Photonic-Crystal Band-pass Resonant Filters Design Using the Two-dimensional FDTD Method

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Abstract

Recently, band-pass photonic crystal filters have attracted great attention due to their important applications in the fields of optical interconnection network and ultrahigh speed information processing. In this paper we propose the design of a new type of photonic crystal band-pass resonant filters realized in one-missing-row waveguide by decreasing proper defects along the waveguide with broadband acceptable bandwidth. Two types of photonic crystal band-pass filters are utilized and optimized using the Two-dimensional finite-difference time-domain (FDTD) technique. The first one is based on the Fabry-Pérot cavities and in the second one a cavity is introduced in the middle by omitting two neighboring air holes in waveguide. Numerical results show that a band [1.47 µm-1.57 µm] around 1.55µm is transmitted with a maximum transmission of about 68% and as a result wide band-pass filters are designed.

Keywords: *Fabry-Pérot (FP) cavities, integrated optics, band-pass filter, photonic crystal (PhC) waveguide, Finite-difference time-domain (FDTD).*

1. Introduction

Photonic crystals (PhCs) are novel class of optical media represented by natural or artificial structures with periodic modulation of the refractive index. Such optical media have some particular properties which gives an opportunity for a number of applications to be implemented on their basis. During the last years, much attention has been paid to two-dimensional (2D) photonic crystals. These crystals have many potential applications because of their ability to control light-wave propagation and because PhC-based optical waveguides may be integrated into optical circuits. The periodicity is broken by introduction of some defects into the crystals. It has been shown that doped PhCs permit the guiding of waves in two different geometric paths for two distinct wavelength ranges [1]. Such structures can be used to design highly efficient new optical devices. Optical waveguides in two-dimensional (2D) PhCs produced by insertion of linear defects into PhC structures had been proposed [2-3].

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 [4-5]. 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, demultiplexer and couplers [6-11].

One of the key elements of integrated optical devices receiving great consideration is a resonant filters because they can act as a demultiplexer to select a particular channel or multiple channels in Dense Wavelength Division Multiplexed (DWDM) communication system. Many papers have investigated different types of filters in order to improve its transmission characteristics [12-15].

In this paper we present different design strategies, which we have used to improve the performance of various resonant filters. The properties of these PhC structures are numerically investigated by 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 [16]:

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

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

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

Where, the index n denotes the discrete time step, indices i and j denote the discretized grid point in the x-y planes, respectively. The FDTD time stepping is given by:

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

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 $\Delta x = \Delta y \leq \dfrac{\lambda}{10.\sqrt{\varepsilon_r}}$

We have used in this paper a two-dimensional FDTD code that captures the simulation parameters (spatial 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 anti-symmetric). Further details concerning the FDTD method and the Mur absorbing conditions are given in [17-19].

3. Band-pass filters characterization

For simplicity, only a 2D photonic crystal is considered in the present paper as shown in Fig. 1 (a) , i.e., the air holes are infinitely long, 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 the 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 band gap 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. 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.
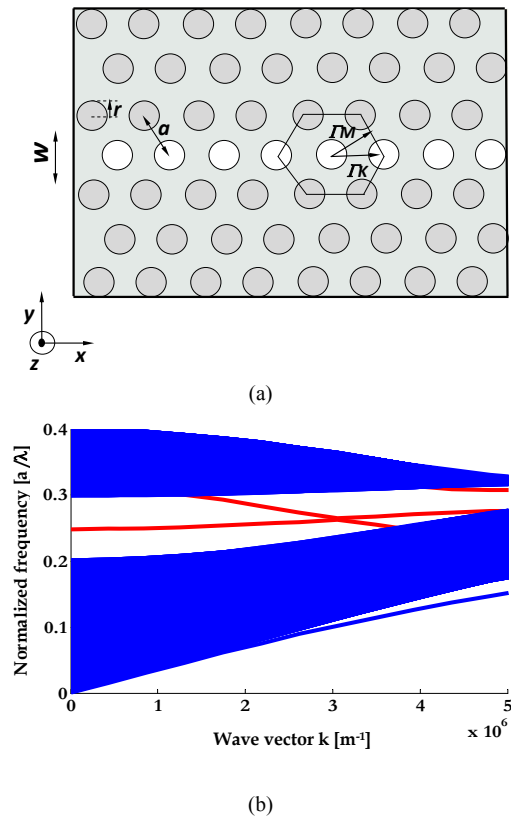

(a)

(b)

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.

4. Simulation results and discussion

In this section, we analyze three different configurations. To determine PhC filters parameters required, we need to specify wavelength range within which filters will be working. In these structures we take one incident wavelengths λ = 1.55 μm since this wavelength is widely used in telecommunications. The waveguide is formed by removing one row of dielectric rods and the Fabry-Pérot (FP) cavities are introduced inside the waveguides by reducing the radius of holes. We note that using one missing row, the mode expansion is suppressed, also the optical volume is then reduced, the mode cannot expand and the excitation of higher order modes is concealed, resulting in efficient filtering. Following the design in Fig. 2, respectively 3, 5 and 7 identical cavities are periodically spaced along the PhC waveguide direction. The size of holes was designed to be r_w= 0.348a and the radius of the inserted holes defects along the PhC waveguide is r_c=0.167a as shown in the inset of Fig. 2.
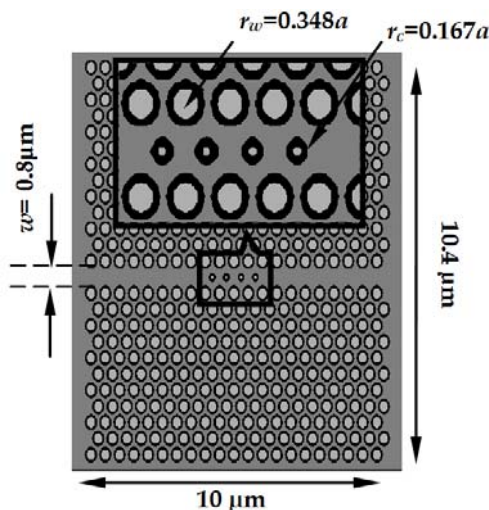

Fig. 2 Design of the triangular photonic-crystal resonant filters using the Fabry-Pérot (FP) cavities.

Structures with three, five and seven cavities are depicted in Fig. 3 (a), (b) and (c).
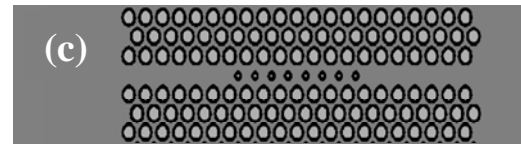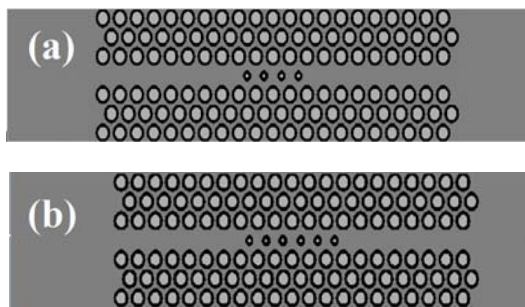

Fig. 3 Resonant band-pass filters realized by cascading Fabry-Pérot (FP) cavities in a one-missing-row PhC waveguide. (a) Three cavities are used utilizing 4 extra rods, (b) five cavities are used utilizing 6 extra rods, (c) Seven cavities are used utilizing 8 extra rods.

Figures 4 and 5, shows respectively the spectral response in transmission and reflection for the pass-band resonant filters and excited by TE mode through a Huygens surface obtained with the 2D FDTD calculation method.
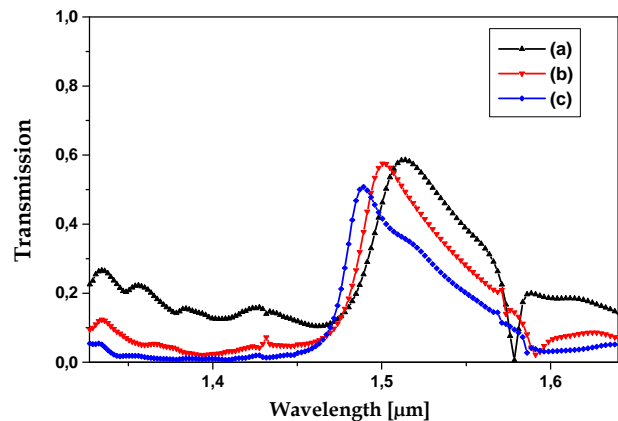

Fig. 4 Normalized transmission spectra obtained by the two-dimensional finite difference time domain (2D FDTD) simulation for the structure illustrated in fig. 3.
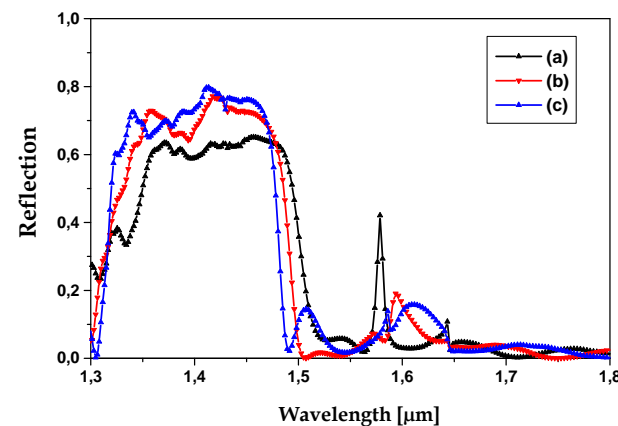

Fig. 5 Normalized reflection spectra obtained by the two-dimensional finite difference time domain (2D FDTD) simulation for the structure illustrated in fig. 3.

Based on our simulation and from fig. 4 we clearly see a selective extraction of the guided light and are transmitted directly toward output (a band that spans the range [1.47 μm-1.57 μm]). The central wavelength 1.55 μm is well covered; such operation can be interpreted as a filter.

Obviously the three curves are different. We obtain a transmission peak of about 62% for the structure (a) and (b) and of about 52% for the structure (c). However, the structure (b) presents good rejection than structure (a). The computed reflection at the transmitted band is almost nul as shown in Fig. 5. It seems that the whole input power is coupled in the waveguide cavities, since it is partially backward scattered into the bus waveguide as shown in Fig. 6 (a), (b) and (c) representing the distribution shape of the magnetic field Hz after 3000 time step. In fact, the reduction of the coupling factor by using small holes yields a reduced backward scattering. These structures act as wide band-pass filters.
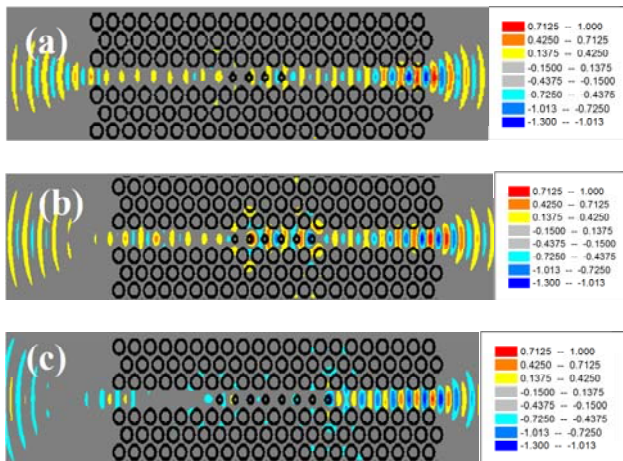

Fig. 6 The distribution shape of the magnetic field Hz excited in TE mode, Δx= Δy=0.04 μm. (a) Three cavities are used utilizing 4 extra rods, (b) five cavities are used utilizing 6 extra rods, (c) Seven cavities are used utilizing 8 extra rods.

In order to improve filtering, a cavity is introduced in the middle by omitting two neighboring air holes in waveguide as illustrated in Fig. 7 (a), (b) and (c). This technique used especially to create resonant cavities.
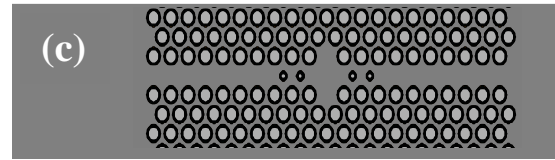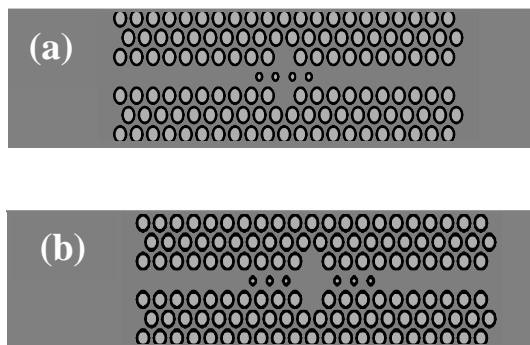

Fig. 7 Resonant band-pass filters realized by cascading (FP) cavities in a one-missing-row PhC waveguide and omitting two neighboring air holes, (a) four cavities are used utilizing 4 extra rods, (b) six cavities are used utilizing 6 extra rods, (c) three cavities are used utilizing 4 extra holes.

The computed transmission and reflection spectra of the simulated filters for TE like polarization of incident light obtained with the 2D FDTD calculation method are depicted respectively in Fig. 8 and 9.
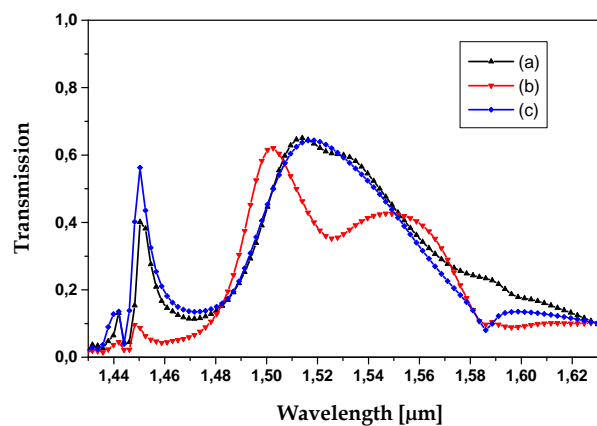

Fig. 8 Normalized transmission spectra obtained by the two-dimensional finite difference time domain (2D FDTD) simulation for the structure illustrated in fig. 7.
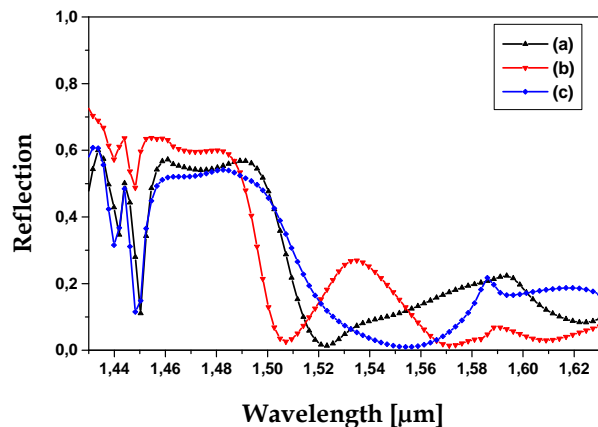

Fig. 9 Normalized reflection spectra obtained by the two-dimensional finite difference time domain (2D FDTD) simulation for the structure illustrated in fig. 7.

From Fig. 8, it is clear that the proposed structure filter the wavelength band [1.47 µm-1.57 µm] around 1.55µm and the maximum peak obtained from output filter (c) is of about 68%. The structure (a) present a wide band than structure (c) as seen from Fig. 8 but the structure (c) presents a good rejection than structure (a). A maximum transmission of about 62% is obtained for structure (b) in the transmitted band. The corresponding reflection at the peak of transmission is null as can be seen from the observation of Fig. 9 for the three structures. The transmission properties are clearly improved with this configuration. If we compare our structure with some litteratures like [20] when the waveguide is combined with a PhC microcavity, the results have shown the extraction of the wavelength 1.55 µm with only [1.54 µm -1.56 µm] band. In addition, the double ring photonic crystal add-drop filter referenced in [21-22] showed a maximum band obtained is [1.537 µm -1.59 µm].

Fig. 10 shows the two-dimensional finite difference time domain simulation results of the magnetic field maps Hz performed on the filters after 3000 time steps.
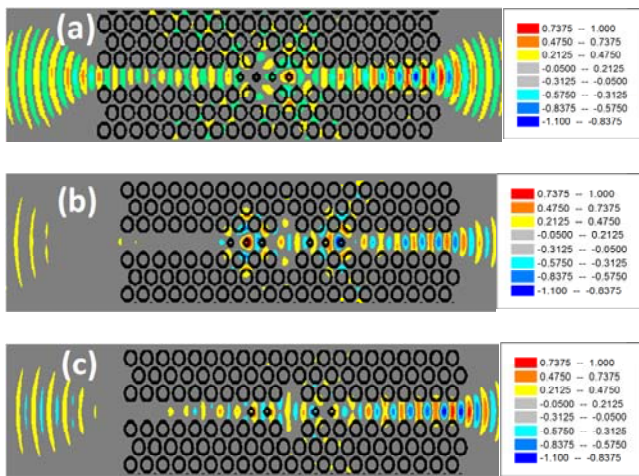

Fig. 10 The distribution shape of the magnetic field Hz excited in TE mode, Δx= Δy=0.04 µm. (a) four cavities are used utilizing 4 extra rods, (b) six cavities are used utilizing 6 extra rods, (c) three cavities are used utilizing 4 extra holes.

Fig 10 respectively shows clearly the return of rejected power to the input waveguide and resonance phenomena in the formed cavities. 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 waveguide.

5. Conclusion

In this paper, a novel filters were proposed and their properties were theoretically investigated by using the Two-dimensional finite-difference time-domain method.

We have proposed two types of filters, the first one is based on the Fabry-Pérot cavities by using one missing row and in the second one a middle cavity is introduced by omitting two neighboring air holes in waveguide. Numerical results show that a band [1.47 µm-1.57 µm] around 1.55µm is transmitted with a maximum transmission about 68% and as a result wide band-pass filters are designed.

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