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Modeling of 2D photonic crystals waveguides

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Abstract

Photonic crystals are nanometric structures which are composed of periodic elements of different permittivity in two or three dimensions. The periodic variation of the refractive index prevents the propagation of electromagnetic waves of certain frequencies. This implies the existence of photonic band corresponding to the frequency band in which the radiation cannot propagate. Their guide mechanism is completely different from that existing in conventional waveguides, since it is not the total reflection due to the difference in refractive indices which ensures the guiding, but the existence of a photonic band gap. This property is based on the design and development of new components based on photonic crystals for optoelectronics applications. In this paper, the parameters of structures, and the electromagnetic field propagation analyze, are determined based on 2D photonic crystal. Several guiding structures two-dimensional photonic crystals (W1 waveguide, the photonic crystal (PhC)-based L-junction waveguide T-shaped and waveguide intersection) and their electromagnetic fields distribution are optimized, using FDTD method (Finite Difference Time Domain) method and the software RSOFT with its simulation modules BandSolve, FullWAVE.

Keywords: 2D Photonic Crystal; FDTD; waveguide; T-shaped

1. Introduction

Photonic crystals are the analog of semiconductors for controlling photons. These dielectric materials have a refractive index varies periodically according to the different spatial directions and present photonic energy bands for electromagnetic waves. They create now a new materials class for optoelectronics and integrated optics. Otherwise, in some domain of wavelength of the order of the material period, the light cannot propagate in them and will be reflected whatever its incidence. The concept of photonic crystals has been proposed for the first time in 1987 by Eli Yablonovitch and S. John [1, 2]. Rayleigh [3] demonstrates that a periodic structure, Bragg mirror type, can create a frequency band in which the electromagnetic propagation is impossible for all incident angles and polarizations, in one or more frequency bands. High transmission unidirectional mirrors and waveguides with low losses or original properties of light refraction, these photonic crystals allow the control and manipulation of light for optical telecommunications applications. Three-dimensional photonic crystals, the only ones that provide a photonic band gap whatever the direction of propagation of the light wave in space, are especially difficult to manufacture. However, two-dimensional photonic crystals can be manufactured using techniques commonly used in nano-optics. It is for this reason that this type of photonic crystals has been the most studied until now, particularly in guided optic.

2. Two-dimensional photonic crystal waveguides

Researchers have often concentrated on 2D structures since the two-dimensional photonic crystals are excellent mirrors in the photonic band gap and they can guide a light signal and manipulation of waves optical. Two-dimensional structures are periodic in two directions in space, and endless following the third. 2D PhCs have two types of configurations: rode-type-2D photonic crystals (disconnected structure) are constructed by periodic arrays of dielectric rods with a high refractive index embedded in the background material with a low refractive index. The hole-type photonic crystal (connected structure) is described by periodic arrays of cylindrical air holes pierced in a background material with a high refractive index (Fig.1). This structure has relatively simple geometry that facilitates the theoretical and experimental studies.

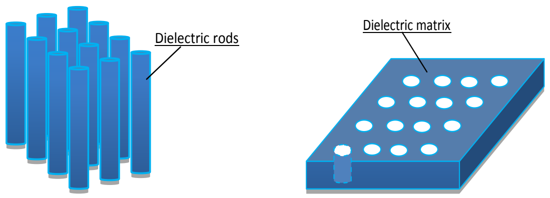


Figure 1. Two-dimensional periodic structure: rods-type-2D and hole-type-2D photonic crystal

Guiding and confining light using waveguides are two fundamental optical functions that enable a range of all-optical devices to be created. A structure that has recently attracted a lot of attention is photonic waveguide of two-dimensional. Photonic waveguides are used in many other devices such as waveguide laser, junctions, waveguides can also be employed for splitting and combining light beams (integrated optical interferometers). In the future generation, silicon waveguides in electric circuit may be used for fast optical data transmission. The think of using line defects in photonic crystals to guide light was proposed by Meade et al. [3]. Mekis et al. [4] have developed the theoretical foundation of understanding 90 bends in the 2D photonic crystals.

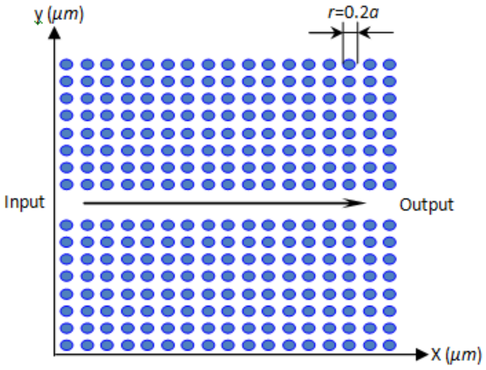


Figure 2. Structure of a two-dimensional photonic crystal (PC) waveguide disconnected.

Two-dimensional PCs waveguides are obtained by creating a line defect in a two-dimensional crystal. Among these effects, modes having a frequency within the photonic band gap may exist. This linearity of defects can guide the propagation of light in a chosen direction. A photon will remain confined in the guide if its energy is located within the band gap. The guidance process in these waveguides is based on the existence of an omnidirectional band gap in the plane and the guide is modulated in the propagation direction. This results in special properties such as the existence of mini band gaps due to this modulation or the appearance of guide modes with low group velocity.

The study of guided modes in photonic crystal waveguides is very important for understanding the propagation of the electromagnetic wave, properties of photonic band gap and the light signal transmission. For this reason, that we based ourselves on numerical methods effective for the modeling of these photonic structures.

3. Modeling methods

Modeling of photonic crystals properties, to calculate the electromagnetic field and the band gap as a function of the structure size, usually requires a large investment in programming and numerical analysis. The main calculation tool used to study our structures is Finite Difference Time Domain (FDTD). Simulation using FDTD method is the most used technique in optical system [5]. The first algorithm was proposed by Yee in 1966 [6]. Many researchers use this method to solve Maxwell's equations [7]. The FDTD method decomposes the space-time in a grid of elementary cells. For this, a mesh of the real space is performed to truncated the fields and calculate their derivatives. Fields are calculated in transient state to establish the spectrum which is performed by the Fourier transform. FDTD not only allows the calculation of band diagrams but also used to simulate the light propagation in photonic crystals structures.

In the field calculation algorithm (Fig.3), perfectly matched layers (PML) are used as absorbing boundary conditions. PML layers are absorbs the total fields at the edges of our structure and set the field values to zero. This technique is based on reflection free truncation of the computational domain. So, the typical value of the thickness of the perfectly matched layers is 6 grid cells to provide the reflection free truncation.

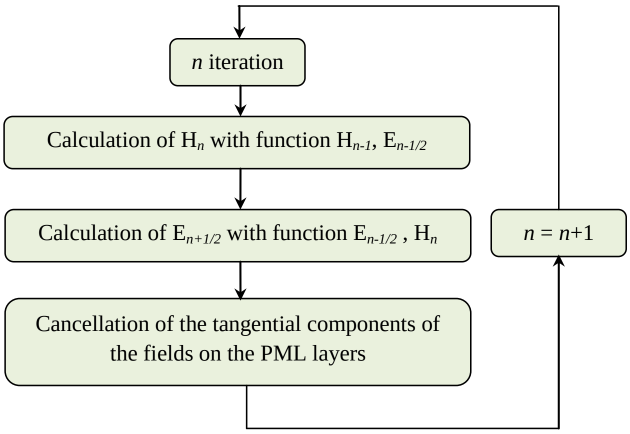


Figure 3. Fields calculation algorithm by FDTD

Absorption of the PML layers is introduced due to the conductivity of our material, i.e., the conductivity is different for different propagation directions, so each electromagnetic field component is subdivide according to the following equations:

$$\begin{cases} \varepsilon \dfrac{\partial E_{xz}}{\partial t} + \sigma_z E_{xz} = -\dfrac{\partial (H_{yx} + H_{yz})}{\partial z} \\ \varepsilon \dfrac{\partial E_{yz}}{\partial t} + \sigma_z E_{yz} = \dfrac{\partial (H_{xy} + H_{xz})}{\partial z} \\ \varepsilon \dfrac{\partial E_{yx}}{\partial t} + \sigma_x E_{yx} = -\dfrac{\partial (H_{zx} + H_{zy})}{\partial x} \\ \varepsilon \dfrac{\partial E_{zx}}{\partial t} + \sigma_x E_{zx} = \dfrac{\partial (H_{yx} + H_{yz})}{\partial x} \\ \varepsilon \dfrac{\partial E_{xy}}{\partial t} + \sigma_y E_{xy} = \dfrac{\partial (H_{zx} + H_{zy})}{\partial y} \\ \varepsilon \dfrac{\partial E_{zy}}{\partial t} + \sigma_y E_{zy} = -\dfrac{\partial (H_{xy} + H_{xz})}{\partial y} \end{cases} \qquad (1.a)$$

$$\begin{cases} \mu_0 \dfrac{\partial H_{xz}}{\partial t} + \sigma_z^* H_{xz} = \dfrac{\partial \left(E_{yx} + E_{yz} \right)}{\partial z} \\ \mu_0 \dfrac{\partial H_{yz}}{\partial t} + \sigma_z^* H_{yz} = -\dfrac{\partial \left(E_{xy} + E_{xz} \right)}{\partial z} \\ \mu_0 \dfrac{\partial H_{yx}}{\partial t} + \sigma_x^* H_{yx} = \dfrac{\partial \left(E_{zx} + E_{zy} \right)}{\partial x} \\ \mu_0 \dfrac{\partial H_{yx}}{\partial t} + \sigma_x^* H_{yx} = \dfrac{\partial \left(E_{zx} + E_{zy} \right)}{\partial x} \\ \mu_0 \dfrac{\partial H_{xy}}{\partial t} + \sigma_y^* H_{xy} = -\dfrac{\partial \left(E_{zx} + E_{zy} \right)}{\partial y} \\ \mu_0 \dfrac{\partial H_{zy}}{\partial t} + \sigma_y^* H_{zy} = \dfrac{\partial \left(E_{xy} + E_{xz} \right)}{\partial y} \end{cases} \qquad (1.b)$$

Where μ_0 and ε_0 are the permittivity and permeability of free space, respectively. ε_r is the relative permittivity of the medium considered ($\varepsilon_0 \varepsilon_r = \varepsilon$). σ_x, σ_y and σ_z are electric conductivities and σ_x^*, σ_y^* and σ_z^* are magnetic conductivities within directions x, y and z, respectively.
These field components can be takes the following form:

$$\begin{cases} E_x = E_{xy} + E_{zx} \\ E_y = E_{yx} + E_{yz} \\ E_z = E_{zx} + E_{zy} \end{cases} \qquad (2.a)$$

$$\begin{cases} H_x = H_{xy} + H_{xy} \\ H_y = H_{yx} + H_{yz} \\ H_z = H_{zx} + H_{zy} \end{cases} \qquad (2.b)$$

In Transverse Magnetic (TM), the electromagnetic field reduces to three components H_y, H_x and E_z and in Transverse Electric (TE), the electromagnetic field reduces to E_y, E_x and H_z.

The computation area with perfectly matched layer of a photonic crystal waveguide we consider is shown in Figure.4 with PML regions A, B, and C (the four corner regions). This figure shows the original photonic crystal structure remains as is, and defined PC based PML
The PML parameters are defined by the following equation [8]:

$$S_i = 1 - j \frac{3\lambda}{4\pi n e} \left(\frac{\rho}{e} \right)^2 ln \frac{1}{R} \qquad (3)$$

Where
S_i: are PML parameters according to 3 axes (S_x, S_y, S_z) and $S_z = 1$
λ : is the wavelength
n : is the refractive index of the medium in the adjacent computational domain
ρ : is the distance from the beginning of the PML
e : is the thickness of PMLs
R : is the theoretical reflection coefficient for the normal incident wave at the interface of the PML and the computational domain., in our structure equals to 10^{-9}

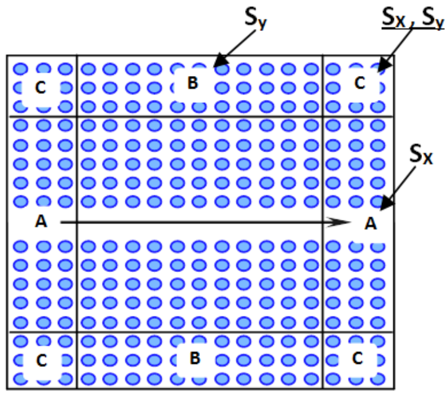


Figure 4. The computation areas of perfectly matched layer (PML)

4. Results and discussion

From an optical point of view, a photonic crystal is characterized by its band gap. We calculated by modeling technique FDTD with perfectly matched layers (PML) by Matlab software, the 2D band structures of a square lattice in both polarization modes. A band structure, or dispersion relation defines the electromagnetic wave propagation in a two-dimensional photonic crystal is described by a PBGs which relates the frequency of modes or normalized frequency ω*a*/2πc=*a*/λ (axis y), to the wave-vectors k=2π/*a* (axis x). Where λ is the wavelength of light in vacuum and *a*=1μm is the lattice period. The way made by the wave vector when it describes the contour formed by the high symmetry points Γ, X, M of the first Brillouin zone.

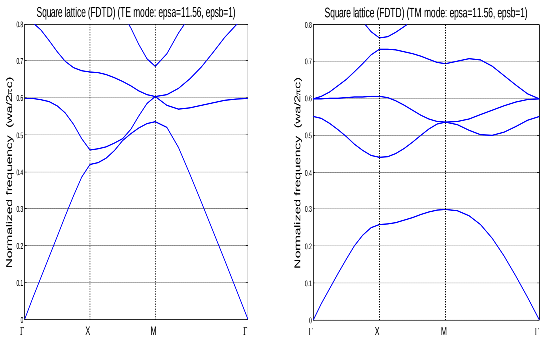


Figure 5. Band structure of a disconnected 2D square lattice for both TE and TM polarizations

The PBGs of 2D-photonic crystals are calculated for both polarization TM, in which the magnetic field is in the (x,y) plane and the electric field is perpendicular z (parallel to the rods), and polarization TE, in which the electric field is in the plane.

Figure.5 shows the band structure of a two-dimensional photonic crystal of a disconnected square lattice composed of dielectric rods (relative permittivity equals to 11.56) in air with radius of the rod r/*a* =0.2 [9]. The band structures in two polarizations modes should be superimposed to form a total band gap. In this case the diagrams of this structure reveal a large band gap for the TM polarization in frequency range [0.2948-0.4393] ω*a*/2πc, This frequency domain corresponds to the range wavelengths [2.27-3.29]µm for the two directions ΓX and ΓM, and get at the guided optics domain including 1.55µm, contrary to TE mode where no band is observed.

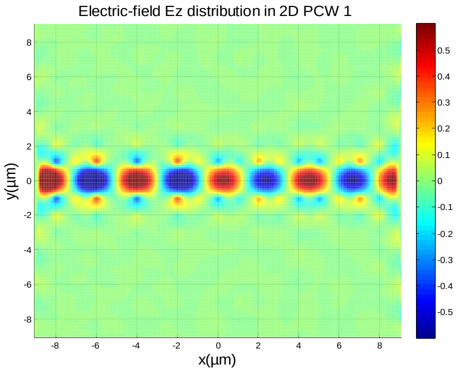


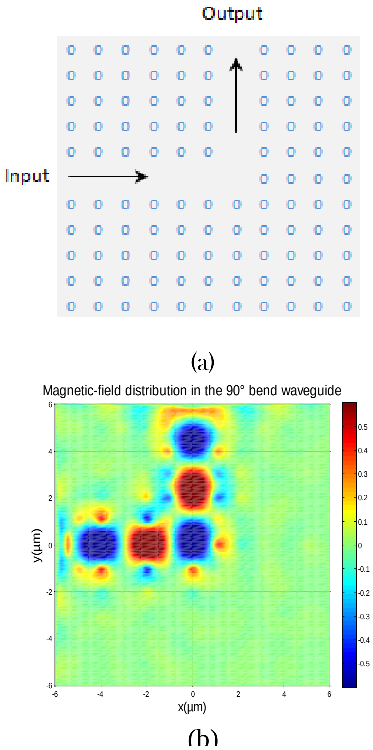
Figure 6. Electric-field distribution in two-dimensional photonic crystals waveguide (PCW1)

The two-dimensional photonic crystals waveguide use extended defects for trapping light in photonic structures and also guiding light. Thus, a linear defect is introduced (removing a row of dielectric rods) into 2D photonic crystal to guide light along the z direction. A sinusoidal source adjusted on the defect and radiates at a frequency belongs into the band gap cannot propagate in the rest of the crystal.

Our photonic crystal waveguide structure (Fig.2) is constituted by central horizontal line, which is removed to form a waveguide which the light in z direction is guided with the angular frequency ω= 0.36.

This linear defect in the periodic structure acts as photonic crystals waveguide is called guide W1. It is shown in Fig. 6 that for frequencies within the band gap of the crystal, the light cannot propagate in (x, y) plane, and it is confined by the index contrast in direction z. So, we modelled this structure by the FDTD method, and determined the distribution of the electric field E_z for several guiding structures based on a disconnected two-dimensional photonic structure. The photonic crystal is composed of a cylindrical dielectric rods lattice of silicon (n=3.4) of periodicity a=1µm and we use a finite-size structure (17× 17 rods in air) [10].

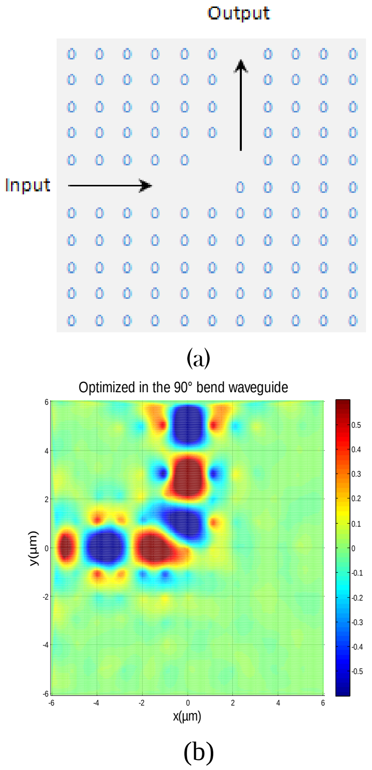
In this guide, the confinement is due to a photonic band gap effect, this is an advantage compared to conventional guides. The electromagnetic modes introduced by the removing row are called defect modes. It is a mode in which the frequency can be situated into the band gap and is located around the defect site. From this guide we can also achieve a curved guide [11].



(a)

(b)

Figure 7. (a).Bend 90° structure, (b).Magnetic-field distribution of waveguide bends 90° (L-shaped)



(a)

(b)

Figure 8. (a).Optimized bend 90° structure, (b).Magnetic-field distribution of waveguide bends 90° (L-shaped)

The bend is composed of two arms forming between them a 90° bend and the light cannot penetrate within the photonic crystal; it is constrained to propagate along the bend. Experiments in the wave guiding demonstrated a transmission of about 80% for 90∘-bend structures [12].

In 90° (L-shaped) bent photonic crystal waveguide (Fig.8), the optimization was performed at corner with the mirror (changed of the rod at the corner of bend) and the only mode that exists at is the single-mode.

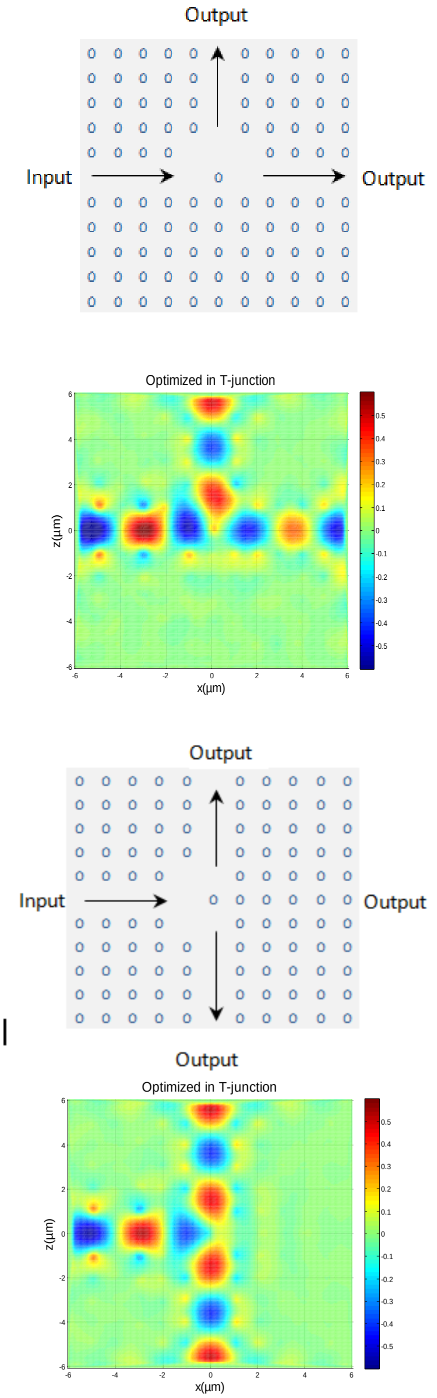


Figure 9. Optimized waveguide structures and magnetic-field distribution in the waveguides type T

Our aim is to optimize such a bend waveguide to reduce the bending losses as the wave is guided through the bend and increases the transmission spectrum. Using a finite-difference time-domain method, we have simulated by Matlab software the various structures of waveguides based on 2D photonic crystals.

Figure 9 shows the optimization of the magnetic field distribution for photonic crystal waveguide consisting of a square lattice of dielectric rods (ε=11.4) in air and normalized frequencies equal to 0.38. Waveguide types T in a two-dimensional photonic crystal consist of one input port only and two output port. So the figure 10 shows the optimization of the magnetic field distribution for 2D waveguide intersection consists of one input port only and three outputs port.

In this optimization, we changed of the rod at three corner of bend and it is seen that with this structure a better optimization can also be obtained for improvement of photonics structure and its transmission since light cannot escape, light will propagate without any loss in the waveguide [13].

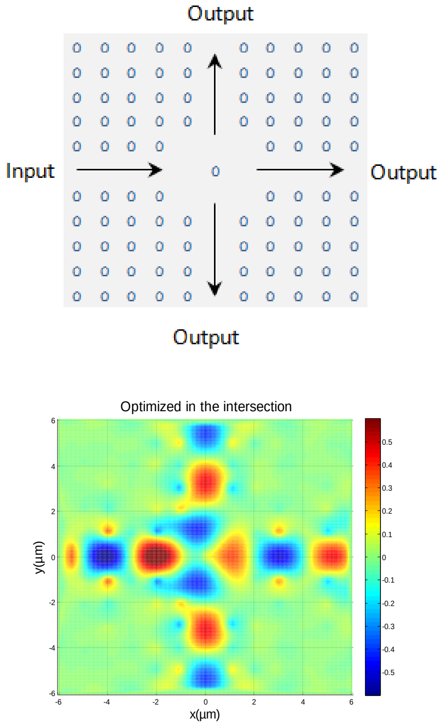


Figure 10. Optimized waveguide structure and magnetic-field distribution in the waveguide intersection

The intersection is created by two orthogonally crossing straight photonic crystal waveguides, for which the band gap in the bulk material prevents any radiation losses and allows the improvement of the quality factor. The principle is to optimize the structure for guided the EM wave propagation direction lossless.

The T-shaped photonic crystal junctions have an important role in PC based nano-optic and the study of future integrated photonic devices [14]. A photonic crystal (PC)-based T-junction has been investigated during the past years, proposed for to expanded range of transmission power [15]. Due to their important role in guided optical, we demonstrated a new photonic crystal (PC)-based T-junction for control the flow of EM waves of power output [16]. We proposed T-Shaped structure composed an input port only and two output ports. For this structure, electromagnetic field has been analyzed with software RSOFT using the impulse signal. The dimension frequency is equal to a/λ, where a = 664.8 nm is the lattice constant of the rods and λ is the wavelength of the propagation equal to 1547 nm.

The band diagram is calculated for both polarizations, TE in which the electric field is in the plane (x, y), and the magnetic field is perpendicular of z (parallel to the rods) and TM, in which the magnetic field is in the plane and the electric field is perpendicular z axis. The normalized frequency is plotted along the high symmetry point's ΓXMΓ of irreducible Brillouin zone. The frequency game obtained from the band diagram of square PC lattice in figure.11 is [0.3052-0.4408] a/λ. So, this frequency domain corresponds in optic guided including 1550nm.

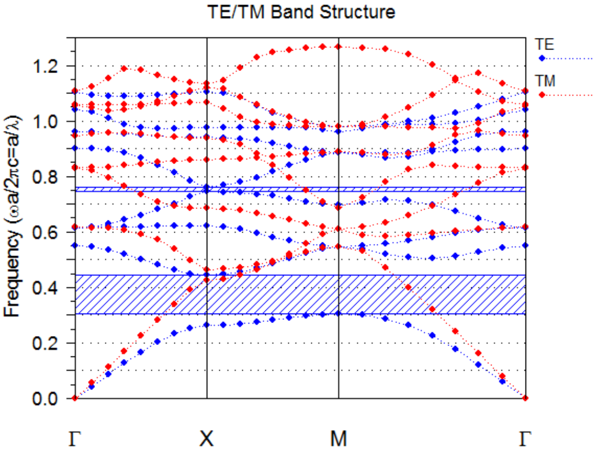


Figure 11. Band diagram for a PC a square lattice of GaAs rods

A schematic structure of a photonic crystal T-Shaped is shown in figure.12, which is formed of a two waveguides L-Shaped in a 2D PC consisting of a square lattice of dielectric rods of GaAs (refractive index n=3.4) in air. The radius of the rods is r = 0.19a.

Table 1. Design parameters of the T-Shaped

Parameters	values
Rod shape	Circular
Lattice structure	Cubic/square
Lattice constant	664.8nm
Radius of the rod	0.19 a
Refractive index of the rod	3.4
Dielectric constant of GaAs rods	12.6
Radius of the central rods r_1, r_2	0.077a

In this figure a basic T-junction is introduced in the 11×11 square lattice PC structure by removing rods in the L-shape. A Gaussian wave corresponding to the forbidden mode in the lattice is launched with unit power. The design parameter of the proposed our structure is listed in Table 1.

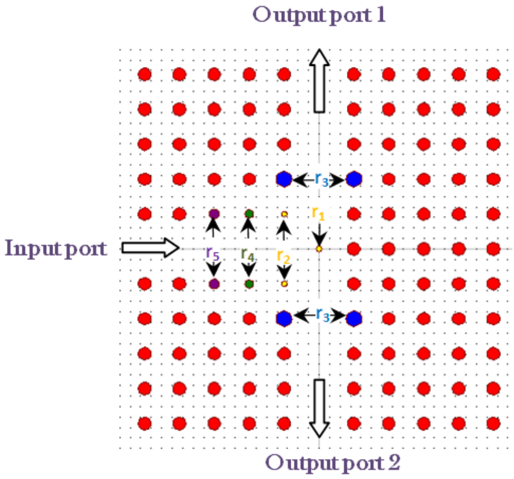


Figure 12. The T-shaped photonic crystal topology designed for TM polarized incident light.

In this structure, rod radii are r_1 = r_2= 0.077a, r_3 = 0.225 a, r_4 = 0.121a, r_5 = 0.142 a, and r_1 = 0.077 a is the radius of the coupled linear waveguide, where a is the lattice constant.

To illustrate the optimization of our T-Shaped, we show the electric field distribution in Figure. 13.

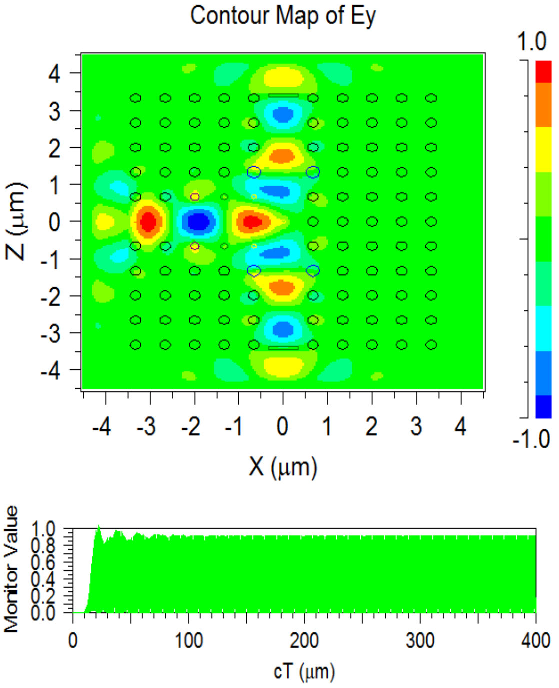


Figure 13. The Electric field distribution for the optimized T-shaped photonic crystal

The reference [16] shows that transmitted powers to each of outputs are equal to 49% of input power. Therefore, efficiency is very high and about 98% for the wavelength of 1550 nm. Our simulation results show that adding rod only in the junction section can enhance the electromagnetic fields and increase in transmission power of output ports >49% more than 20%. The radius of these rods is determined from the optimization process.

5. Conclusion

Confinement of light to nanostructures has important implications for optical guided. So, waveguide structures are used for confine light in the PBG structure and control the propagation of the light.

The two-dimensional photonic crystals waveguide (2D PCWG) defined in a disconnected structure shows that guidance is optimized for several geometries: have been optimized the bend structure to reduce the bending losses and reflections induces for increase the bandwidth and to achieve a level of the transmission 100%. The structure at intersection is modified to control the flow of EM waves.

To obtain high transmission in a large frequency range, we realize an optimization by modifying of radium of dielectric-rods in T junction .This structure is useful in designing all-optical signal processing circuits, optical computer systems and the logics functions : XOR" and "AND.....

References

[1] E. Yablonovitch, Phys. Rev. Lett., 58, (1987)2059

[2] S. John, Phys. Rev. Lett., 58, (1987)2486

[3] R. D. Meade, A. Devenyi, J.D. Joannopoulos, O. L. Alerhand, D. A. Smith ey K. Kash, J. App. Phys. 75, (1994)4753

[4] A. Mekis, J. C. Chen, I. Kurland, S. Fan, P. R. Villeneuve, and J. D. Joannopoulos, Phys. Rev. Lett., 77, (1996)3787–3790

[5] A. N. Bogolubov, G. V. Belokopytov, and Z. O. Dombrovskaya, Moscow University Physics Bulletin, , 68, 5, (2013)344–350

[6] Kane S. Yee, IEEE Transactions on Antennas and Propagation, 14, (1966)S. 302-307

[7] ShangpingGuo, Feng Wu, SachariaAlbin, RbertS. Rogowski, Optics Express, 12, (2004)1741

[8] C. P. Yu and H. C. Chang, "Opt. Express, vol. 12, (2004)6165–6177

[9] A. Ghaffari, F. Monifi, M. Djavid and M. S. Abrishamian, Journal of Applied Science, 8(8), (2008)1416-1425

[10] Shahrbanoo, Ghorbanzadeh, Journal of Basic and Applied. Appl. Sci. Res., 3, (2013)734-737

[11] L. Dekkiche, R. Naoum, journal of applied sciences, 8(13), (2008)2449-2455

[12] S-Y. Lin, E. Chow, V. Hietala, P. R. Villeneuve, and J. D. Joannopoulos, Science 282, (1998)274-276

[13] Zhen Hu and Ya Yan Lu, Journal of the Optical Society of America B, 29, (2012)1356-1360

[14] E. haq Shaik, N. Rangaswamy, IEEE International Conference on Industrial and Information Systems (ICIIS), 2017.

[15] S. Foghani, H. Kaatuzian, M. Danaie, Optica Applicata, XL(4), 2010.

[16] M. Danaie , R. Nasirifar, A. Dideban, Turkish Journal of Electrical Engineering & Computer Sciences, 25, (2017)4398-4408