Analysis Add- Drop Filters Based on two-dimensional Photonic Crystal by the Finite Difference Time Domain Method

Shahrbanoo, Ghorbanzadeh

Department of Engineering, Aliabad Katoul Branch, Islamic Azad University, Aliabad Katoul, Iran

ABSTRACT

Among various photonic crystal devices, ultra compact channel drop filters based on resonance coupling between waveguide modes of line defects and cavity modes of point defects have attracted researchers attention due to the substantial demand in wavelength division multiplexed (WDM) optical communication systems. We will investigate the properties of resonant modes which arise from the introduction of local defects in two-dimensional ($2D$) photonic crystals and will show that the properties of these modes can be controlled by simply changing the nature and the size of the defects. The time, polarization, symmetry, and distribution of the resonance modes will be computed by solving Maxwell's equations in the time domain. The results of the theoretical modeling have been applied to design a 2D PC-based five-channel drop filter with a simple structure. The performance of the designed filter has been simulated using the finite-difference time-domain (FDTD) method.

KEYWORDS: photonic crystal. Channel drop filter. Photonic crystal multi/de multi planer FDTD method.

INTRODUCTION

Channel drop filter plays a key role in the integration of photonic circuits. It is used in the area of optical communication and sensor systems. Various functional elements, such as, multiplexers, switches, and directional coupler can be realized by channel drop filters.

A range of energies which the photonic crystal does not allow photons to propagate, regardless of their direction and polarization is called a complete photonic band gap (PBG) [1]. If a defect is introduced to a perfect photonic crystal, a mode (or group of modes) may be appeared at a frequency (or several frequencies) within the PBG [2].

In this paper, the numerical methods for analysis and simulation of photonic crystals are reviewed. The wave propagation in photonic crystal cavities, waveguides and several channel add-drop filters are simulated by the two-dimensional ($2D$) finite difference time-domain (FDTD) method. The analysis areas are surrounded by the perfectly matched layer (PML) to simulate the unlimited analysis boundaries.

Photonic crystal structure and band gap

The photonic crystal under study consists of a perfect array of infinitely long dielectric rods arranged in a square lattice. Each rod has a radius of 0.20a, where a is the lattice constant and a refractive index of 3.4, which is related to Si(Silicon). We investigated the propagation of electromagnetic fields in the plane normal to the rods. Since the rods have translational symmetry along their axes, the waves can be decoupled into two transversely polarized modes, of |TE| and |TM|. There is a large photonic band gap for the TE polarization between frequencies of 0.29 ($2\pi c/a$) and 0.42 ($2\pi c/a$), as depicted in fig.1.
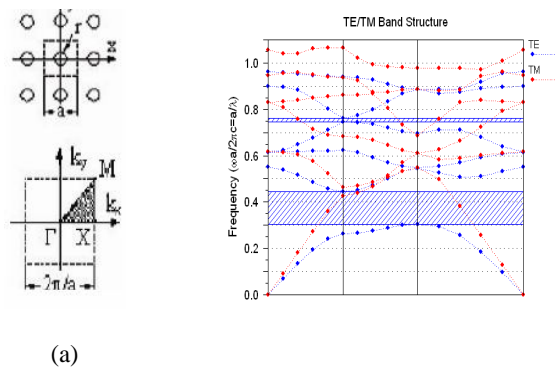

(a)   (b)

Figure 1. Basic properties of a perfect crystal and its band structure; (a)**:** Original lattice, 1st (irreducible) Brillouin zone, lattice constant and material properties. (b): Band diagram for TM and TE polarizations. Band gaps exist only for TE polarization (gray areas).

*Corresponding Author: Shahrbanoo, Ghorbanzadeh, Department of Engineering, Aliabad Katoul Branch, Islamic Azad University, Aliabad Katoul, Iran. e-mail: sh_ghorbanzadeh@yahoo.com

PC Defect Modes

A defect is now introduced into the perfect array of rods. The defect can posses any shape or size; it can be made by changing the refractive index of a rod, modifying its radius, or removing a rod altogether. The defect could also be made by changing the index or the radius of several rods. Here we modify the radius of a single rod. The modes in the crystal are derived using a super cell approximation, which consists of placing a large crystal with a defect into a super cell and repeating it periodically in space. The considered super cell crystal contains a 7×7 rows . We begin with a perfect crystal, where every rod has a radius of 0.2a, and gradually reduce the radius of a single rod. Initially, the perturbation is too small to localize a mode in the crystal. When the radius reaches 0.15a, a resonant mode appears in the vicinity of the defect. Since the defect involves removing dielectric material in the crystal, the mode appears at a frequency close to the lower edge of the band gap. As the radius of the rod is further reduced, the frequency of the resonance mode sweeps upward across the gap, and eventually reaches f = 0.38c/a when the rod is completely removed. Figure 2 depicts the frequency of the mode for several values of the rod radius. The frequency of the mode can be tuned by simply adjusting the size of the rod.
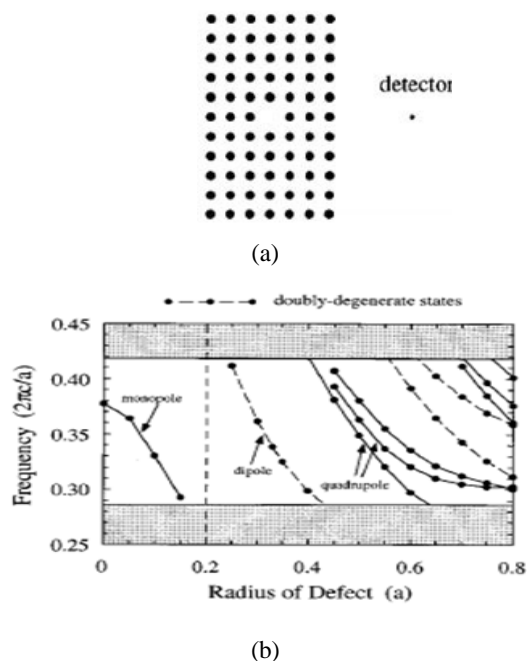

(a)

(b)

Figure 2. Frequency of the defect states in an array of dielectric rods with radius 0.20a. The defect is introduced by changing the radius R of a single rod. The case where R = 0.20a corresponds to a perfect array, while the case of R= 0 corresponds to the removal of a rod. The shaded regions indicate the edges of the band gap.

The electric field distribution of the resonance mode is shown in Fig. 3(a) for the specific case which the defect rod radius is 0.10a.
The electric field is polarized along the axis of the rods and decays rapidly away from the defect. Since the field does not have a node in the azimuthal direction, it is labeled a monopole. The frequency of the mode is f = 0.32 c/a. Instead of reducing the size of a rod, it would also have been possible to increase its size. Again, starting from a perfect photonic crystal, we gradually increase the radius of a rod.
When the radius reaches 0.25a, one doubly degenerate mode appears at the top of the gap. Since the defect involves adding material, the modes sweep downward across the gap as the radius increases. The modes eventually disappear into the continuum below the gap when the radius becomes larger than 0.40a (see Fig 2).
The field distribution of the one doubly degenerate mode is shown in Figs 3(b) for the case where
R= 0.33a. The modes are labeled dipoles since they have two nodes in the plane. By increasing the radius further, a large number of resonant modes can be created in the vicinity of the defect.
This is shown again in Fig 2. Several modes appear at the top of the gap: first a quadruple, then another (no degenerate) one, followed by a second-order monopole and two doubly degenerate hexa poles. These modes also sweep downward across the gap as the defect is increased.
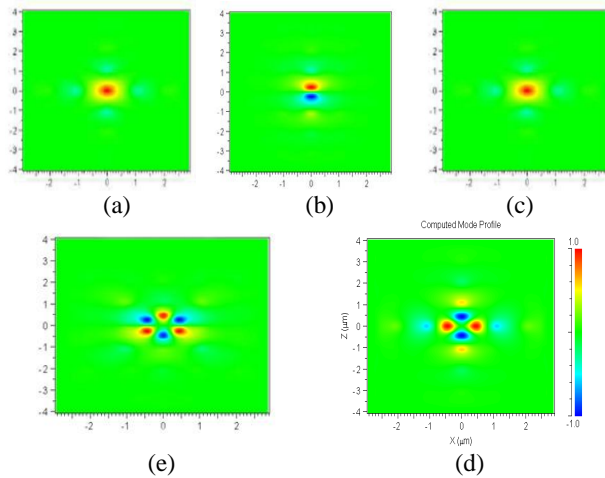The modes are shown in Figs 3(c) – 3(d) and 3(e) for the case which R = 0.60a.

(a)   (b)   (c)

(e)   (d)

Figure 3. Electric-field distribution of TE defect states in
an array of dielectric rods for various defect sizes.

(a)   Monopole, R= 0.10a (b) Doubly degenerate dipoles,
(b)   R = 0.33a, R = 0.60a. (c) Second-order monopole,
(c)   R = 0.60a. (d) and (e) Doubly degenerate hexapoles,
(d)   R= 0.60a. The white circles indicate the position of the rods.

A line defect within a photonic crystal can guide photons through the system. If the frequency of light lies within the PBG, it will be confined to the defect line, since propagation is forbidden through the rest of the photonic crystal. The advantage of such a system compared to the conventional optic- al fibers or waveguides is that in this case the light confinement does not rely on total internal reflection.
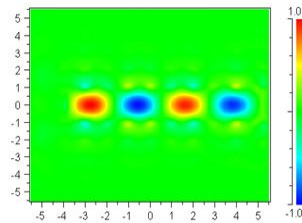

Figure 4: Electric-field distribution of TE line defect (wavguide).

Five Channel Drop Filter

The schematic view of our proposed five-channel drop filter is demonstrated in fig 5(a). The numerical and the bus waveguide are terminated with another channel drop filter composed of a directly coupled resonator rather than the closed end to save the device area. Simulation of the transmission specter from the bus to each drop waveguide is plotted in Fig 5(b). When a resonator is directly coupled to the bus/drop waveguide, resonant transmission of 100% is naturally obtained [8]. The channel at the end of the bus waveguide works as a reflector for the other channels.
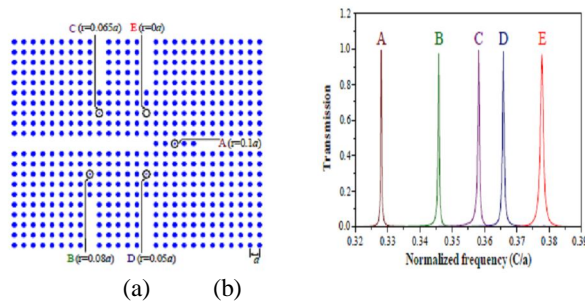

(a)   (b)

Figure 5: (a) Schematic view of the proposed 5 channel drop filter, where channels are located on both sides of the bus waveguide the bus waveguide is terminated with another channel, in order to use the space more efficiently.
The dielectric constant of all rods is 11.56. (b) Transmission spectrum of the proposed filter,
which has been calculated using the 2D-FDTD method.

In order to use the space more efficiently and make the device compact, channel drop filters are placed on both sides of the bus waveguide, channel drop filters are placed on both sides of the bus waveguide. Channel drop efficiencies higher than 96% wave have been achieved in all channels. Figures 6(a) and 6(b) show the field distributions at the resonance frequencies of the drop filters at port C (with defect radius of r = 0.065a) and port B (with defect of r=0.08a), respectively.
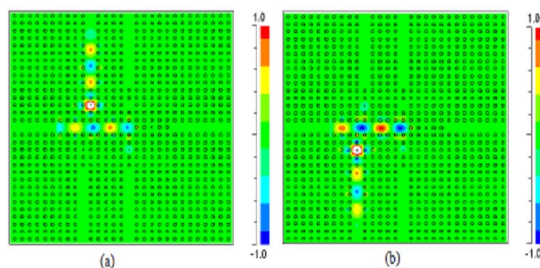

Figure 6: (a) The wave propagation at the resonant frequency (f = 0.3582 C/a) of the drop filters at port C (r = 0.065a) and (b) (f = 0.3458 C/a) of the drop filter at port B (r = 0.08a).

CONCLUSION

In this paper, a channel drop filter, an important component in the optical wavelength division multiplexing (WDM) systems in a two dimensional photonic crystal has been proposed. Line defect waveguide and point defect cavities near a two dimensional photonic crystal the structure which can be used for the trapping and emission of photons, and perform as a five channel drop filter .also Based on the theoretical modeling, a five-channel drop filter with a simple structure has been designed.

The performance of the designed filter has been demonstrated by using the 2D FDTD method. It has been shown that for all channels in the designed filter, channel drop efficiencies higher than 96% have been achieved. In practical filters, the proposed structure should be realized in different forms, such as PC slabs, in which vertical confinement is provided and 3D calculation is required for design. In such practical structures, performance of the channel drop filter will be degraded by imperfect vertical confinement.

The theoretical modeling presented can be easily extended for the practical structures by including the vertical loss of the resonators.

REFERENCES

[1] B.-K.Min, J –E, Kim, amd H. Y. Park, "Channel drop filters using resonant tunneling processes in two dimensional triangular lattice photonic crystal slabs," Opt. Commun. 237.59-63.(2004).

[2] S A. Shinya, M. Notomi, Mitsugi, E. Kuramochi, T.Kawabata, S. Kondo, T. Watanabe, and T. Tsuchizawa "Photonic crystal devices combining width tuned waveguides and cavities," in Technical Digest of international Symposium on Photonic and Electronic Crystal Structures V, (Kyoto, Japan, 2004).

[3] S. Noda, B. S. Song, Y. Akahane, and T. Asano, "In plane hetero photonic crystals," in Technical Digest of international Symposium on Photonic and Electronic Crystal Structures V, (Kyoto, Japan, 2004), pp. 86.

[4] C-S. Kee, D-H. Cho, J-H. Jung, I.park, H. Lim, S.-G. Lee, and H. Han, "Photonic crystal multi-channel add/drop filters," in Abstract book of MRS 2003 Spring meeting. (SanFrancisco, Calif, 2003), pp.64.

[5] M. Moghimi,[a] S. Mirzakuchaki,[b] N. Granpayeh,[c] N. Nozhat,[c] G.H. Darvish[a] [a]Islamic Azad University (IAU), Science and Research Branch, Tehran, Iran.[b]Faculty of Electrical Engineering, Iran University of Science and Technology, Tehran, Iran.[c]Faculty of Electrical and Computer Engineering, K. N. Toosi University of Technology, Tehran, Iran Canadian Journal of Physics, 2012, 90(2): 175-180, 10.1139/p2012-001

[6] A. Taflove, Computational Electrodynamics: The Finite-Difference Time-Domain Method (Artech House INC, Norwood, 1995).

[7] H. A. Haus and Y.Lai, "Theory of cascaded quarter wave shifted distributed feedback resonators," J.Quantum Electron. 28, 205-213. (1992).

[8] A. Dorazio, M. De Sario, V. Marrocco and F- Prudenzano, "Photonic crystal drop Filter Exploiting Resonat Cavity Configuration, " IEEE TRANS NANO TECHNOLOGY, (2008).

[9] M. Bahrami, M.S. Abrishamian and SA. Mirtaheri " Tunable an isotropic photonic crystal channel-drop Filter," j- optics. 13, 160-165. (2011).