Here, at the '01' condition the input B and the reference is set high, while input A is set low. Observing the destructive interference, we rotate input B 180° according to the beam interference theory. The XOR function results in a high output.

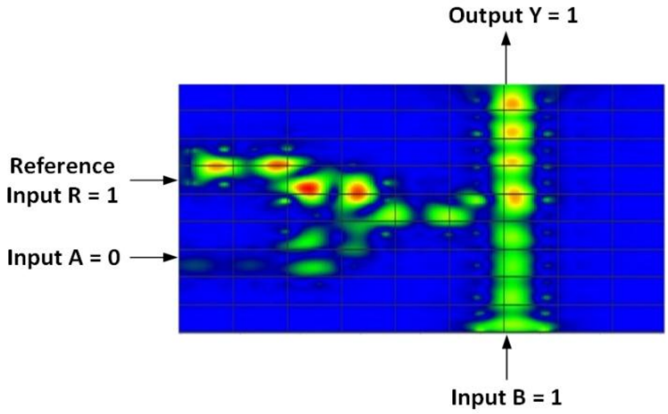

Fig 6: XOR-'01' Condition

3.1.3 Case 3: (Input port A is '1', B is '0'; LOGIC '10')

The input '10' condition consists of an active signal incident from port A and a reference signal and inactive signal present from port B. In junction J1, there is constructive interference where the output is high and XOR is satisfied.

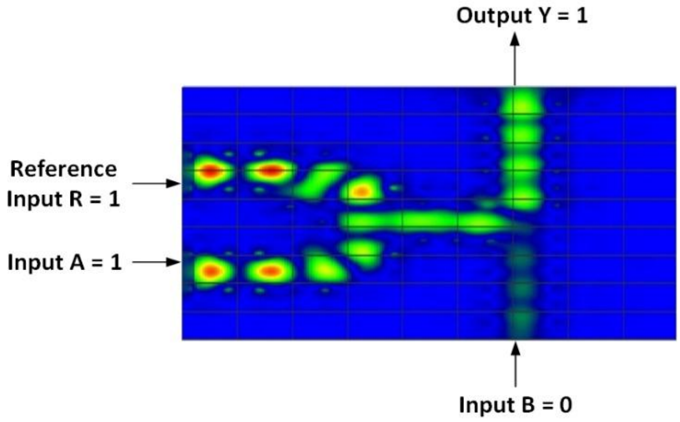

Fig 7: XOR-'10' Condition

3.1.4 Case 4: (Input port A is '1', B is '1'; LOGIC '11')

The condition '11' consists of an active signal coming from all the input ports -inputs A, B, and reference. Junction J1 is subject to constructive interference, whereas junction J2 is subject to destructive interference, resulting in a low output. XOR also meets the final condition.

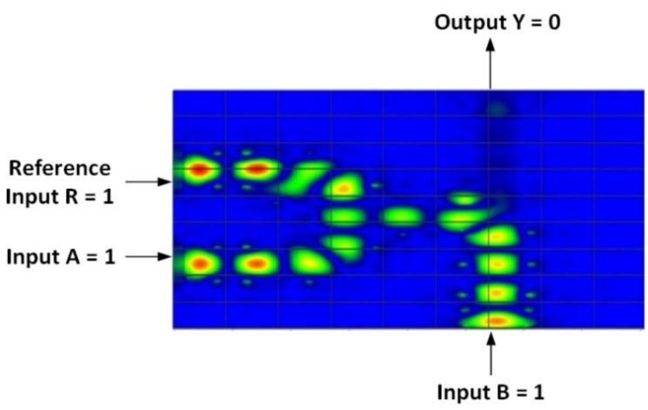

Fig 8: XOR-'11' Condition

Intensity of light at the output for different refractive index values of XOR gate

XOR is verified and analysed under various refractive indexes, and the refractive index of 3.42 has been determined to be the best refractive index that will simultaneously satisfy all the conditions of the truth table of XOR with maximum output.

The Contrast Ratio (CR) is calculated as follows:

$$CR=10 \log_{10} (P_1/P_0)$$

Where; CR is the Contrast Ratio

P_1 indicates the output power at 1 logic value

P_0 indicates the output power at 0 logic value

Table 1: Output values of XOR for different Refractive Indexes

Input		Output power					
		RI variations					
A	B	3.40	3.42	3.44	3.46	3.48	3.50
0	0	0.15	0.14	0.14	0.14	0.15	0.13
0	1	0.75	0.74	0.70	0.72	0.72	0.68
1	0	0.60	0.59	0.57	0.54	0.60	0.54
1	1	0.12	0.11	0.12	0.09	0.14	0.10
Contrast ratio(C.R)		7.95	8.27	7.65	9.03	7.11	8.32

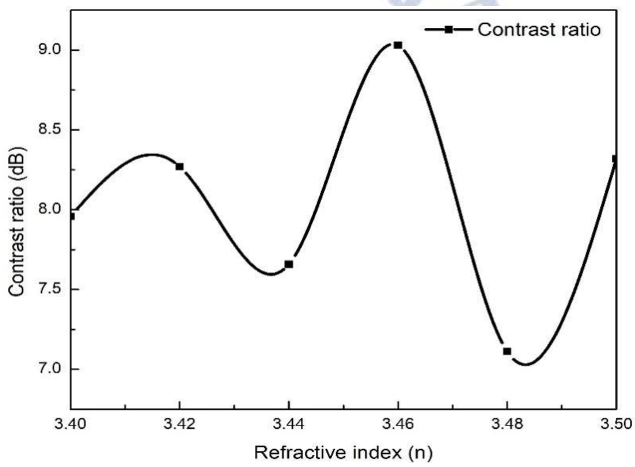

Fig 9: Contrast ratio for all-optical XOR gate for different values of refractive index

XNOR Simulation Results

3.2.1 Case 1: (Input port A is '0', B is '0'; LOGIC '00')

In this input condition, both input planes exhibit an inactive signal, and reference is always high. As input A and B are low and have no phase, no signal is observed at the output port, as no interference took place in this case as there is only one input signal, which is a reference. The truth table of our designed XNOR gate satisfied this condition.

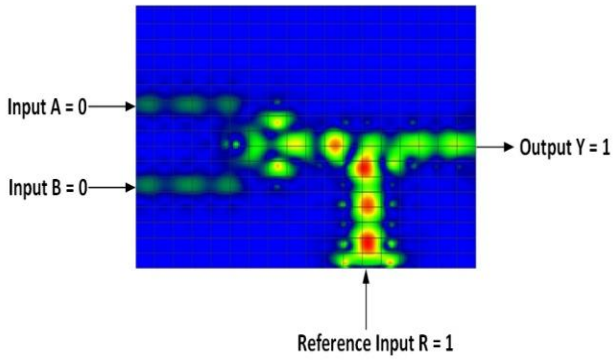

Fig 10: XNOR-'00' Condition

3.2.2 Case 2: (Input port A is '0', B is '1'; LOGIC '01')

During this input condition, the input port A shows an inactive signal, and the input port B and reference show an active signal. Constructive interference is noted at the output port at the junction. The truth table of XNOR confirms this condition.

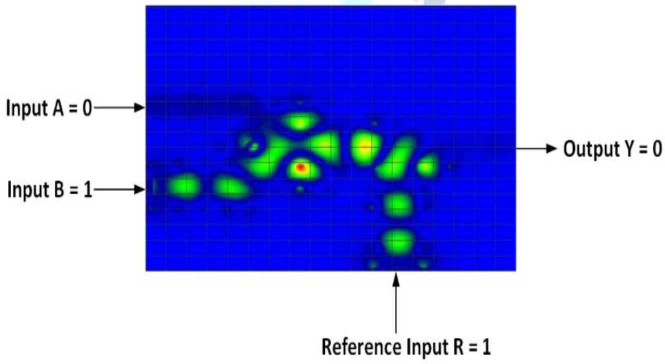

Fig 11: XNOR-'01' Condition

3.2.3 Case 3: (Input port A is '1', B is '0'; LOGIC '10')

It is observed that port A and the reference signals are both active and port B is inactive. Constructive interference can be observed at the output port when the phase of the input signal A and the reference signal are both 0°. With phase and path differences, this condition satisfied the truth of XNOR and beam interference.

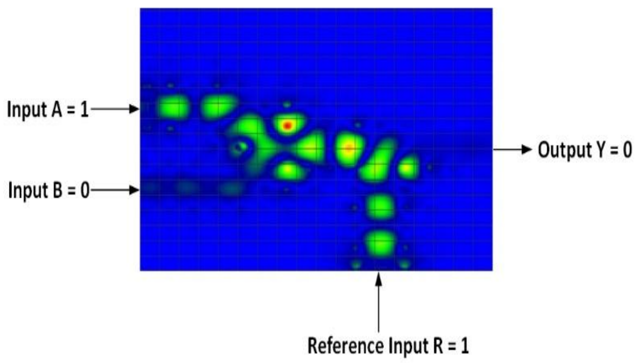

Fig 12: XNOR-'10' Condition

3.2.4 Case 4: (Input port A is '1', B is '1'; LOGIC '11')

During this input condition, all input A, B, and reference ports are active. The inputs A and B have 0 phase difference, causing constructive interference at junction J1, while at junction J2, there is destructive interference, caused by the path difference. Thus, in order to satisfy the XNOR truth table, we set the reference phase to 180°. Finally, XNOR is completed.

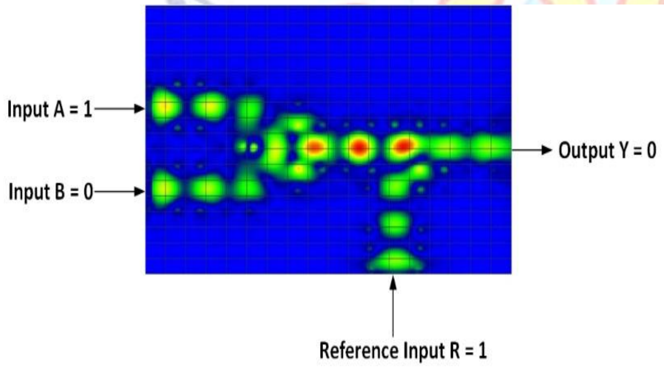

Fig 13: XNOR-'11' Condition

Based on testing and analysing XNOR under various refractive indexes, 3.42 were determined to be the best refractive index to simultaneously satisfy the truth table of XNOR.

Table 2: Output values of XNOR for different Refractive Indexes

Input		Output power					
		RI variations					
A	B	3.40	3.42	3.44	3.46	3.48	3.50
0	0	0.17	0.52	0.27	0.19	0.27	0.21
0	1	0.04	0.04	0.13	0.04	0.15	0.07
1	0	0.03	0.04	0.14	0.04	0.16	0.07
1	1	0.67	0.94	0.73	0.85	0.72	0.81
Contrast ratio(C.R)		7.95	8.27	7.65	9.03	7.11	8.32

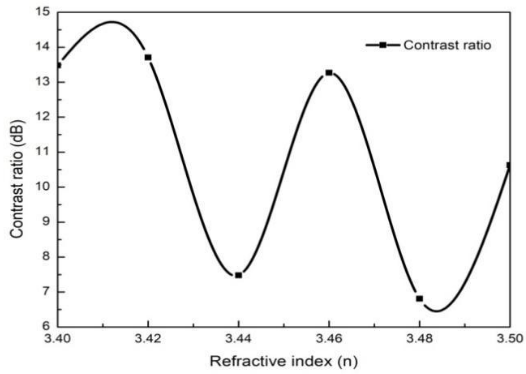

Fig 14: Contrast ratio for all-optical XNOR gate for different values of refractive index

CONCLUSION

In this design, two logic gates, XOR and XNOR, are implemented by using Photonic Crystal Waveguides and square lattice silicon rods. Simulations of the designs are carried out using the FDTD Method. At 1550nm wavelength, the XOR and XNOR provide CRs of 6.928 dB and 13.71 dB, respectively. Both T- and Y-shaped waveguides are used in this design. As a result, optical networking and computing could be enabled by it.

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