Design and Simulation of All-Optical OR Logic Gate based on 2-D Photonic Crystal

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ABSTRACT
In this paper, we present the design of All-optical OR logic gate based on 2-D (two dimension) photonic crystals. To realize this, we consider the photonic crystals (PCs) with a square lattice of dielectric rods (refractive index=3.40). These rods are surrounded by air (refractive index=1).First we design the structure using the Finite Difference Time Domain (FDTD) method and in second step, we compute the band gap by plane wave expansion (PWE) method. These methods are kept to analyze the behavior of the structure. Band gap width is 0.2516 and normalized central frequency of band gap is 0.6451. Overall size of the logic gate designed is 13µm * 8µm i.e. 104 μm^2 with the lattice constant 540 nm.

General Terms
One- dimensional (1D), Two- dimensional (2D,) Three-dimensional (3D), Defects, Square cavity, waveguide, Q-factor, Optical logic gate.

Keywords
Photonic Crystals (PCs), plane wave expansion (PWE) method, photonic band gap (PBG), Transverse Electric (TE), Finite Difference Time Domain (FDTD).

1. INTRODUCTION
Photonic crystals (PCs) are the optical materials, which are formed either naturally or artificially. In PCs, the refractive index (RI) [1, 2] is periodically modulated depending on the order of the wavelength of light. It is form by a periodic arrangement of material so it is said to be a "crystal" and the term "photonic" is added since these crystals are designed to affect the propagation properties of photons (light).
Depending on the dimension of periodicity, the PCs can be divided into one- dimensional (1D) [3-6], two- dimensional (2D)[7-12] and three-dimensional (3D)[13-17] structures. In two- dimensional (2D) structures, PCs impose periodicity of the permittivity in X and Z direction while in the third direction Y the medium is homogeneous.

Under certain conditions, PCs can create a photonic band gap (PBG) [18-20].So photonic crystals are also named as photonic bandgap structure. PBG could manipulate beams of light in the same way as semiconductors control electric currents and photonic crystals cannot support photons lying in the photonic bandgap. By preventing or allowing light to propagate through a crystal, light processing can be done. The PBG of the material can be calculated by plane wave expansion (PWE) method [21].By adding or removing dielectric material in a PCs structure defects [22-24] (point defect or line defect or both) can be created in these periodic structures. The periodicity and thus the completeness of the PBG are entirely broken which allows to control and manipulate the light [25-26]. It ensures the localization of light in the PBG region. All-optical logic gates are used as key elements for real-time optical processing and information communication. Because of recent advantages in nanophotonic fabrication, the amount of compactness and low loss of photonic crystal (PC) structures make them one of the best candidates for constructing ultra-fast All-optical logic gate [27]. Because of the ease of fabrication and analysis, 2D photonic crystals have attractive attention of large number of researchers and engineers to design optical devices based on PCs.

In this paper, we proposed a new approach for All-optical OR logic gate based on the principle of square cavity and in-line quasi waveguides. In photonic crystal, using the material property variation (at one point or several points) forms the point defect by removing pillars, filling the holes, or changing the size of pillars or holes, etc. This point defect sometimes behaves like a cavity that has a very high quality factor Q [28]. The Q-factor defines the shape of resonant peaks and consequently the value of the Full Width at Half Maximum (FWHM) and it is expressed as follows:

$$Q = \frac{f_c}{f_2 - f_1} = \frac{f_c}{\Delta f} \qquad \text{------ (1)}$$

Where,
fc is center frequency and Δf is the peak bandwidth or the -3dB frequency bandwidth i.e. shown in figure 1.

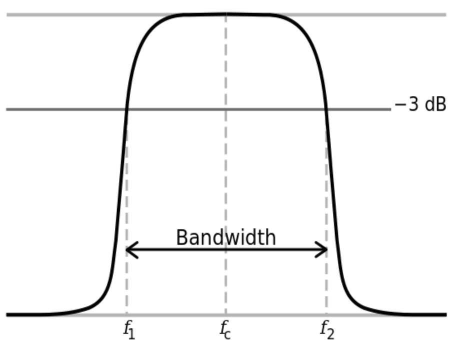


Fig 1: Quality factor of the cavity. [en.wikipedia.org/wiki/Q-factor]

The line defects that are formed by removing a line of pillars or filling holes are sometimes treated as photonic crystal waveguide. In photonic crystal waveguide, wave modes are confined by the photonic bandgap.

The paper is arranged in four sections, II section describes the working principle and structure design of All-optical OR logic gate, Simulation and results are discussed in section III and finally section IV concludes the results obtained.

2. OPERATING PRINCIPLE AND STRUCTURE ANALYSIS

In this paper, an All-optical OR logic gate is proposed with 13μm*8μm square lattice 2-D photonic crystals, which consists of one square cavity and two in-line quasi waveguides of circular rods placed in a background of air (refractive index=1). . The refractive index of dielectric rods are 3.40 with permittivity ε_r =11.56.In square lattice, the number of rods in X direction is 15 and in Z direction it is 24.The distance between the two adjacent rods is kept 540nm, which is lattice constant and denoted by 'a' as shown in figure 2.

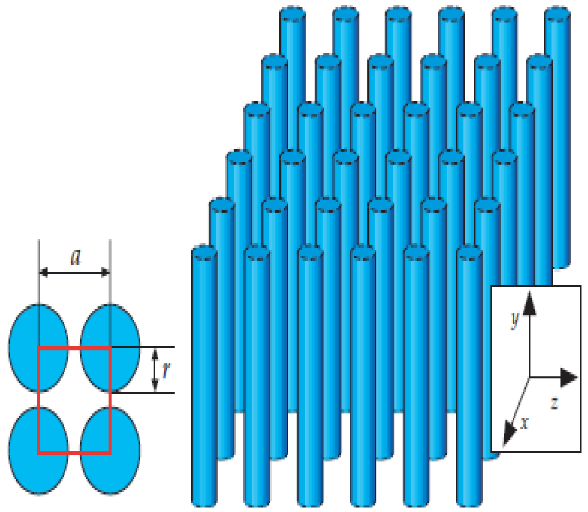


Fig 2: Structure of 2-D photonic crystal. This material is a square lattice of dielectric rods in air with the radius r and dielectric constant ε_r. The material is homogeneous along the Y direction and periodic along X and Z direction with lattice constant 'a'. Ref [26]

As shown in figure 3, scatterer rods are placed at all the four corners of square cavity. This square cavity is used to trap the light in the photonic crystal structure. Other coupling rods are positioned between the in-line quasi waveguides and square cavity. By using waveguide, light can be guided from one location to another. The scatter rods of radius 0.15μm and coupling rods of radius 0.10μm are used in this structure.

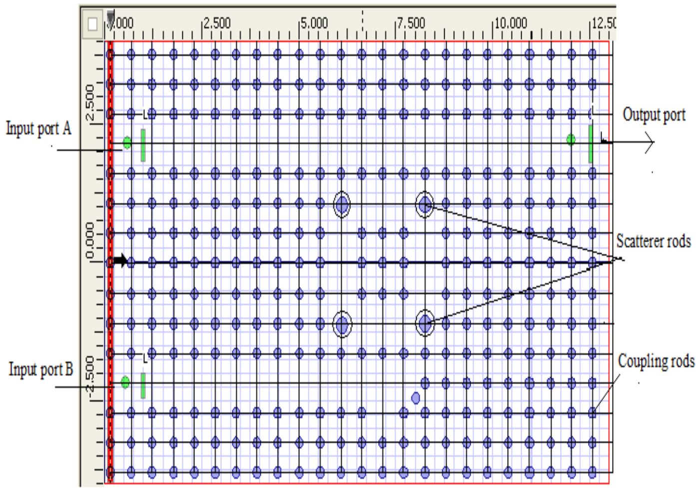


Fig 3: Design of All-optical OR logic gate of two-dimensional photonic crystals (in X-Z plane) using optiFDTD

The band diagram in figure 4 gives a good forbidden band gap. This band gap is obtained in the normalized frequency range of 0.5502≤ (1/λ) ≤0.8033 for Transverse Electric (TE) modes whose electric field is parallel to the rod axis. Therefore, band gap width is 0.2516 and normalized central frequency of band gap (1/λ) is 0.6451.The frequency of the photonic crystal structure is ω/2πc=1/λ, where 'ω' is the angular frequency, 'c' is the velocity of light in free space and 'λ' is the free space wavelength.

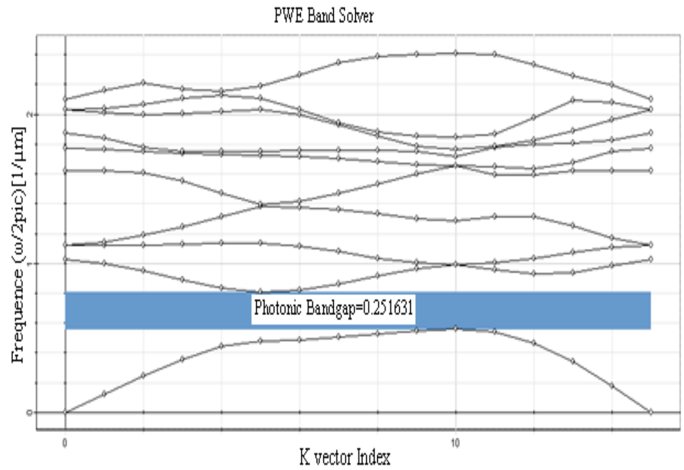


Fig 4: Band diagram of 13μm*8μm square lattice 2-D photonic crystals after introduction of line and point defects

Figure 5, shows the symbol of OR gate. Basic operation of the OR gate is output "ON" (1), when any one input is "ON" (1) and output "OFF" (0), when both inputs are "OFF" (0). This operation implements with All-optical OR logic gate based on the 2-D photonic crystal.

Fig 5: Basic symbol of OR gate

3. SIMULATION AND RESULT

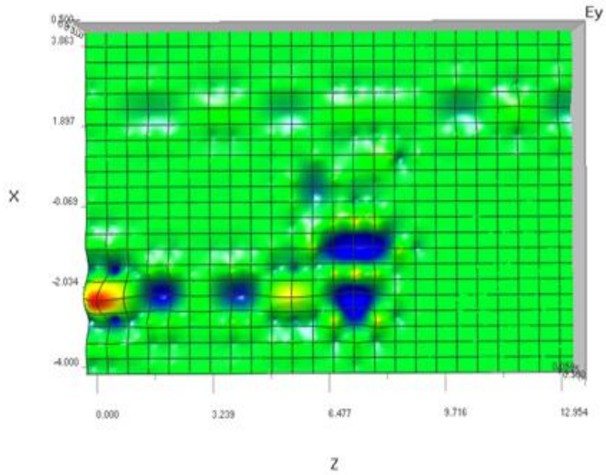
A 2-D 32 bit simulation is carried out using numerical FDTD methods with the transverse electric (TE) polarization to obtain the All-optical OR logic gate. A Gaussian input signal is launched for the different combination of the input ports. This Gaussian input signal is injected by the vertical input plane at the two ports A and B with the wavelength of 1.55µm. In addition, output is measured by vertical line at output port. In our simulation results, we could find that the optimum value of scatterer rod radius is 0.15µm. Table 1 show the output power for different condition of input signal.

Table 1. Truth table of All-optical OR logic gate

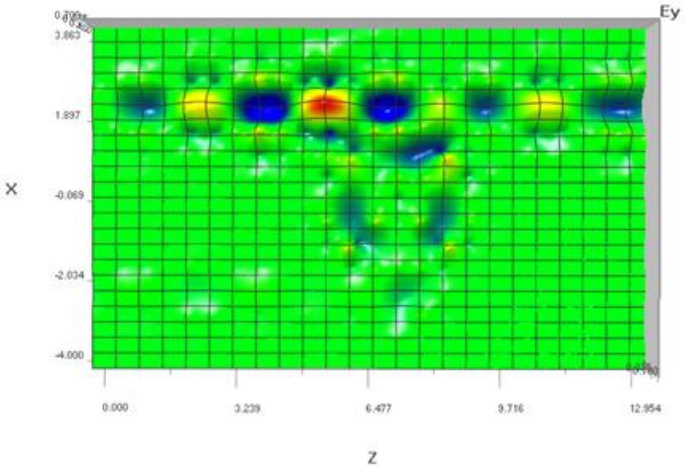
Input port A	Input port B	Output	Output power(W/m)
0	0	0	0
0	1	1	9.192
1	0	1	8.161
1	1	1	9.416

As shown in above table 1, when the output port is "ON" (1), the output transmission power is more than 8.0 W/m and the feedback power is less than 2 W/m. The logic 0 and 1 in the truth table indicate without and with input/output signal respectively.

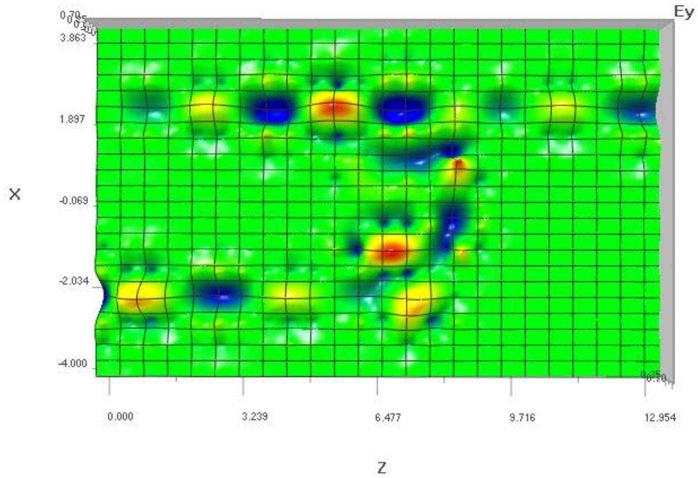
The signal (light) which propagates through the crystal is analyzed by the electric field pattern. Figure 6(a),(b)and (c) show the electric field pattern of All-optical OR logic gate.



(a): Electric field pattern when: A=0, B=1



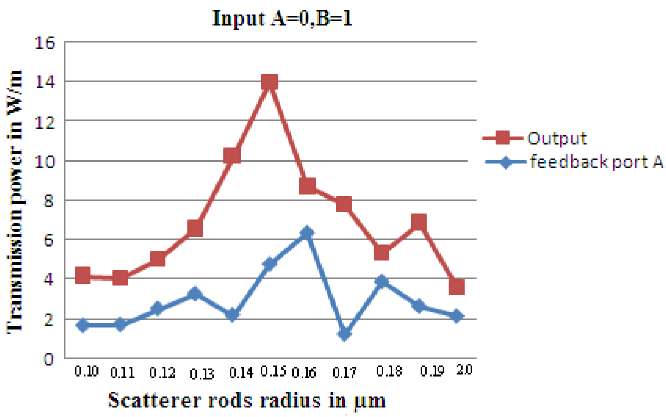
(b): electric field pattern when: A=1, B=0



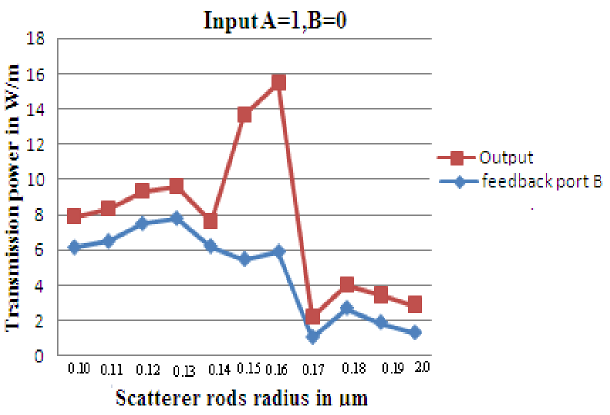
(c): electric field pattern when: A=1, B

Fig 6: (a), (b) and (c) show the electric field pattern of All-Optical OR logic gate at 1550nm

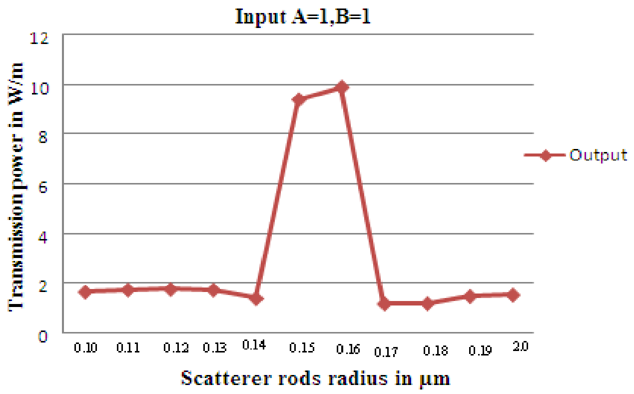
Figures 7(a), (b) and (c) show the graph of transmitted and reflected feedback power with different scatterer rod radius.



(a)



(b)



(c)

Fig 7: (a), (b) and (c) shows the graph of the transmission power with different scatterer rod radius

4. CONCLUSION

In this paper, we have proposed a design structure of All-optical OR logic gate based on 2-D photonic crystal square cavity using optiFDTD method. Inputs are applied with a vertical input plane at a waveguide form by line defect of the PCs that are partially transmitted and reflected by square cavity and output was observed at the output port i.e. also a waveguide. This square cavity created by point defects and reflected signal is considered as a feedback. Square cavity consists of four scatterer rods at the corner with 0.15 µm radius. The analysis is done by varying the output power with respect to the radius of scatterer rods. Moreover the structure of proposed All-optical OR logic gate has very small size of about 13µm * 8µm and operate at 1.55 µm wavelength i.e. most widely used third optical window. Optical logic gates are the fundamental components in optical digital information processing. All-optical communication is one of the solutions for the electronic bottlenecks viz speed and size .Hence, such kind of devices are very useful to Photonic Integrated Circuits for future optical networks.

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