All-Optical AND Logic Gate Based On 2-D Photonic Crystal

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***Abstract* —** In this paper, All-optical AND logic gate with square cavity in 2-D (two dimensions) photonic crystal have been proposed. The square cavity is created by removing rods of dielectric GaAs from a rectangular lattice in air substrate. Photonic crystal (PC) has periodic dielectric structure that has an important characteristic of PC known as photonic band gap (PBG). The property of PBG is that, wavelength within the band gap cannot propagate through the crystal. In this research work, this property is used to design an All-optical AND logic gate. The band diagram gives a good forbidden band gap in the normalized frequency range of $0.554859 \leq (1/\lambda) \leq 0.811549$ for Transverse Electric (TE) modes. Therefore, band gap width is 0.25669 and normalized central frequency of band gap is 0.6451.The AND optical logic gate is of very small size 13μm×8μm and the operation of this logic gate is verified at third optical window i. e. 1550 nm, which is the most widely used window in present optical communication system.

***Keywords* —** Photonic Crystal (PC), plane wave expansion (PWE) method, Square cavity, photonic band gap (PBG), Finite Difference Time Domain (FDTD).

I. Introduction

All-optical logic devices are an indispensable part of modern integrated optical circuits. There are two ways to construct optical logic gates: the first one is based on nonlinear optical effects in Semiconductor optical amplifier (SOA) [1-10] or periodically poled lithium noibate (PPLN) waveguide [11-13]. This type of optical logic devices are based on mature techniques of optical computing but it requires large space, power consumption and is not feasible for micro or nano integration. The second one is based on the use of Photonic crystals. Today photonic Crystal (PCs) [14] based technology attracts the scientist and researchers for the realization of optical devices for next generation of Photonic Integrated Circuits (PICs) [15-17] which can be implemented in micrometer size instead of centimeter and millimeter size. Photonic Crystal also used for intelligence and communication network such as power generation system: Low-Temperature Thermo photovoltaic, Tunable IR Camouflage system, High-Power Photonic crystal laser for Power Beaming.

Photonic Crystals are periodic structures made up of natural dielectric or artificial materials in which the dielectric constant changes in one [18-21], two [22-27] or three dimensions[28-32] to affect the propagation of electromagnetic waves inside the structures . Because of this periodicity, PCs exhibit some unique optical properties such as Photonic band gap (PBG) [33-35] i.e. a frequency window, similar to the electronic band gap in semiconductor. Photonic Band Gap (PBG) has been calculated by plane wave expansion (PWE) method [36]. By removing rods, we can create a defect [37-39] in the structure. In this defected structure the periodicity and completeness of the band gap is tainted and the light cannot propagate in the PBG region i.e. there are no modes and no spontaneous emission in this region. Thus, light (Photons) can be trapped at the defected region with the frequency corresponding to the defect frequency inside the band gap. This peculiar behavior will lead to design and realize many interesting PC based optical components for optical networking applications and Photonic Integrated Circuits (PIC). In this paper, a novel approach for design of All optical AND logic gate is proposed which is based on photonic crystal square cavity. The propagation of light in

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the photonic crystal can be numerically simulated by using the finite-difference time-domain (FDTD) [40] method. The FDTD method consists of approximating the space and time derivatives by finite differences in Maxwell's equations [41-42]. Thus, using FDTD method Maxwell's equations can be solved numerically by time stepping the propagation of the fields. The time step is determined by the Courant limit along the X and Z directions are Δx and Δz, respectively

$$\Delta t \leq 1/\left(C\sqrt{1/(\Delta x)^2 + 1/(\Delta z)^2}\right) \quad \textbf{(1)}$$

Where

C = speed of light in vacuum i.e. 3×10^8 m/s

This method has found widespread use in modeling the wave-propagation in photonic crystals, as it is very flexible, based on structure geometries and can handle large index variations.

The complete paper comprises of five sections, II section describes the design structure and band diagram, III section elaborates the principal of operation of the design, section IV explains the simulation and result part and finally section V concludes the results obtained.

II. Structure Design and Band Diagram

All-optical AND gate have served as sampling gates in optical sampling oscilloscopes [43] due to their ultrafast operation compared to conventional electrical methods. Some application as address recognition, packet-header modification and data-integrity verification are performed using AND logic gate. In this paper the 2-D rectangular lattice is used for designing the All-optical AND logic gate. In rectangular lattice, the number of rods in X direction is 25 and that in Z direction is 15. In photonic crystals, the lattice constant '**a**' i.e. distance between the two neighbor rods must be in the range of 100nm−1μm. In this structure a= 540 nm and two types of rods coupling rods and scatterer rods are used. The radius of coupling rods are 0.185a, which is closed to 0.1μm and radius of scatterer rods are 0.203a, which is closed to 0.11 μm. The refractive index of dielectric rods are 3.40 with permittivity ε_r =11.56. These rods are surrounded by air (refractive index=1). Thus, there is high index contrast ratio between rods and air.

To analyze the behavior of the wave, dispersion diagram i.e. known as band diagram is studied to have the idea of band gap. Dispersion diagram, using the plane wave expansion method (PWE) as shown in figure 1 gives the propagation modes of the 13μm×8μm photonic crystal lattice. Photonic crystal structure has a Photonic Band Gap in the structure without creating defect for Transverse Electric (TE) modes whose electric field is parallel to the rod axis. Defect is created for the proposed design of AND gate. The band diagram gives a good forbidden band gap in the normalized frequency range of 0.554859 ≤ (1/λ) ≤0.811549 for Transverse Electric (TE) modes. Band gap width is 0.25669 and normalized central frequency of band gap is 0.6451.

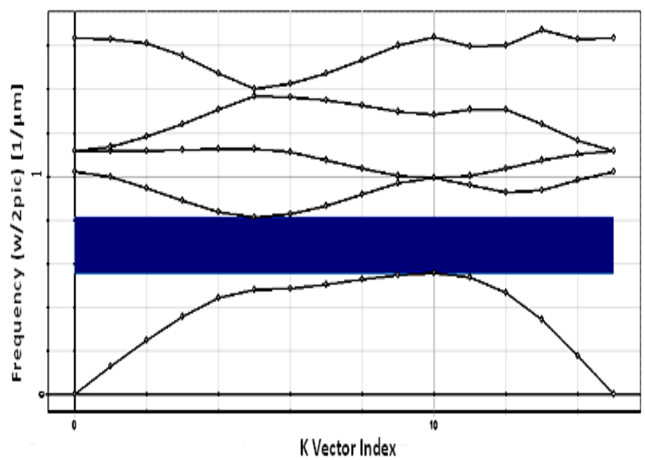

Figure 1: Band gap for AND logic gate without defect for TE mode.

Figure 2 shows the proposed structure of All-optical AND logic gate based on two dimensional photonic crystal square cavity. This device is designed using optiFDTD tool of Optiwave software.

Scatterer rods at all the four corners of square cavity are highlighted using circle. Both point and line defects are utilized to design All-optical AND logic gate. As observed from Figure 2 that there are three in-lines quasi waveguides and a resonant square cavity placed between them consisting of two rings. This resonant square cavity possesses dielectric scatterer rods at all the four corners that provide high spectral selectivity. The coupling rods are positioned between the in-line quasi waveguide and resonant square cavity. A Gaussian modulated continuous wave signal is injected by vertical input plane at the two

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input ports A and B with the wavelength of 1.55 µm and the output is observed by placing the observation vertical line at the output port. The analysis of this All-optical AND logic gate based on 2-D photonic crystal is done by varying the radius of scatterer rods and optimizing the extinction ratio. In addition, power at output port is optimized with respect to wavelength of operation.

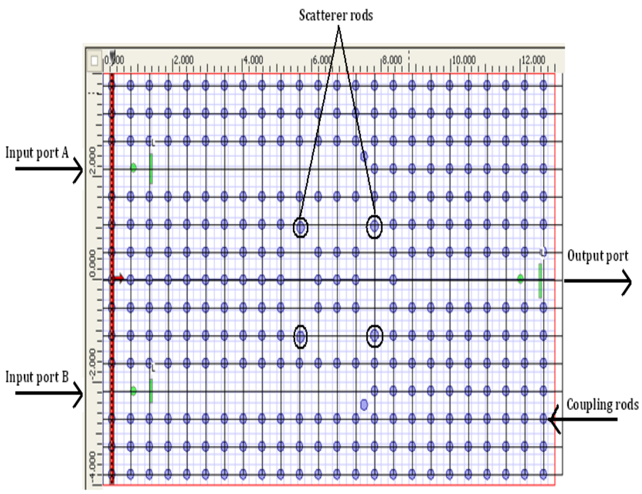

Figure 2: Design of two dimension photonic crystal based All-optical AND logic gate in X-Z plane using optiFDTD.

III. Operation Principle

Figure 3 shows the basic symbol of AND gate. Basic operation of the AND gate is ,output "ON"(1), when both inputs are "ON"(1) and output "OFF"(0) ,When any one input is "OFF" (0). This operation is implemented in All-optical AND logic gate based on the 2-D photonic crystal. In All-optical AND logic gate, inputs are applied through vertical input plane and output is observed by placing the observation vertical line at the output port. Table 1: shows truth table of All-optical AND logic gate with the output.

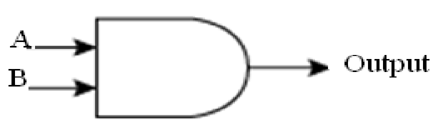

Figure 3: Basic symbol of AND gate

Table 1: Truth table of All-optical AND logic gate

Input A	Input B	Output=A.B	Output power level mW/mm
0	0	0	0
0	1	0	1.087
1	0	0	3.903
1	1	1	9.206

IV. Simulation and Results

The computational simulation is carried out by using finite-difference time-domain (FDTD) method with TE polarization for the different combinations of the inputs. For the condition that the input port A is "OFF", B is "ON" and vice versa, the output is "OFF". On the other hand, when the input port A and B both are "ON" the output is "ON" and light coming from these input ports, will be coupled in the resonant square cavity. Figure 4.1(a & b) shows the distribution of electrical field and Discrete Fourier Transform (DFT) when both inputs A and B are "ON". In this case, the output power level is 9.206 mW/mm. Figure 4.2 (a & b) shows the distribution of electrical field and Discrete Fourier Transform (DFT) when the input A is "ON" and B is "OFF". In this case, the output power level is 3.903 mW/mm. Figure 4.3 (a & b) shows the distribution of electrical field and Discrete Fourier Transform (DFT) when the input A is "OFF" and B is "ON". In this case, the output power level is 1.087 mW/mm Thus the proposed design has the characteristics of All-optical AND logic gate which is verified not only by measurement of power at the output but also predicted by the Electric field distribution and Discrete Fourier Transform (DFT) shown in Figure 4.1,4.2 and 4.3.

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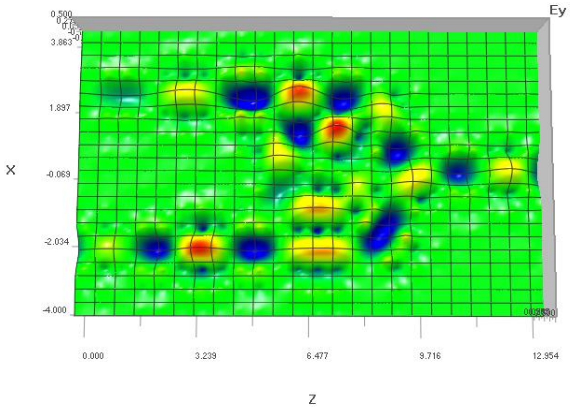

Figure 4.1 (a) Electric Field distributions for All-optical AND logic gate. When A=1, B=1.

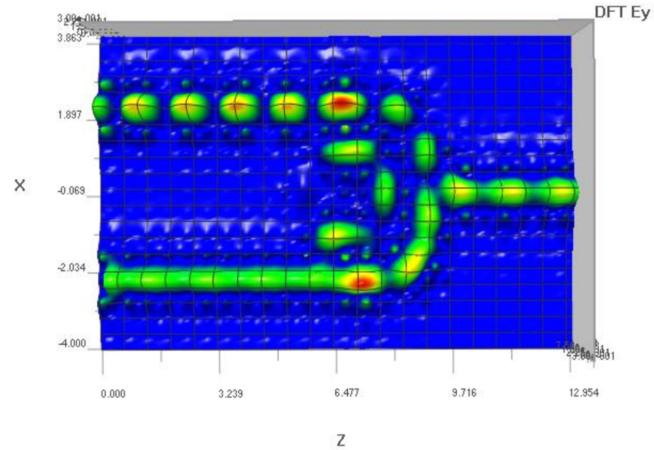

Figure 4.1 (b): DFT of All-optical AND logic gate: When A=1, B=1.

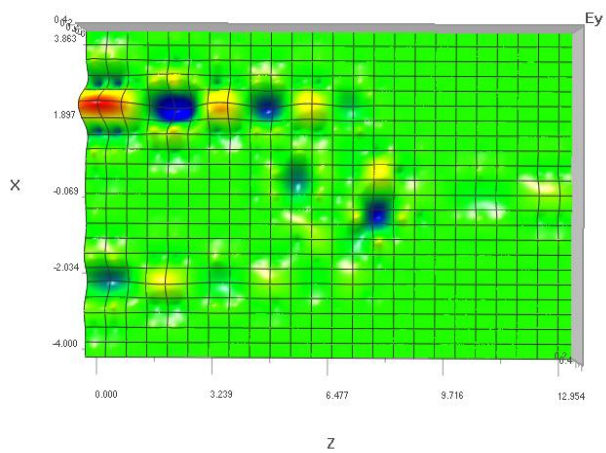

Figure 4.2(a): Electric Field distributions for All-optical AND logic gate When A=1, B=0.

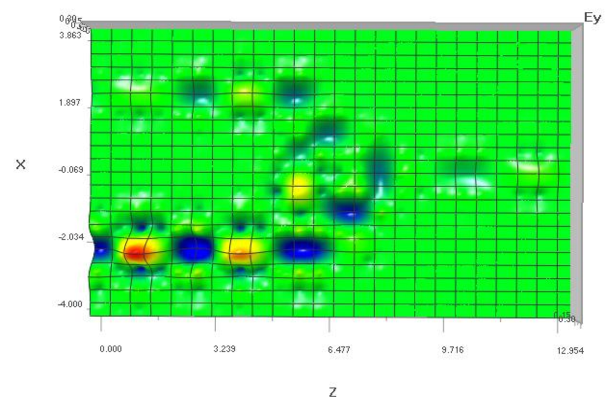

Figure 4.3(a): Electric Field distributions for All-optical AND logic gate. When A=0, B=1.

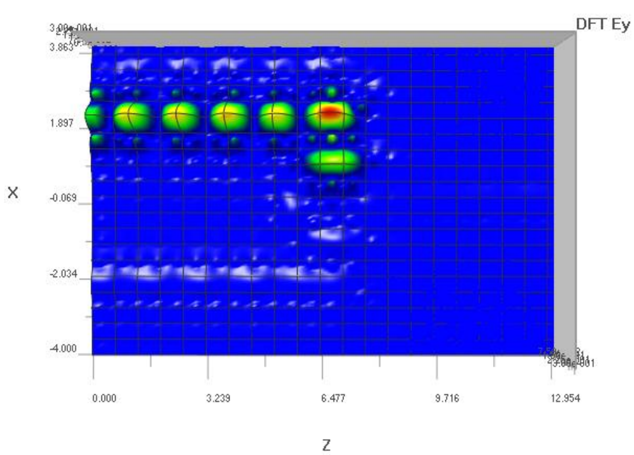

Figure 4.2(b): DFT of All-optical AND logic gate: When A=1, B=0.

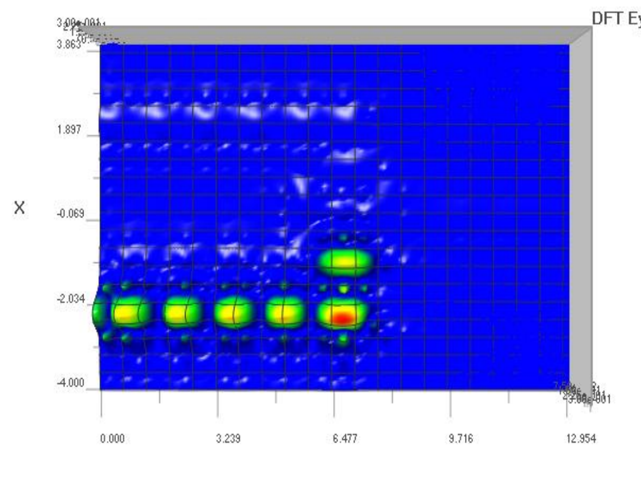

Figure 4.3(b): DFT of All-optical AND logic gate: When A=0, B=1.

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For the proposed design structure, extinction ratio is measured. Extinction ratio [44] is used to describe the optimal biasing conditions and how efficiently logic device works in communication system. Digital optical communication system, binary data transmit using two levels of optical power, where the higher power level P_1 represents a binary 1 that indicate the light source “ON” and the lower power level P_0 represents a binary 0 that shows the light source “OFF”. Extinction ratio (r_e) may be given by the minimum power of P_1 to maximum power of P_0.

$$r_e = \frac{P_{1mi}}{P_{0mi}} \quad (2)$$

Table 2 and 3 describe the variation of extinction ratio with radius of scatterer rods and wavelength of input signal respectively for All-optical AND logic gate.

Table 2: Variation of Extinction ratio with scatterer rod radius for All-optical AND logic gate.

Scatterer rods radius in µm	**Extinction ratio**	
	r_e	**r_e(dB)**
0.08	2.0736	3.1672
0.09	4.0878	6.1148
0.10	3.8508	5.8555
0.11	8.4691	9.2783
0.12	3.8025	5.8006
0.13	2.8664	4.5733
0.14	0.9221	-0.3522

Table 3: Variation of Extinction ratio with input wavelength for All-optical AND logic gate.

Wavelength of vertical input in µm	**Extinction ratio**	
	r_e	**r_e(dB)**
1.40	4.1739	6.2054
1.45	1.5733	1.9681
1.50	2.5521	4.0689
1.55	8.4654	9.2764
1.60	0.5631	-2.4941
1.65	1.5125	1.7969
1.70	0.5090	-2.9328

Figure 5(a) shows the extinction ratio for different scatterer rod radius. Using this we observed that the maximum Extinction ratios obtained for scatterer rod radius 0.11µm. Figure 5(b) shows the extinction ratio for different wavelength. Using this figure we observed that optimum performance of All-optical AND logic gate is obtained at 1.55µm wavelength.

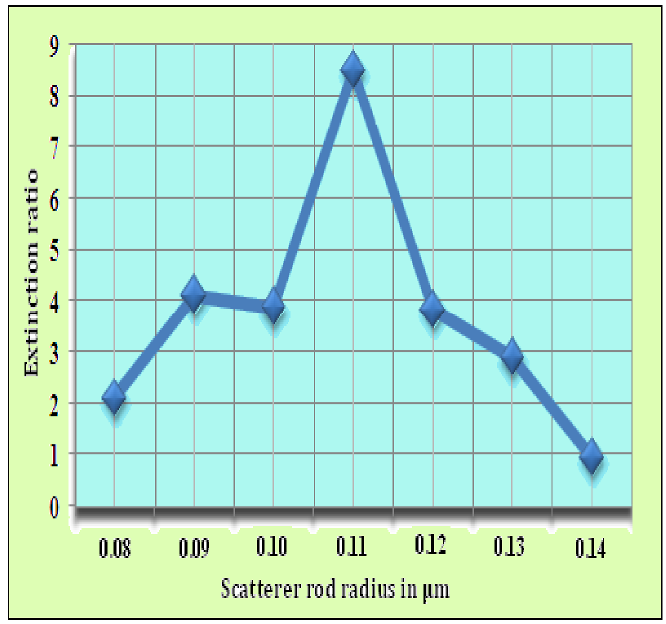

Figure 5 (a): Extinction ratio for different scatterer rods radius.

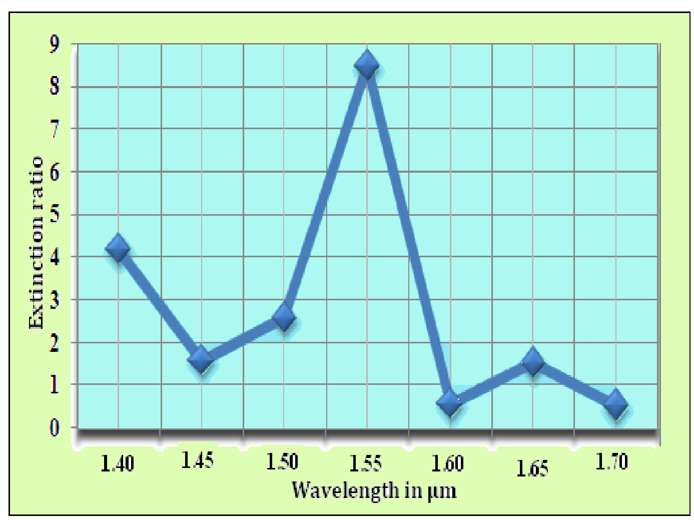

Figure 5(b): Extinction ratio for different wavelength.

V. Conclusion

In this paper, we have proposed a design structure of All-optical AND logic gate based on 2-D photonic crystal square cavity. Inputs are applied with a vertical input plane at a line defect of the PCs that are partially transmitted and reflected by square cavity. This square cavity consists of four scatterer rods at the corner. The analysis is done by varying the output power with respect to the radius of scatterer rods and wavelength of input signal. Using figure 5(a) and 5(b) we analyze that maximum extinction ratio obtained is at 1.55µm wavelength with 0.11 scatterer rod radius. While comparing the result of proposed All-optical AND logic gate with the previous work [45], the result quoted is that the size of the square lattice is about 15µm*15µm and the power reaches to about 90% of the input, where as in the proposed design which has small size of about 13µm*8µm, the power reaches to about 92% of the input power .Similarly in ref [46], two extra control waveguides are used and an input signal of 60 W/m is given but in the proposed design there is no need of extra control waveguide and the value of input signal applied is also small i.e. 5.1432mW/mm. The proposed device has a simple and small structure with clear operating principle which shows that it is very useful in the ultrafast optical logic operation of optical digital integrated circuit for future optical network.

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BIOGRAPHY

Kajal Bhadel is presently working as assistant professor at Govt. Engineering College, Ajmer. She has in 6 years of teaching experience. She has presented her research work in international conference with publications in IEEE (Computational Intelligence and Communication Networks (CICN), 2014) and International Journal of Computer Applications (IJCA).

Rekha Mehra, presently working as associate professor and Head (ECE) at Govt. Engineering College, Ajmer, is a recipient of national, state and sponsored scholarships at school level. She also received Best Project Award for project work in BTech Examination. After completing her BTech from Allahabad University, she joined as project engineer (R&D) with Hindustan Cables Ltd., Naini. (Central Govt. Undertaking) and was later promoted to assistant manager (R&D). She joined the Govt. Engineering College as assistant professor (ECE) and was later selected as associate professor (ECE) in the same institution. She has in 21 years of experience, with 14 years of teaching and seven years of R&D experience. She is a life member of ISTE, member of IEEE and fellow of OSI. She was officiating director at Ajmer Institute of Technology, Ajmer. She has delivered expert lectures in the field of Optical Fiber Technology as a resource person in DST workshop organized by Jai Narayan Vyas University Jodhpur, in meetings of Ajmer Engineers Institution and in National conferences. She has presented her research work in international conferences with publications in refereed journals. She has reviewed papers of international conferences with publications in refereed journals and chaired the technical session in the International and national conferences