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Optimized 1×4 Y Shaped Splitter for Integrated Optics

[1]Hadjira Badaoui, [1]Mohammed Feham, [2]Mehadji Abri

[1]Laboratoire STIC, Faculté de Technologie, Université Abou Bekr Belkaid, 13000 Tlemcen, Algeria.
[2]Laboratoire de télécommunication, Faculté de Technologie, Université Abou Bekr Belkaid, 13000 Tlemcen, Algeria.

Abstract: In this paper we design a brick that will form the photonic crystals network. In particular, we focus on the optimization of a 1×4 Y-Shaped Splitter used for routing light exhibiting high transmission. A total transmission of about 88 % at output ports is obtained. Photonic crystals are considered a good way for realizing compact optical splitters. Propagation characteristics of proposed device are analyzed utilizing two-dimensional finite difference time domain (FDTD) method. The FDTD method will easily perceive the mechanisms involved in this device. The PhCs transmission properties are then presented and discussed.

Key words: Photonic crystals, finite-difference time-domain (FDTD), 1×4 Y-Shaped Splitter, optimization.

INTRODUCTION

Photonic crystal (PhC) structures are suitable for a large number of optical applications, thanks to their unique linear and nonlinear properties as well as the possibility this technology offers to fabricate highly compact devices. The use of periodic structures on a nanometeric scale combines novel features with an integration platform for densely packed photonic circuits, which is particularly attractive for optical communications. 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.

Photonic Crystal structures have been heralded as a disruptive technology for the miniaturization of opto-electronic devices, offering as they do the possibility of guiding and manipulating light in sub-micron scale waveguides (Astratov, 2000; Lin 2002; Soljai, 2002; Olivier, 2003; Meade, 1994). Applications of photonic crystal guiding the ability to send light around sharp bends or compactly split signals into two or more channels. Splitters are important components for designing photonic circuits. While straight waveguides and bends have now been studied extensively, the very important problem of bends and junctions that is essential for the operation of more complex circuits which are built around PBG structures has only recently received attention (Hung-Ta Chien, 2006; Ghaffari, 2008; Shanhui Fan, 2001; Kaatuzian, 2009; Danaie, 2008; Li, 2009).

In this paper an attempt was made to design compact Photonic Crystal structure used for routing light ie a 1×4 Y-Shaped Splitter which consists of one input PhCW and four output PhCWs with optimized transmission characteristics. The simulation was performed using the two-dimensional finite difference time domain (FDTD) method.

2.Tthe Pwe Method:

The propagation of light in a photonic crystal is governed by four Maxwell equations. Let us consider an isotropic medium in which there are no sources of light so that ρ and J are equal to zero in Maxwell equations. Also assume that the dielectric constant has no frequency dependence. Finally, consider that the material is transparent so that ε(r) is purely real and positive. With these considerations the four Maxwell equations will be in the following form:

$$\nabla \cdot H(r,t) = 0$$

$$\nabla \cdot [\varepsilon(r)\, E(r,t)] = 0$$

Corresponding Author: Hadjira Badaoui, Laboratoire STIC, Faculté de Technologie, Université Abou Bekr Belkaid, 13000 Tlemcen, Algeria.
E-mail: elnbh@yahoo.fr

$$\nabla \times E(r,t) + \mu_0 \frac{\partial H(r,t)}{\partial t} = 0 \tag{1}$$
$$\nabla \times H(r,t) - \varepsilon_0 \varepsilon(r) \frac{\partial E(r,t)}{\partial t} = 0$$

Assuming H(r, t) and E(r, t) to be in the form of complex values as in Eq. (2) and substituting them into Eq. (1) we will finally obtain Eq. (3). Therefore, H(r) and its corresponding frequencies can be found as follows:

$$H(r,t) = H(r)e^{-i\omega t}, \quad E(r,t) = E(r)e^{-i\omega t} \tag{2}$$

$$\nabla \times \left[\frac{1}{\varepsilon(r)} \nabla \times H(r) \right] = \left(\frac{w}{c} \right)^2 H(r) \tag{3}$$

According to Bloch's theorem the modes in a periodic structure can be written as:

$$H(r) = e^{k \cdot r} h(r) e_k$$
$$h(r) = h(r + R_1) \tag{4}$$

Where $\mathbf{R_l}$ is an arbitrary lattice vector and $\mathbf{e_k}$ is the unit vector perpendicular to the vector **k** and parallel to **H**. Since ε and *h* are periodic functions we can write them as their Fourier expansion:

$$\varepsilon(r) = \sum_{G_i} \varepsilon(G_i) e^{i\, G \cdot r}, \qquad \frac{1}{\varepsilon(r)} = \sum_{G_i} \varepsilon^{-1}(G_i) e^{i\, G \cdot r} \tag{5}$$

$$h(r) = \sum_{G_i} h(G_i) e^{i\, G \cdot r} \tag{6}$$

Therefore H will be written as:

$$H(r) = \sum_{G,\lambda} h_{G,\lambda} e_\lambda e^{i\,(k+G) \cdot r} \tag{7}$$

As Equation (7) demonstrates, **H** is written as the sum of plane waves, where λ= 1, 2, ...; **k** is the wave vector of the plane wave, **G** is the reciprocal lattice vector, $\mathbf{e}_\lambda$represents the two unit axis perpendicular to the propagation direction (**k** + **G**); (**e1**, **e2**, **k** + **G**) are perpendicular to each other; $h_{G,\lambda}$ is the coefficient of the *H* component along the axes **e**λ.

Finally, substituting (5) and (7) in to (3) yields:

$$\sum_{G'} |K+G| \, |K+G'| \varepsilon^{-1}(G-G') \begin{bmatrix} e_2 \cdot e'_2 & -e_2 \cdot e'_1 \\ -e_1 \cdot e'_2 & e_1 \cdot e'_1 \end{bmatrix} \begin{bmatrix} h_{1,G'} \\ h_{2,G'} \end{bmatrix} = \frac{w^2}{c^2} \begin{bmatrix} h_{1,G} \\ h_{2,G} \end{bmatrix} \tag{8}$$

This is a matrix showing the relation between λ and k. This equation is a standard eigenvalue problem and it can be solved using numerical methods. The number of plane waves required to achieve adequate accuracy depends on structural details of the unit cell. When high accuracy is required for higher frequency ranges or when the atom structure is complicated, the number of plane waves should be increased (Guo, 2008).

RESULTS AND DISCUSSION

To validate our results numerically, we use a finite-difference time-domain (FDTD-2D) method to simulate the wave propagation inside the 1×4 Y-shaped splitter in a two-dimensional photonic crystal.

3.1 1×4 Y-Shaped Splitter Design:

For simplicity, only a 2D photonic crystal is considered in the present paper. Figure 1 (a) shows the design of the triangular photonic-crystal wave guide. The 2D PhC structure support a photonic band gap in the region 0.205<c/a<0.301 for TE polarized light. Even a W1KA PhC waveguide has two guided modes, as shown in Fig. 1 (b) (The guided modes in the PhC waveguide are calculated using the PWE method). 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.

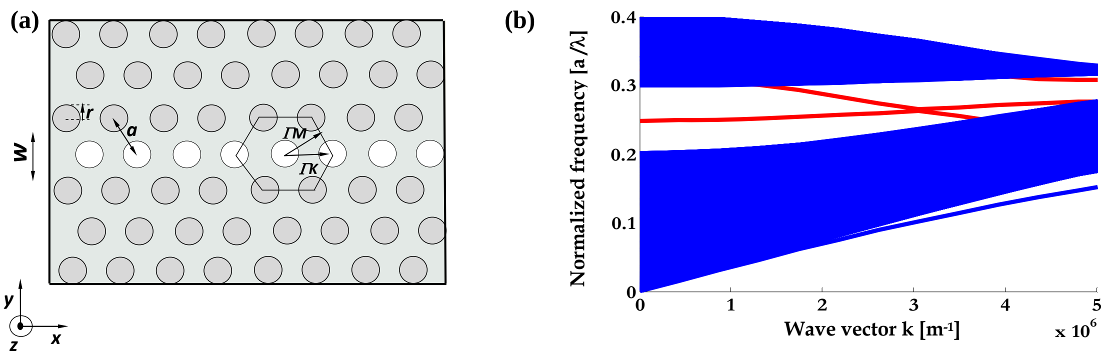


Fig. 1: (a) Design of the triangular photonic-crystal waveguide. (b) Dispersion curves of the guided modes in a W1KA PhC waveguide. The photonic crystal is a triangular lattice of air holes (r = 0.348a) in a dielectric medium (ε = 10.5). The W1KA PhC waveguide is obtained by removing 1 row of air holes.

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 this by the introduction of resonance, while reducing operating range of the 1×4 Y-shaped splitter. To clearly visualize this problem, we are interesting to analyze the PhC 1×4 Y-shaped splitter response. The adopted method to conduct the numerical study is illustrated in Fig. 2. The injection of the fundamental mode is directly in the guide of width w. 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 splitting function.

Let us consider the 2D photonic crystal 1×4 Y-shaped splitter illustrated in Fig. 2. We design the PhC structure 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). The lattice constant is set 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. 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 literature (Taflove, 2000; Koshiba, 2001; Mur, 1981). This paper presents only the conditions of absorption-type wall that simulate an infinite domain containing the entire structure study by investigating the lowest digital interfaces. In our simulations Δx= Δy=0.04 µm and the total number of time steps is 5000. The size of the computing window is 10.4 µm×10 µm. The length of the channel is 0.8 µm.

Fig. 3 shows respectively the spectral response in transmission and reflection for the 1×4 Y-shaped splitter and excited by TE mode through a Huygens surface.

The results of the 2D FDTD simulation shows clearly the very low transmission obtained in the range [1.30 µm-1.60 µm], we also recorded a null transmission in the four ports. Notice that the power reflection is important and reaches 62% this explains that there are no guided modes in this splitter due to losses at the 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.

The tow-FDTD results of the simulated magnetic field maps Hz for the modelled structure is shown in Fig. 4 (a, b, c). The wavelength of the incident plane wave is set to 1.55 µm.

From fig. 4 (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 5 respectively shows clearly the scattered light in the region between the different bends and the return of power to the input splitter reflecting a strong reflection and a weak transmission. Although most of the light that reaches the edge of the computational cell is absorbed by the boundaries, some light gets reflected back from the end of the splitter.

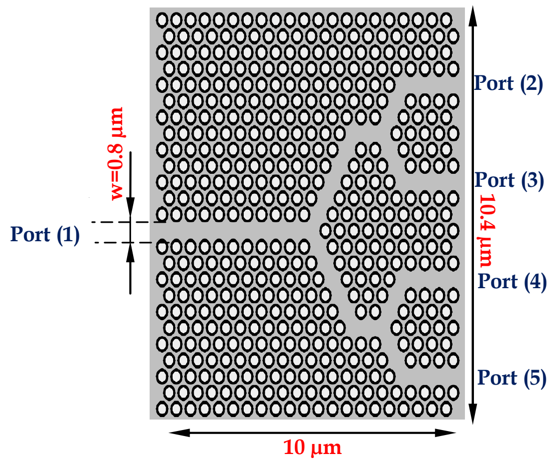


Fig. 2: Layout for the FDTD modeling of the transmission through a 1×4 Y-shaped splitter. The photonic crystal is a triangular lattice of air holes (r = 0.348a) in a dielectric medium (ε = 10.5). The W1KA PhC waveguide is obtained by removing 1 row of air holes.

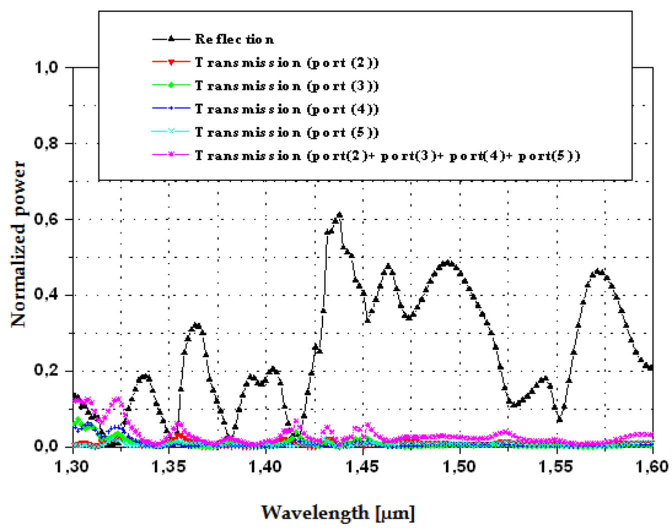
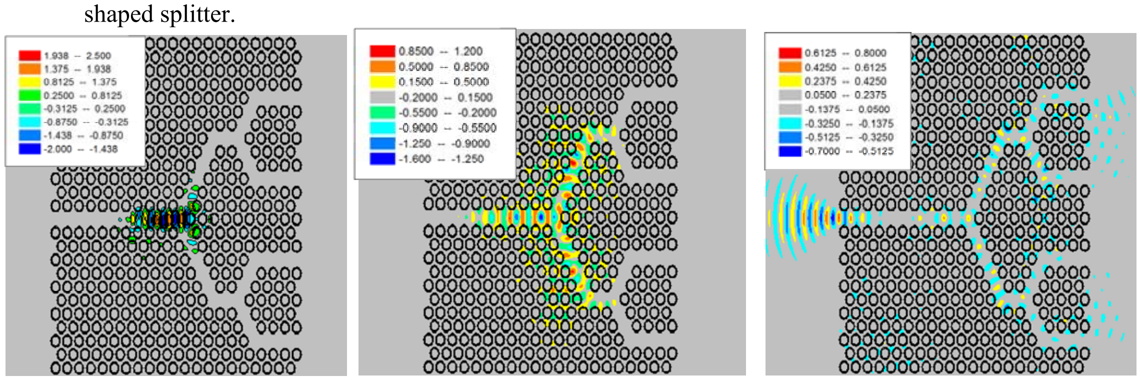


Fig. 3: Normalized reflection and transmission spectra at the input and output port for the not optimized 1×4 Y-shaped splitter.



(a) (b) (c)

Fig. 4: The distribution shape of the magnetic field Hz excited in TE mode. (a) for 1500 iterations. (b) for 2000 iterations. (c) for 3000 iterations.

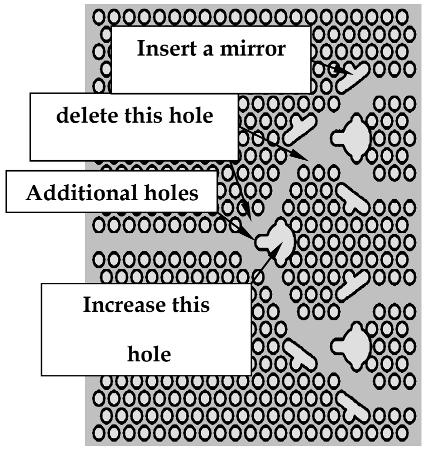


Fig. 5: Topology optimization design of the splitter.

Notice from fig. 6 that there is a transmission recorded at 1.55 µm of about 27% for port (2), 22% for port (3), 20% for the ports (4) and 19% for the ports (5). The total transmission for the four ports reaches the value 88% at the output ports as show in fig. 6. In fact, the ideal maximum transmission that must be obtained is 25% for each port. The corresponding reflection is of about 8%. We note that adding holes at the center of the junction, the mode expansion is suppressed, also the optical volume is then reduced, the mode cannot expand and the excitation of higher order modes is suppressed, resulting in clean and efficient splitting. The propagation mode is not affected by the accident posed by the corners, allowing the wave to follow the direction of bends. The transmission properties are improved with this configuration and the total transmission at the output ports is improved in comparaison with the not optimized splitter, this is clearly seen in fig. 7 (a), (b) and (c) schematically Hz field distribution in the structure for TE polarisation at different iterations.

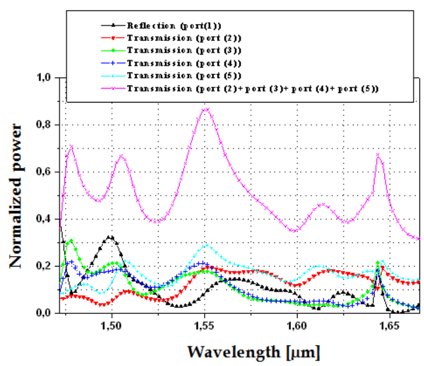
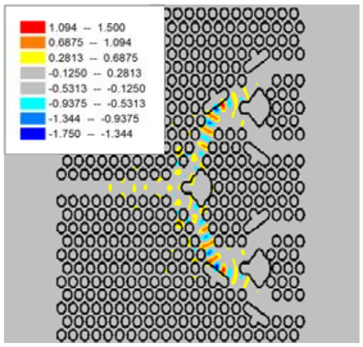


Fig. 6: Computed transmission and reflection spectra of the optimized splitter obtained by the two-dimensional finite difference time domain (FDTD) simulation for the structure illustrated in fig. 5.

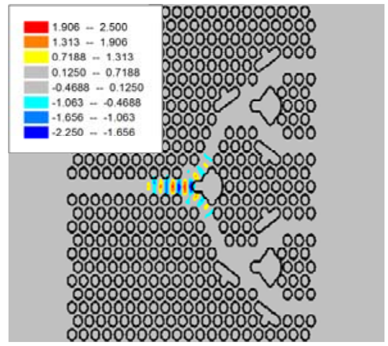
The distribution shape of the magnetic field Hz (TE polarization) for respectively 1500, 2000 and 3000 iterations as show in fig. 7 (a, b, c) demonstrates clearly the guided phenomenon of the fundamental mode in the double bends and the light reaches the end of the splitter.

4. Conclusion:

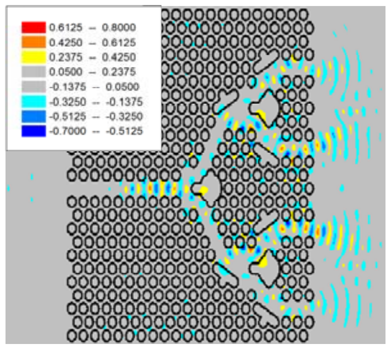
In this paper, we have designed a 1×4 Y-Shaped optical splitter made of linear-defect waveguides in PhC structure, and analyzed their properties using the two dimensional finite-difference time-domain method. Our analysis focused on the problem of splitting, supported by numerical results, they suggest that the availability of effective splitters. To reduce the mode expansion at the branching region, we have performed numerical simulations on Y-shaped waveguide branches in the splitter, and achieved an improvement of transmission by placing the defects of extra rods in the branching region and mirrors in the corners. We have found that the incident power splits in the four output ports with acceptable transmission efficiency and the total transmission obtained at the out ports is 88 %.



(a)



(b)



(c)

Fig. 7: The distribution shape of the magnetic field Hz of the optimized splitter excited in TE mode. (a) for 1500 iterations. (b) for 2000 iterations. (c) for 3000 iterations.

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