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Asymmetrical Light Propagation in 2D Photonic Crystal Structure

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Abstract

In this work, using Plane Wave Expansion (PWE) and two-dimensional Finite Difference Time Domain (2D-FDTD) methods, we design a structure that shows the high asymmetry in propagation of light. Structure is based on two-dimensional Photonic Crystal (2D-PC) consisting of square lattice $(39\ X\ 39)$ *of infinitely long circular rods of refractive index 2.9 in the background of refractive index 1. Radius of rods is* $0.15a$*, where a is the lattice constant and chosen as 0.5 μm. To achieve the asymmetry in propagation of light, shape of rods of one of the diagonals of the proposed structure are modified from circular to elliptical. Structure is having less footprint area and high signal contrat ratio. Observed signal contrast ratio is 0.549 at operating frequency* $a/\lambda = 0.569$*. Being linear and nonmagnetic, proposed structure may be useful to construct optical logical devices and circuits, and would facilitate for realization of photonic networks.*

Keywords: Photonic Crystals, Self-collimation, Two Dimenssional Finite Difference Time Domain (2D-FDTD), Plane Wave Expansion (PWE) Methods.

INTRODUCTION

Photonic crystals (PCs) are manmade crystals having periodic variation of refractive index in different directions. Depending on the variation of refractive index, these crystals have been categorized as one, two and three dimensional PCs [1–2]. PCs have gained lot of attention due to their extreme capabilies to control and manipulate the flow of light. Light can be allowed to propagate/guide through PCs using Photonic band gap guidance (PBG) and Self-collimation (SC) phenomenon, based on complex spatial dispersion properties [3]. Firstly, in PBG guidance, light of specific wavelengths (belonging to PBG) are allowed to propagate through the defects of PCs. Secondly, SC allows some specific wavelengths of light to propagate without any divergence in specific directions through the defectless PC. SC has been a matter of recent interest. Several optical devices/components like beam splitters [3–4], optical logic gates and switches [5–6], all-optical diode [7], optical junction [8] and Mach-Zhender Interferometer (MZI) [9–10] etc. have been designed and modeled using SC in PCs.

Difference in the transmission at output port, when input and output ports are interchanged, reveals asymmetric transmission or diode like behavior of light [11]. Asymmetric transmission of light has shown to be possible with nonlinear and magnetic PCs by breaking time reversal symmetry [12–15]. Low value of nonlinear susceptibility and magneto-optic coefficient of traditional materials will require high input power and high magnetic field to achieve asymmetric transmission of light. It restricts the application of these possibilities in different fields [7].

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Hence, asymmetric transmission of light obtained in linear and nonmagnetic structures is an important issue in the field of optics. For this purpose several proposals are made to realize asymmetric transmission of light in linear and nonmagnetic structures [16–18]. Based on refraction phenomenon, a system of two square PCs of the same lattice constant but different scatterer radii, which are cut and brought into contact along their body diagonals, has been investigated to facilitate unidirectional transmission of light [16]. This work shows high contrast between forward and backward propagating light but has a large foot print area. In Ref. 17, concept of unidirectional flow of light has been numerically investigated and experimentally validated in a structure made from the hetero junction between two different silicon two-dimensional square-lattice photonic crystal slabs with directional bandgap mismatch and different mode transition. Three port asymmetric ordered routing of light has been obtained in a linear, non magnetic and time independent system having diagonal interfacing of two different PCs made up of infinitely long rods of elleiptical and circular crosssection in the background of air [18]. This work demonstrates good signal contrast between forward and backward propagating signals at two sucessesive ports for wide range of frequencies.

In this paper, using Plane Wave Expansion (PWE) and two-dimensional Finite Difference Time Domain (2D-FDTD) methods, we design and simulate 2D-PC structure which offers high asymmetry in transmission of light when input and output ports are interchanged. Structure is based on two-dimensional Photonic Crystal (2D-PC) consisting of square lattice $(39 \mathrm{X} 39)$ of infinitely long circular rods of refractive index 2.9 in the background of refractive index 1. Proposed structure is completely linear and nonmagnetic, hence best suited for implimentation in future photonic circuitry.

The complete paper comprises of four sections. II section describes the design of proposed structure and presents dispersion analysis. III section deals with 2D-FDTD numerical method, investigations and discussions. Finally, conclusion of the work is given in section IV.

PROPOSED STRUCTURE AND DISPERSION ANALYSIS

Figure 1(a) shows the schematic of proposed structure. It is based on a square-lattice 2D-PC consisting of 39×39 layers of long circular rods of refractive index 2.9 surrounded by the background of refractive index 1 [18]. Circular rods are of radius $r = 0.15a$, where a is the lattice constant and is chosen as *0.5 µm*. Shape of rods of one of the diagonals of the proposed structure are modified from circular to elliptical in order to achieve the asymmetry in propagation of light. Radius of the rods of elliptical crosssection is $r_a = 0.25a$ and $r_b = 1a$ along the minor and major axis respectively. Structure is having two horizontal and vertical ports X1, X2 and Z1, Z2 respectively. Propagtaion of light in PCs is controlled by despersion surfaces. These surfaces provide a graphical representation in k space of the spatial change of spectral properties. Light propagtes in directions perpendicular to the dispersion surfaces. Crossesction of these surfaces at a constant frequency is called as Equi-frequency contours (EFCs) and are used to predict the light propagation. The direction of light propagation is given by the group velocity $\mathrm{v_g} = \nabla_\mathrm{k}\omega(\mathrm{k})$, which is perpendicular to the EFCs. SC is offered for the frequency for which shape of EFC is flat [18–19]. The EFCs can be obtained using the plane wave expansion (PWE) method [20]. We obtain EFCs for 2D transverse electric (TE) mode (the electric field is parallel to the length of the rods) and those are shown in Figure 1(b). It is clear in Figure 1(b) that for frequency $\mathrm{a}/\lambda = 0.569,$ the shape of EFC in ΓX and ΓX1 directions is a almost straight line and therefore enables light to self-collimate through the structure in both the directions.

NUMERICAL INVESTIGATIONS AND DISCUSSIONS

Two-dimensional Finite Difference Time Domain (2D-FDTD) method [21–22] solves Maxwell's equation in space and time domain and is used here to investigate light propagation through the proposed structure. FDTD method is powerful numerical technique enables real time analysis of the complex structures. It is a well known method and presented here for the sake of clearity. Maxwell's curl equations in source free region, can be arranged in the following form [22]

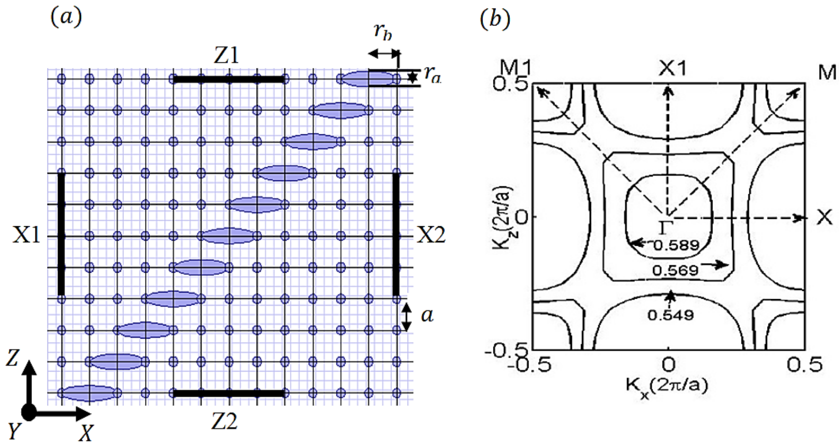

Figure 1. (a) shows schematic of designed structure which is based on a square-lattice 2D-PC consisting of 39×39 layers of long circular rods of refractive index 2.9 surrounded by the background of refractive index 1 and (b) shows Equi-frequency Contours for TE polarization of designed structure. For frequency $a/\lambda = 0.569$, the shape of EFC in ΓX and $\Gamma X1$ directions is a almost straight line which enable light to self-collimate through the structure in both the directions.

$$\frac{\partial \boldsymbol{H}}{\partial t} = -\frac{1}{\mu}\nabla \times E - \frac{\rho}{\mu}H \tag{1}$$

$$\frac{\partial E}{\partial t} = \frac{1}{\epsilon}\nabla \times H - \frac{\sigma}{\epsilon}E \tag{2}$$

Where ε, μ, σ and ρ are the permittivity, permeability, electric conductivity and equivalent magnetic conductivity of the material, respectively.

In 2D-FDTD method for TE mode, Maxwell's equations can be written as

$$\frac{\partial E_y}{\partial t} = \frac{1}{\epsilon}\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - \sigma E_y\right) \tag{3}$$

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_y}{\partial z} - \rho H_x\right) \tag{4}$$

$$\frac{\partial H_z}{\partial t} = -\frac{1}{\mu}\left(\frac{\partial E_y}{\partial x} + \rho H_z\right) \tag{5}$$

Solution of equations (3), (4) and (5) could be obtained with the help of Yee's Algorithm by discretizing in space and time [23].

Further, in order to obtain the stable results in FDTD, The spatial and temporal steps are related through the following equation and known as Courant stability condition [24]

$$c\Delta t \le \frac{1}{\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta z^2}}} \tag{6}$$

where c is the speed of light in vacuum and Δx and Δz are the spatial grid size in the x and z directions, respectively and chosen to $a/20$. Δt is temporal step. FDTD method commonly encounter problem of back reflections from the boundaries of the simulation domain. In order to avoid the back reflections from the end of simulation boundaries, Perfectly Matched Layers [PML] are used [25–26]. Plane of propagation of light is X-Z plane. We mention here that Optifdtd module (32 bit) of Optiwave simulation software have been used to simulate/investigate the proposed structure.

We mention that, considered input is a TE polarized continuous wave (CW) Gaussian beam of normalized frequency $a/\lambda = 0.569$. Half width of CW Gaussian beam is chosen to $2.5a$. To measure the transmission at the different ports, power monitors (shown with thick black solid lines in Figure

1(a)) of width $16a$ have been placed at different ports X1, X2 and Z1, Z2. Normalized transmission is calculated by taking the ratio of steady-state power at different ports to steady-state power at input port.

Firstly, we launch input at horizontal port X1 of the designed structure. Light is self-collimating in ΓX direction through the structure. When it arrives at the diagonal layer of the structure consisting of elliptical rods, it divides into three orthogonal parts. Steady state electric field profile at different ports is shown in Figure 2a. It is clear from Figure 2a that after passing through the diagonal layer, most of light incident at horizontal port X1 appears at horizontal port X2. Only a small portion of light can be seen at vertical ports Z1 and Z2. Steady-state normalized transmission at port X2, Z1, and Z2 are 0.712 (71.2%), 0.184 (18.4%), and 0.0652 (6.52%) respectively.

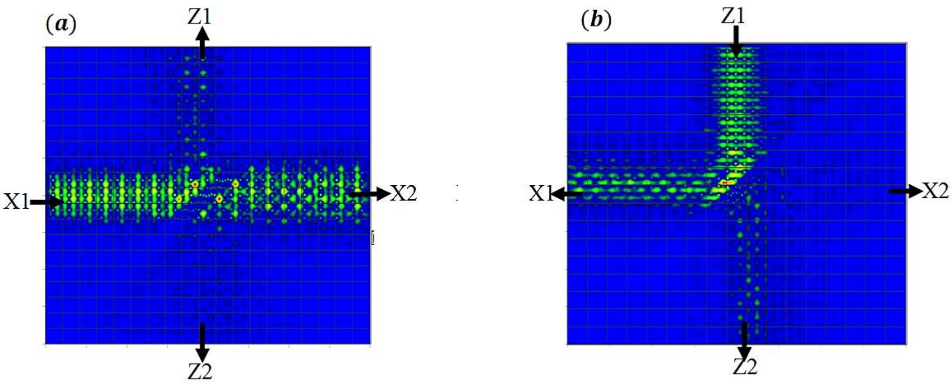

Figure 2. (a) shows steady-state electric field profile at different ports when light of normalized frequency $a/\lambda = 0.569$ is launched at horizontal port X1. Steady-state normalized transmission at horizontal port X2, vertical ports Z1, Z2 are 0.712 (71.2%), and 0.184 (18.4%), 0.0652 (6.52%) respectively. (b) when same light is launched from vertical port Z1 in downward direction, steady-state normalized transmissions at vertical port Z2, and horizontal ports X1, X2 are 0.236 (23.6%) and 0.633 (63.3%), 0.0291 (2.91%) respectively.

Now, we launch input from vertical port Z1 in downward direction. Steady-state electric field pattern for this case is obtained and presented in Figure 2b. Light is self-collimating in $\Gamma X1$ direction. When it reaches to the diagonal layer, it divides in three parts. As per symmetric propagation of light, most of the portion of the light is to be appearing at vertical port Z2 and remaining at other horizontal ports X1 and X2. However, as can be seen in Figure 2b, most of the light appears at horizontal port X1. Steady-state normalized transmissions at port Z2, X1, and X2 are 0.236 (23.6%), 0.633 (63.3%), and 0.0291 (2.91%) respectively. Clearly, designed structure shows asymmetric transmission of light. Here It is worth to mention that asymmetry in transmission of light is due to shape of the diagonal rods. It would not be possible if the diagonal rods are to be taken as circular. Signal contrast ratio (C)between any two cyclic ports, is defined as $C = (T_F - T_R/T_F + T_R)$, where T_F and T_R represent normalized transmission in forward and reverse direction, respectively [16]. Signal contrast ratio between ports X1 and Z1 of the proposed structure is 0.549 at operating frequency $a/\lambda = 0.569$.

CONCLUSION

In conclusion, asymmetric transmission of light on interchanging input and output ports, in linear and non-magnetic 2D-PC has been obtained. Plane wave expansion (PWE) and two dimmensional finite difference time domain (2D-FDTD) numerical methods have been used for design and simulation of the proposed structure. The designed structure offers high asymmetry in light propagation and has less footprint area. Observed signal contrast ratio is *0.549* at operating frequency $a/\lambda = 0.569$. Proposed structure may be useful to construct optical logical devices and circuits, and would facilitate for realization of photonic networks.

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