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Analysis and Simulation of a Photonic Crystal Power Divider

N. Nozhat and N. Granpayeh
Faculty of Electrical Engineering, K.N. Toosi University of Technology, Tehran, Iran

Abstract: In this research, the properties of a power divider that composed of two dimensional (2-D) Photonic Crystals (PC) have been analyzed. There is a large photonic band gap in transmission spectrum of the 2-D photonic crystal and by introducing a defect in the structure, some modes appear in it and propagate in the line defect waveguide. The PC power divider consists of a y-shaped line defect. The defect can be created by changing the size or removing the triangular PC defect rods. We have used an effective numerical method based on the Finite-Difference Time-Domain (FDTD) scheme to compute the evolution of the electric and magnetic fields in the structure. We have demonstrated the electric field evolution and calculated the insertion loss, isolation and coupling factors of the PC power divider.

Key words: Finite-difference time-domain method, photonic band gap, photonic crystal power divider, photonic crystal line defects, insertion loss, isolation factor, coupling factor

INTRODUCTION

Photonic crystals have been the subject of considerable research in recent years, because of their attractive applications. They are artificial dielectric or metallic periodic structures in one, two or three dimensional that forbid light propagation at certain frequencies, called Photonic Band Gap (PBG) (Yablonovitch, 1987). Due to their potential properties, various optical communication devices incorporating photonic crystals, such as high-Q resonant cavities, Fabry-Perot resonators with lossy dielectric, thresholdless Laser Diodes (LDs), Mach-Zehnder interferometers, low-loss, sharp bend waveguides and channel add-drop filters have been proposed and fabricated (Beaky *et al*., 1999; Imada *et al*., 2002; Loncar *et al*., 2000; Mekis *et al*., 1996; Ozbay *et al*., 2002; Ren *et al*., 2006; Song *et al*., 2005). They are useful devices to use in compact Planar Lightwave Circuits (PLCs), due to their small dimensions.

By introducing some defects in the PC structures, some modes appear in their band gap. Creation of a line defect in the 2-D photonic crystal waveguides have been proposed (Meade *et al*., 1994) and fabricated (Baba, 1999).

Since, the fabrication of 3-D photonic crystals is difficult, it is more convenient to try to derive a complete photonic band gap with 1-2 dimensional PCS.

By using two line defects in y-junction form in the structure, we can construct a photonic crystal power divider. A power divider is ideally a lossless reciprocal device which can perform vector summation of two or more signals and thus is sometimes called a power combiner. In typical power-splitting applications, the input power is divided into a number of smaller amounts for exciting the radiating elements in an array antenna. They are also used in balanced power amplifiers both as power dividers and power combiners (Collin, 1992).

In present study, we have analyzed and simulated the electric field evolution in a PC power divider. Also, the insertion loss, isolation and coupling factors of the power divider have been calculated. The effect of different parameters of the y-junction on the coupling and insertion loss is studied.

NUMERICAL ANALYSIS

There are many numerical methods for analysis of photonic crystals, including Plane-Wave Expansion method, exact Green's function method, transfer matrix method and the Finite-Difference Time-Domain method. In present analysis, we have used a 2-D FDTD method for simulation of evolution of the electromagnetic fields in the photonic crystals, because comparing to the PWE method, that the computational time growth is in the order of N^3 (where N is the number of plane waves), this method is in the order of N (where N is the number of discretization points), therefore, the computation time and memory requirements are reduced (Qui and He, 2000, 2001).

We have assumed that the structure is infinite in z-direction, thus using 2-D FDTD. The polarization of the incident wave to the structure, can be divided into two parts of TEz (H polarization), where the E-field is in a plane normal to the infinite axis of the dielectric rods and TMz (E polarization), which E-field is parallel to the axis of rods.

It is assumed that the material is linear, isotropic and lossless; therefore, the Maxwell's equations have the following form (Taflove, 2005):

Corresponding Author: N. Nozhat, Faculty of Electrical Engineering, K.N. Toosi University of Technology, Tehran, Iran

$$\frac{\partial \mathbf{H}}{\partial t} = -\frac{1}{\mu(r)}\nabla\times\mathbf{E} \qquad (1)$$

$$\frac{\partial \mathbf{E}}{\partial t} = \frac{1}{e(r)}\nabla\times\mathbf{H} \qquad (2)$$

Where, **E** and **H** are the electric and magnetic field intensity, respectively and ε(r) and μ(r) are the position dependent permittivity and permeability of the material, respectively.

Using the Yees algorithm, for TMz we can write (Taflove, 2005):

$$H_x\Big|_{i,j+1/2}^{n+1/2} = H_x\Big|_{i,j+1/2}^{n-1/2} - \frac{\Delta t}{\mu_0}\left(\frac{E_z\big|_{i,j+1}^{n} - E_z\big|_{i,j}^{n}}{\Delta y}\right) \qquad (3)$$

$$H_y\Big|_{i+1/2,j}^{n+1/2} = H_y\Big|_{i+1/2,j}^{n-1/2} - \frac{\Delta t}{\mu_0}\left(\frac{E_z\big|_{i+1,j}^{n} - E_z\big|_{i,j}^{n}}{\Delta x}\right) \qquad (4)$$

$$E_z\Big|_{i,j}^{n+1} = E_z\Big|_{i,j}^{n} + \frac{\Delta t}{e_{i,j}}\times\left[\left(\frac{H_y\big|_{i+1/2,j}^{n+1/2} - H_y\big|_{i-1/2,j}^{n+1/2}}{\Delta x}\right) - \left(\frac{H_x\big|_{i,j+1/2}^{n+1/2} - H_x\big|_{i,j-1/2}^{n+1/2}}{\Delta y}\right)\right] \qquad (5)$$

Where, Δx and Δy are the lattice increments in the x and y directions, respectively and

$$\Delta t \le \frac{1}{c\sqrt{(\Delta x)^{-2} + (\Delta y)^{-2}}}$$

is the time increment. Similar equations can be derived for TEz polarization.

We have used Berengers Perfectly Matched Layer (PML) as absorbing boundary condition to numerically simulate the optical properties of the structure (Taflove, 2005). The number of PML layers is assumed to be 10.

In PML each vector field component is split into two orthogonal components, for instance, for TMz, Ez field is assumed to be split into additive subcomponents of E_{zx} and E_{zy}.

RESULTS AND DISCUSSION

First let us consider the geometry of a 2-D photonic crystal, with a triangular lattice of dielectric rods in air. The radius of the rods is r = 0.2a, where a is the lattice constant and the relative permittivity of the dielectric rods is $\varepsilon_r = 11.4$. In FDTD computation, the unit cell includes 2500 (50×50) grid points and the total number of time steps is 32768. We have used a 19×11 rod photonic crystal, as shown in Fig. 1, but without defect.

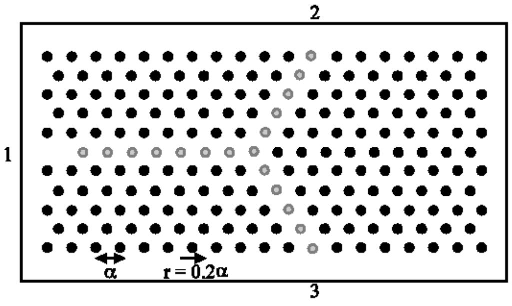

Fig. 1: Structure of a photonic crystal power divider consisting of a triangular array of dielectric rods in air, with y-shaped line defect

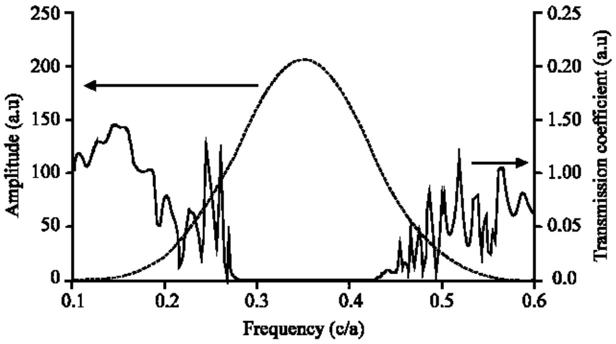

Fig. 2: Gaussian input pulse to the PC (dashed line) and transmission coefficient calculated at the output of the structure (solid line)

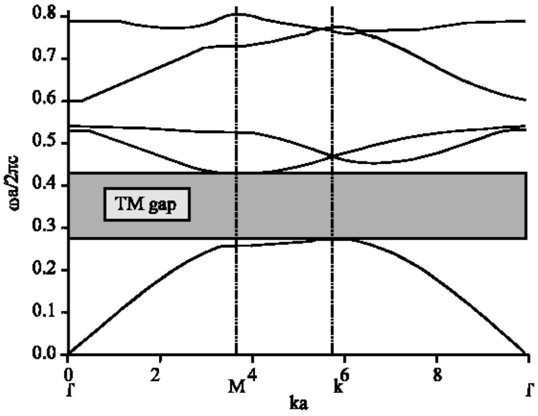

Fig. 3: Band diagram for triangular lattice of dielectric rods ($\varepsilon_r = 11.4$, r = 0.2a) in air

The source is a Gaussian pulse with central frequency of 0.35 (c/a) and a width of 0.2 (c/a), as demonstrated in Fig. 2. The selected photonic crystal structure has a band gap for TM modes, but not for TE modes. As shown in Fig. 3, the band gap associated with this structure varies in the range of f = 0.28 (c/a) to

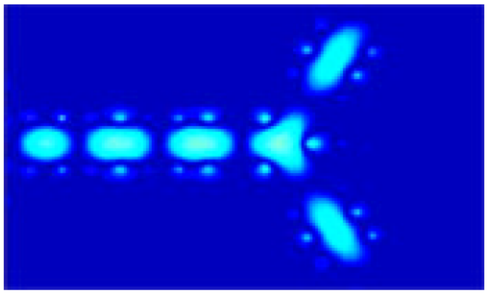

Fig. 4: Evolution of TMz electric-field in the y-shaped line defect of a triangular lattice of dielectric rods located in air

f = 0.43 (c/a) for TMz polarization. The spectrum of the transmission coefficient of the structure in Fig. 2 also approves this band gap.

A line defect in y-junction form, as demonstrated in Fig. 1, can be presented in the structure, either by changing the refractive index or the radius of some rods. We have investigated the effect of variation of both of the refractive index and radius of the defect, in order to measure and optimize the amount of powers that are coupled to the output ports of the power divider.

Figure 4 shows the evolution of the wave in a power divider. In this case we have used a single mode sinusoidal excitation source.

The important identification of a power divider is its coupling factor, insertion loss and isolation factor. Coupling factor is the ratio of the power at each of the output ports 2 or 3 to the input power launched from input port 1. Insertion Loss is the amount of power reflected and dissipated within the structure. The isolation factor is the ratio of the output power from port 3 to the input power launched from port 2.

For the PC power divider of Fig. 1, which is composed of y-junction line defect by removing some rods, only 25.18% of the input power reaches to any of the two output ports. Therefore, the coupling factor and insertion loss are 5.989 and 1.26 dB, respectively. In order to improve the output power we have analyzed various structures with different defect radius and refractive index. Figure 5 shows the insertion loss of the y-junction power divider versus the refractive index of the defect rods for three different defect radii of r = 0.1a, 0.3a and 0.4a.

To improve the coupling factor and reduce the insertion loss of the PC power divider, we can change the radius or/and the refractive index of the rods in the y-shaped line defect.

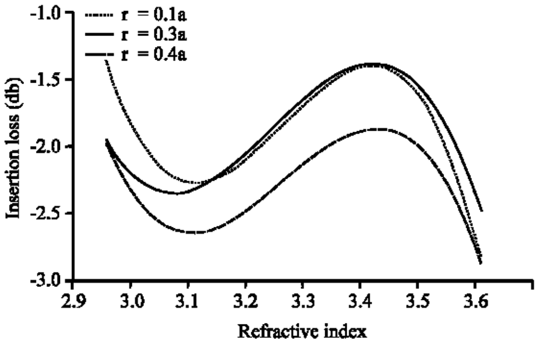

Fig. 5: Variation of the insertion loss in a PC power divider versus the refractive index of the line defect rods, for different defect radii

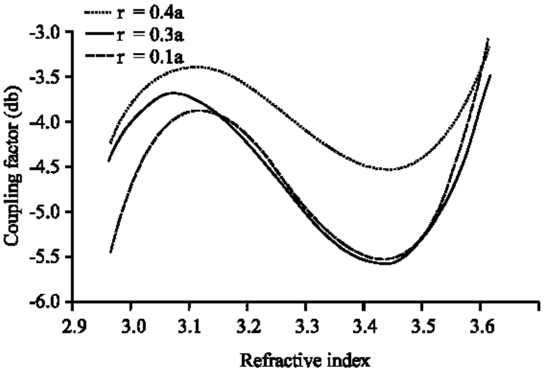

Fig. 6: Variation of the coupling factor in a PC power divider versus the refractive index of the line defect rods, for different defect radii

As shown in Fig. 5, when the refractive index of the defect rods increases, the insertion loss is decreased and the output power is increased. Only when the defect rods have the refractive index the same as that of the structure (n = 3.376), the output power is low and as shown in Fig. 5, the insertion loss increases. This is because when we only change the size of the defect rods, the new structure band gap has an overlap on the original photonic crystals and therefore, the transmission of light in the structure is forbidden which means that the insertion loss increases (Nozhat and Granpayeh, 2007). Variation of the lightwave frequency may change this result. We have been calculated the coupling factor of the PC power divider as demonstrated in Fig. 6. When the refractive index increases, the coupling factor is also increased. There is an exception in n = 3.376, due to the overlap of the band gap of this structure with original PC.

Comparing three curves, it is clear that when the radius of the defect rods is r = 0.4a, the amount of input power coupled to the output ports is increased and the insertion loss is decreased, because the energy of the electromagnetic waves will tend to confine in the enhanced rod size (Chien *et al*., 2006).

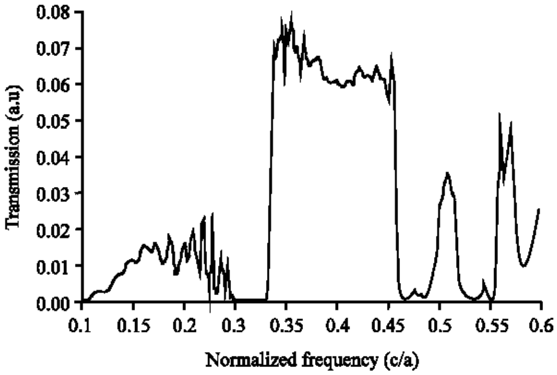

Fig. 7: Spectrum of the PC power divider isolation between ports 2 and 3 of Fig. 1

The isolation spectrum of the power divider is shown in Fig. 7. The average isolation between ports 2 and 3 is 0.06 (12.22 dB).

CONCLUSION

In this study, we have presented the existence of a large PBG in a triangular lattice photonic crystal. We have calculated the insertion loss, isolation and coupling factors of the photonic crystal power divider. The power divider consists of line defects in y-shape. Creating defects by removing the rods, cause dramatic reduction in coupling factor. Therefore, we have to construct the defects by variations of the size of rods or their refractive index, which reduce the insertion loss and increase the coupling factor. Therefore, the effects of variations of the rod size and its refractive index on the power divider identifications have been analyzed.

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