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Compact and Integrated Routing Photonic Crystals Structures Design Using the Two-dimensional FDTD Method

Hadjira Badaoui*, Mohammed Feham* and Mehadji Abri**

* Laboratoire STIC, Département de Génie Electrique et d'Electronique
Faculté de Technologie, Université Abou-Bekr Belkaïd –Tlemcen-Algeria
** Laboratoire de Télécommunication, Département de Génie Electrique et d'Electronique
Faculté de Technologie, Université Abou-Bekr Belkaïd –Tlemcen-Algeria

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ABSTRACT

The goal of this paper is to design and optimize compact Photonic Crystal structure used for routing light. In particular, we focus on the design of a brick that will form the PhCs network, ie a waveguide W1KA and double bends. Photonic crystals are considered a good way for realizing compact optical waveguides and bend. The PhC consists of a triangular array of holes etched into InP/GaInAsP/InP heterostructure. Propagation characteristics of proposed devices are analyzed utilizing two-dimensional finite difference time domain (FDTD) method. The FDTD method will easily perceive the mechanisms involved in these devices. The PhCs transmission properties are then presented and discussed.

Corresponding Author:

First Author,
Laboratoire STIC, Département de Génie Electrique et d'Electronique
Faculté de Technologie, Université Abou-Bekr Belkaïd -Tlemcen
BP 230, Pôle Chetouane, 13000 Tlemcen- Algeria
Email: elnbh@yahoo.fr

1. INTRODUCTION

Photonic crystals (PhCs), composed of periodic dielectric materials, have been intensively studied in the past decade, because they possess many unique properties to control the propagation of electromagnetic (EM) waves. For instance, it has been demonstrated in PhCs the prohibition of propagating modes at certain frequency regions (the so-called photonic band gap), inhibition of spontaneous emission, and localization of EM waves in cavities [1, 6]. It may very well be possible to create large-scale photonic integrated circuits (PICs) based on PhCs and to improve the performance and cost efficiency of photonic systems.

A PhCW is constructed by introducing a line defect into a perfect PhC to create defect modes within the photonic band gap; thus, the EM wave propagating in the PhCW is guided by the band gap, instead of index-guided as in traditional waveguides. PCWs have various unmatched features such as extremely slow group velocity and zero loss at sharp bends. Many compact photonic devices based on PhCWs have been proposed, e.g., bends, splitters, Mach-Zehnder devices and dispersion compensators [7-11].

Photonic crystals (PhCs) are structures whose dielectric index varies periodically across the wavelength. Indeed photonics engineering such as fiber optics, filters, lasers, amplifiers, microresonators, polarizers and rotators, etc., follow this property to control the light propagation. In a simple vision, simply introduce periodicity defects in selected areas within the crystal to achieve the desired optical components (guides, bends light ...), and pair them to form a true photonic circuit. In particular, the design and implementation of efficient optical waveguides by inserting a linear defect in a triangular 2D periodic lattice where it is expected the existence of localized modes along the linear defect in a selected direction. The various components are produced from as linear defects.

In this paper an attempt was made to design compact Photonic Crystal structure used for routing ie a wave guide W1KA and double bends with optimized transmission characteristics. The simulation was performed using the Two-dimensional finite difference time domain (FDTD) method..

2. TWO-DIMENSIONAL FDTD METHOD

In the presence of non vanishing conductivity, the 2D FDTD time stepping formulas for the TE modes are [12] :

$$H_z\Big|_{i,j}^{n+1/2} = H_z\Big|_{i,j}^{n-1/2} + \frac{\Delta t}{\mu}\left(\frac{E_x\Big|_{i,j+1/2}^{n} - E_x\Big|_{i,j-1/2}^{n}}{\Delta y} - \frac{E_y\Big|_{i+1/2,j}^{n} - E_y\Big|_{i-1/2,j}^{n}}{\Delta x} \right) \tag{1}$$

$$E_x\Big|_{i,j}^{n+1} = E_x\Big|_{i,j}^{n} + \frac{\Delta t}{\varepsilon_{i,j}}\left(\frac{H_z\Big|_{i,j+1/2}^{n+1/2} - H_z\Big|_{i,j-1/2}^{n+1/2}}{\Delta y} \right) \tag{2}$$

$$E_y\Big|_{i,j}^{n+1} = E_y\Big|_{i,j}^{n} + \frac{\Delta t}{\varepsilon_{i,j}}\left(- \frac{H_z\Big|_{i+1/2,j}^{n+1/2} - H_z\Big|_{i-1/2,j}^{n+1/2}}{\Delta x} \right) \tag{3}$$

The numerical algorithm defined by equations (2) and (3) imposes an upper bound on the time step size defined by:

$$\Delta t \le \frac{1}{c\sqrt{\left(\frac{1}{\Delta x}\right)^2 + \left(\frac{1}{\Delta y}\right)^2}} \tag{4}$$

Where c is the light speed, to satisfy the numerical stability condition and Δx and Δy are the intervals between two neighboring grid points along the x- and y-directions in the xy-coordinate system, respectively.

With $\Delta x = \Delta y \le \frac{\lambda}{10 . \sqrt{\varepsilon_r}}$

The algorithm of FDTD-2D, presented in the form shown in fig. 1 allows getting the temporal evolution of electric and magnetic fields.

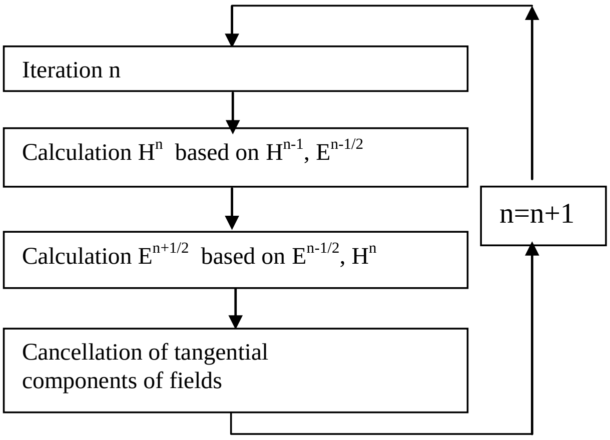


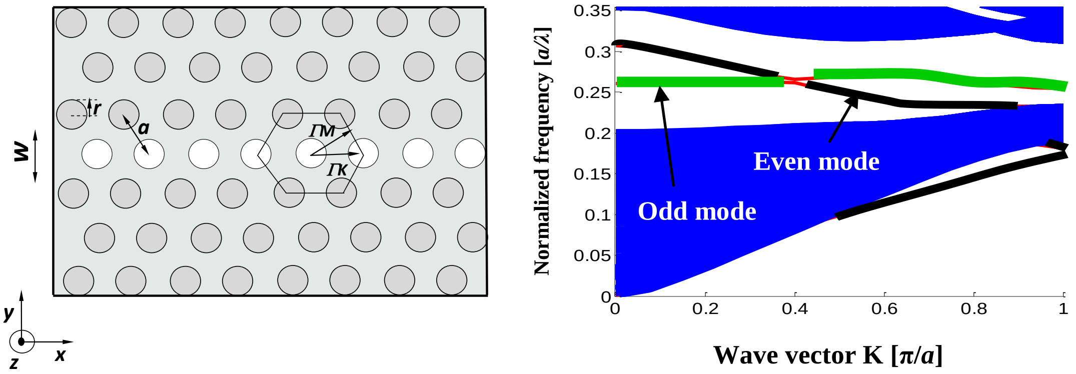
Figure 1. Fields calculating algorithm

This paper presents only the conditions of absorption-type wall [8] that simulate an infinite domain containing the entire structure study by investigating the lowest reflection digital interfaces.

3. SIMULATION RESULTS AND DISCUSSION

3.1. Wave guide design

For simplicity, only a 2D photonic crystal is considered in the present paper. Figure 2 (a) shows the design of the triangular photonic-crystal wave guide. The 2D PhC structure support a photonic band gap in the region 0.23<c/a<0.34 for TE polarized light. Even a W1KA PhC waveguide has two guided modes, as shown in Figure 2 (b) (The guided modes in the PhC waveguide are calculated using the PWE method [13]). However, these two modes have different symmetries (even and odd) with respect to the center line parallel to the waveguide. With carefully chosen input light, only the fundamental (even) guided mode will be excited. Therefore, the W1KA waveguide can be considered as a single mode waveguide in this case. The waveguides, which are obtained by removing one or several rows of rods, are along the direction of the longer side of the computational domain. We design a W1KA waveguide with a triangular lattice of air holes. The dielectric material has a dielectric constant of 10.5 (that is, refractive index of 3.24, which corresponds to the effective refractive index in an InP/GaInAsP/InP structure) to obtain a complete photonic bandgap of 1.55 µm and a lattice constant of 0.48 µm and air filling factor of about 44%. In this paper, this structure is excited with TE polarization. A pulsed Gaussian source is used to excite the fundamental waveguide mode at the entrance of the input waveguide.



(a) (b)

Figure 2. (a) Design of the triangular photonic-crystal waveguide. (b) Dispersion curves of the guided modes in a W1KA PhC waveguide. The photonic crystal is a triangular lattice of air holes (r = 0.348a) in a dielectric medium (ε = 10.5). The W1KA PhC waveguide is obtained by removing 1 row of air holes.

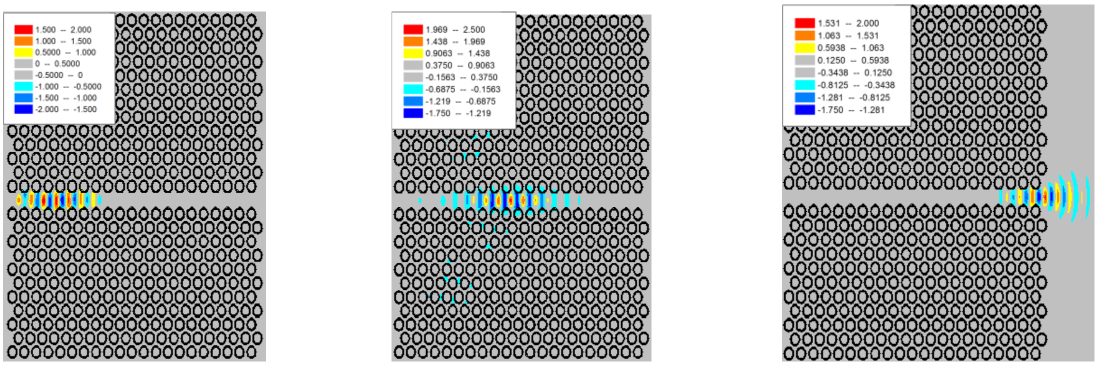
We have used in this paper a two-dimensional FDTD code that captures the simulation parameters (spatial discretization step, simulation mode (TE/TM), number of iterations), the injection conditions (injection of a guided mode through a Huygens surface) and the boundary conditions Type (Wall, symmetric or antisymmetric). Further details concerning the FDTD method and the Mur absorbing conditions are given in [14-15]. In our simulations Δx= Δy=0.04 µm and the total number of time steps is 5000.

The tow-FDTD simulated magnetic field maps Hz for the modelled structure is shown in Figure 3 (a, b, c) in which the size of the computing window is 10 µm×10.4 µm. The length of the channel is 0.8 µm. The wavelength of the incident plane wave is set to 1.55 µm.

The distribution shape of the magnetic field Hz (TE polarization) for respectively 1500, 2000 and 3000 iterations as show in Figure 3 (a, b, c) demonstrates clearly the guided phenomenon of the fundamental mode in the PhC waveguide.

Figure 4 shows respectively the spectral response in transmission and reflection for W1KA waveguide and excited by TE mode through a Huygens surface.

According to Figure 4, we notice that the transmission spans the range [1.3 µm.-2, 2 µm.] which tops up 85% to 1.88 microns. The amount of the calculated transmission wavelength 1.55 µm. is of the order of 75%. These maximums are probably explained by the presence of the guided mode (fundamental mode) without loss that exists at these wavelengths, while weak degradation of the value of the transmission is due the presence of mini band gaps and PBG.



(a) **(b)** **(c)**

Figure 3. The distribution shape of the magnetic field Hz excited in TE mode. (a) for 1500 iterations. (b) for 2000 iterations. (c) for 3000 iterations. Δx= Δy=0.04 µm.

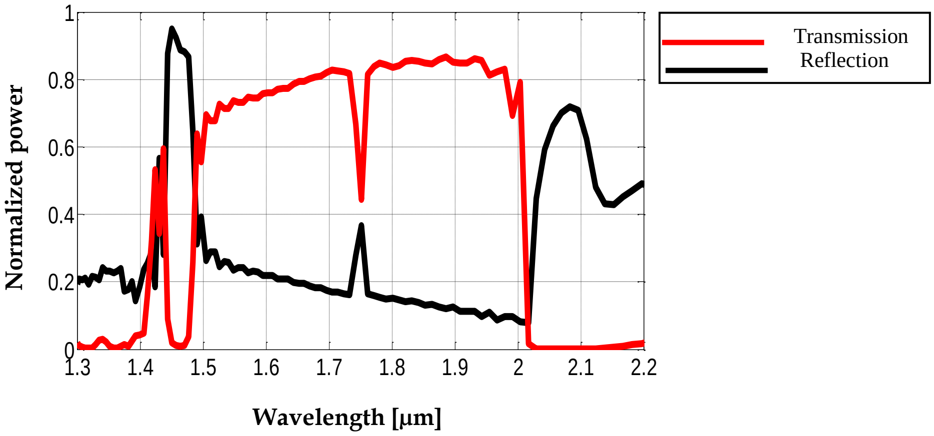


Figure 4. Normalized transmission and reflection spectra at the output port for the PhC waveguide W1KA.

3.2. Double bends design

A photonic band gap (PBG) effective guide must meet certain basic criteria and this must be one that the guide is single mode in the operation range to avoid any possibility of coupling between modes when the periodicity is locally changed. In addition, it is possible to cancel these reflections by the introduction of resonance, while reducing operating range of the bend. To clearly visualize this problem, we are interesting to analyze the PhC bend response. The adopted method to conduct the numerical study is illustrated in Fig.ure 5 to determine the reflection related bend. The PhC structure is inserted between two waveguides of width w directed along the axis ΓK and forming an angle of 60° with the guide directed along the axis ΓM. The injection and detection were done according to a procedure known as: guided approach. In this latter, the injection of the fundamental mode is directly in the guide.

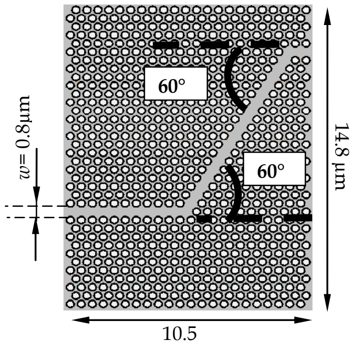
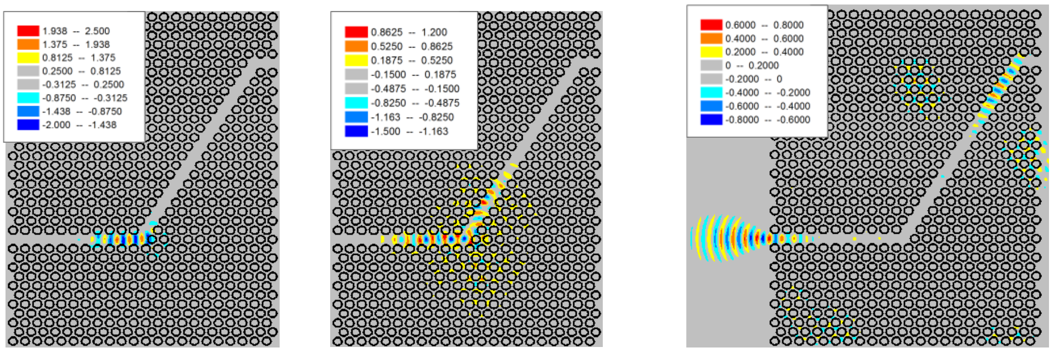


Figure 5. Layout for the FDTD modeling of the transmission through a double bends PhC waveguide. Δx= Δy=0.04 µm.

It is not only to guide the light beam in a rectilinear manner, what interests us is to make the photonic circuitry and more particularly a bend function. The size of the computing window is 10.5 µm×14.8 µm. The length of the channel is 0.8 µm.

The 2D photonic crystal is similar to those in section 3. 1, etched through InP/GaInAsP/InP heterostructures and a fill factor of about 44%, radius of holes r= 0.1673 µm were chosen for a triangular lattice to obtain a photonic band gap (PBG) around 1.55 µm exist for the telecom wavelengths.

Figure 6 shows the results of the two-dimensional finite difference time domain simulation performed on the double bends.



(a) **(b)** **(c)**

Figure 6. The distribution shape of the magnetic field Hz of the not optimized bends excited in TE mode. (a) for 1500 iterations. (b) for 2000 iterations. (c) for 3000 iterations. Δx= Δy=0.04 µm.

From Figure 6 (a, b, c) one can clearly see the resulting map of the wave propagation in the PhC structure at different iterations 1500, 2000 and 3000. Figure 6 (a, b) respectively shows clearly the scattered light in the intermediate part between the two bends and the return of power to the input waveguide reflecting a strong reflection and a weak transmission.

Transmission and reflection spectra on this PhC structure obtained numerically are plotted on figure 7.

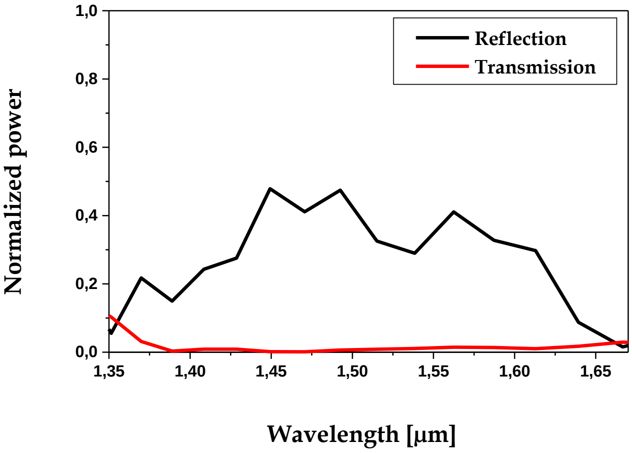
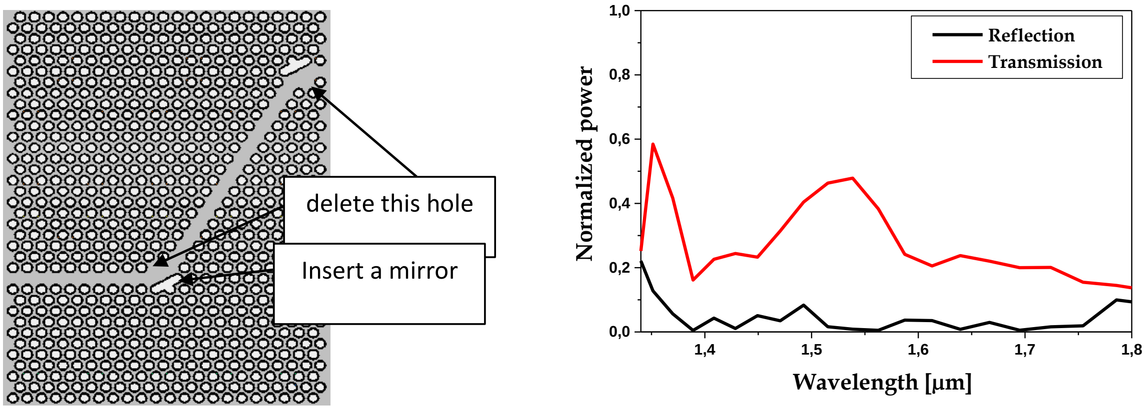


Figure 7. Spectral response in transmission and reflection of the not optimized double bends obtained by the two-dimensional finite difference time domain (FDTD) simulation.

The results of the 2D FDTD simulation shows clearly the low transmission obtained in the range [1.33µm-1.67µm], we also recorded a null transmission with maximum reflection of 50%. This explains that there are no guided modes in this double bend structure due to losses at the two corners. However, the passage of the wave through this PhC, the mode of the straight guide W1KA will be coupled with that of the guide (curved), a coupling efficiency is less than unity where increased losses.

3.3. Optimized double bends design

In this section we focuses on the optimization of the precedent double bends for obtaining better transmission and a wide bandwidth while reducing losses due to bends. We can modify the topology of the defect and deleting them and inserting mirrors in the corners (the addition of several holes glued). The size of holes was designed to be r=0.348a. The resulting optimized bend structure is shown in Figure 8 (a) and the normalized transmission and reflexion spectra at output port for the double bend is displayed in Figure 8 (b).

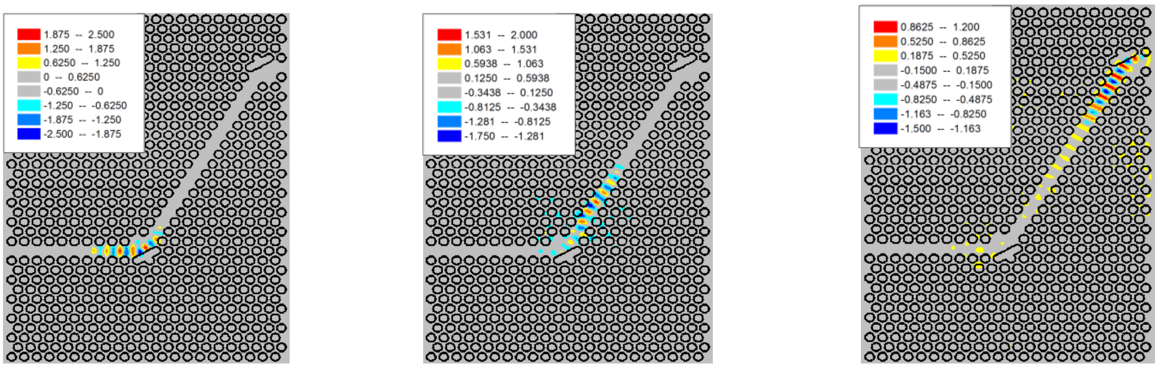


(a)

(b)

Figure 8. (a) Topology optimization design of double Bends. (b) Spectral response in transmission and reflection of the optimized double bends obtained by the two-dimensional finite difference time domain (FDTD) simulation.

According to Figure 8 (b), there is a transmission that exceeds the 30% that spans the range [1.33µm-1.38µm] and [1.47µm-1.57µm]. The maximum value is around 59%. Transmission recorded at 1.55 µm is of about 52%. Reflection computed is null. This reflects an almost total transmission of the wave through double bends. We note that the transmission was significantly altered. The transmission properties are clearly improved with this configuration, the propagation mode is not affected by the accident posed by the corners, allowing the wave to follow the direction of bends. This is clearly seen in Figure 9 (a), (b) and (c) schematically Hz field distribution in the structure for TE polarisation at different iterations.



(a)

(b)

(c)

Figure 9. The distribution shape of the magnetic field Hz of the not optimized bends excited in TE mode. (a) for 1500 iterations. (b) for 2000 iterations. (c) for 3000 iterations.

4. CONCLUSION

In this paper, we have presented a 2D FDTD study of injection, propagation and transmission along linear and double bend line created in a 2D crystal. We showed the advantage of using PhCs to guided optic. These materials, whose dielectric constant varies periodically across the wavelength, have the particularity to present a photonic band gap (PBG) which prohibit the propagation of light in the structure. The use of this effect opens the door to the realization of an optical function as the light guide. By properly choosing the geometric parameters of the crystal it is possible to achieve effective guidance in minimizing losses in the vertical direction. The creation of defects in 2D PC structures, will lead the opening of a licensed frequency band within the photonic band gap. The width and position of the licensed band is managed by the characteristics of defects. Second, our analysis focused on the problem of bends, supported by numerical results, they suggest that the availability of effective bends. To improve the transmission and/or expand the range of frequencies transmitted one inserting mirrors and removing holes. Furthermore, we showed that the double bend PhC circuit transmission curves could reach a high value on a broadband by optimizing the double bands topology.

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