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Channel drop filter based on coupled cavity in photonic crystals

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Abstract

In this paper, a five channel drop filter has been designed in a two dimensional photonic crystal with high dielectric rods in air. Each channel consists of a photonic crystal coupled cavity waveguide with double cavities combined with a line defect waveguide. Desired wavelengths are selected by setting different radii of the two point defects in the photonic crystal coupled cavity waveguides. Defect rods placed at the same channel have an identical radius. The performance of the designed filter has been numerically calculated using the finite difference time domain method. In the designed structure, higher efficiencies in all channels have been achieved.

Keywords: Photonic crystals; channel drop filter; coupled cavity; wavelength; waveguide.

1. Introduction

Photonic crystals (PCs) are envisaged as the main candidates for developing microscale integrated light wave circuits because of their properties for controlling the flow of light on a very small scale [1, 2]. The periodic change in the refractive index of these artificial materials in one, two or three dimension gives rise to photonic band gaps (PBGs) where no electromagnetic waves can propagate inside the crystal. By introducing defects into PCs, it is possible to build waveguides that can channel light along certain paths. It is also possible to construct microcavities that can localize photons in extremely small volumes. Combinations of these defects in photonic crystals structures give rise to a novel phenomena such us the trapping and emission of photons and the tunneling and channeling of photons [3, 4]. These defects are expected to be key building blocks for miniature photonic functional devices and photonic integrated circuits (PICs).Various optical devices can be realized based on PCs such as optical switches [5], band pass filters [6], band stop filters [7], splitters [8], demultiplexers [9], polarizers [10] and directional couplers [11]. In particular, ultra-compact channel drop filters (CDFs) based on resonant coupling between cavity modes of point defects and waveguide modes of line defects have drawn primary interest due to their substantial demand in wavelength division multiplexing (WDM) optical communication systems.

So far, several structures of channel drop filters based on two dimensional (2D) PCs have been proposed, such us by utilizing the direct coupling between the PC waveguides and microcavities [12, 13]; in which the photons trapped by a resonant cavities are coupled to an in-plane waveguide through direct coupling, can be easily extended to multi-channel drop filters by using a set of microcavities of different sizes, i.e., different resonance frequencies or by changing the shape of the scatterers from a traditional circle to an ellipse [14]. The resonant frequency can be adjusted by altering the orientation angle of the ellipse and the frequency scope can be enlarged by increasing the ratio of the major axis to the minor axis of the ellipse. The concept of in-plane hetero photonic crystals, which consist of a series of connected PC regions with different lattice constants, has also been proposed [15]. Another configuration to consider is a photonic crystal ring resonator (PCRR) in which the CDF is based on the resonant coupling between the ring and the waveguide [16, 17].

Photonic crystal coupled cavity waveguide (PCCCW) [18, 19] has an attractive feature that the slope of guided mode in photonic band gap is smaller than that of PC line defect waveguide (PCLDW), namely the frequency range of light propagation in PCCCW is narrower than that of PCLDW, and therefore PCCCW is more suitable for designing channel drop filter [20, 21] with narrow bandwidth.

In this paper, a five channel drop filter has been designed in a two dimensional photonic crystal with high dielectric rods in air. Each channel consists of a photonic crystal coupled cavity waveguide combined with a line defect waveguide. The channels are located on both sides of the bus (input) waveguide which is terminated with another channel drop filter in order to use the space more efficiently. The PC based coupled cavity waveguide can be formed by placing two photonic crystal cavities close together. All photonic resonant cavities are obtained by varying the radius of one rod in the photonic crystal structure. The performance of the designed filter has been numerically calculated using the finite difference time domain (FDTD) method with the perfectly matched layer (PML) absorbing boundaries conditions at all boundaries [22]. In the designed structure, higher efficiencies in all channels have been achieved.

2. Design of the channel drop filter

We consider a two dimensional photonic crystal composed of square lattice of rods in an air background with lattice constant a=0.484 µm. The refractive index of the rods and the air background is 3.4 and 1, respectively. The radius of rods of perfect PC (with no defects) is r=0.2a µm. The dispersion curves of perfect PC are calculated by using plane wave expansion (PWE) method and shown in Fig. 1. The band gap of the perfect PC exists in the frequency ranges of 0.287-0.420 (a/λ), where λ is the wavelength in free space, which corresponds to wavelength range 1.152-1.686 µm for the waves with transverse magnetic (TM) polarization (for which the incident electric field was parallel to the rods).

In general, if an entire row of rods is removed, a single line defect waveguide (SLDW) is obtained. However, if only one of every two or three or n rods of the entire row is removed, a photonic crystal coupled cavity waveguide is formed. Light propagation in PCCCWs is achieved by photon hopping between nearest neighbour cavities because of the overlapping of the modes localized in the defects [23]. The coupling between the strongly localized cavity modes originates a frequency splitting of the single cavity mode into a number of resonance peaks that depend on the number of coupled cavities.

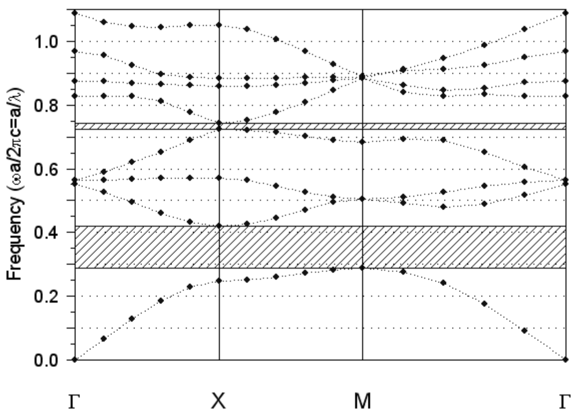
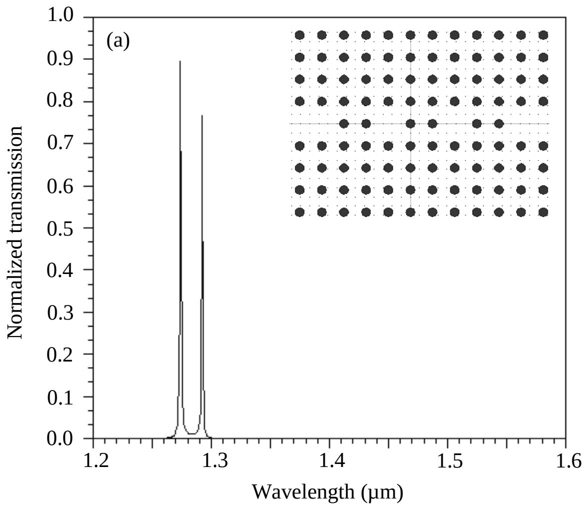


Figure 1. Dispersions curves and band gaps for TM polarization for the photonic crystal structure without defects.

In this paper, we firstly study the PCCCW with double cavities and analyze the effect of changing the distance between cavities on the transmission of it. Fig.2 shows the transmission spectrum of the PCCW for two different distances between the defects. We find from the analysis that when the defects are at close distance from one another, the maximum transmission splits into two peaks, thereby revealing the existence of two different electromagnetic modes (Fig. 2a). However, when the cavity spacing increases, the coupling intensity between neighbouring cavities will become weakened, and a single transmission peak is observed as shown in Fig. 2b.

Based on the above results, we construct a five channel PC drop filter, which is displayed in Fig. 3. The four channels of the CDF are located on the two sides of the bus waveguide. The fifth channel is placed at the end of the bus waveguide. It acts as a channel transmission at its resonance wavelength but works as a reflector for other incident waves at non resonance wavelengths. Each channel consists of a photonic crystal coupled cavity waveguide with double cavities combined with a single line defect waveguide serving as an output waveguide. Desired wavelengths are selected by choosing different radii of point defects in all channels. Every two cavities placed at the same channel have an identical radius of defect. In order to guarantee the negligible coupling between the cavities or the output waveguides, the separation between the cavities were made larger than 4a.



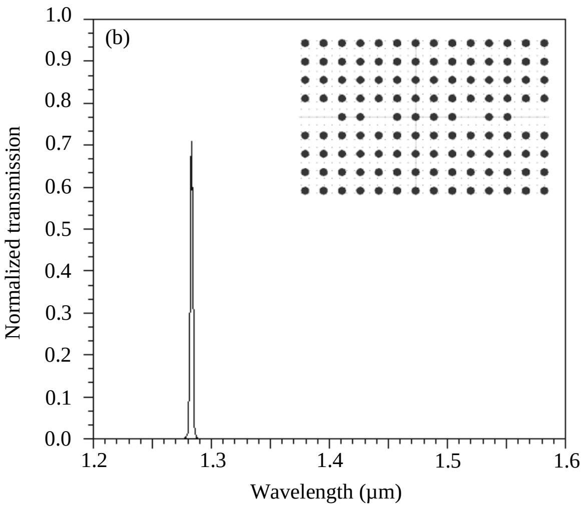


Figure 2. Normalized transmission of the PCCCW with (a) two rods separation, (b) four rods separation. The corresponding waveguide structures are shown in insets, respectively.

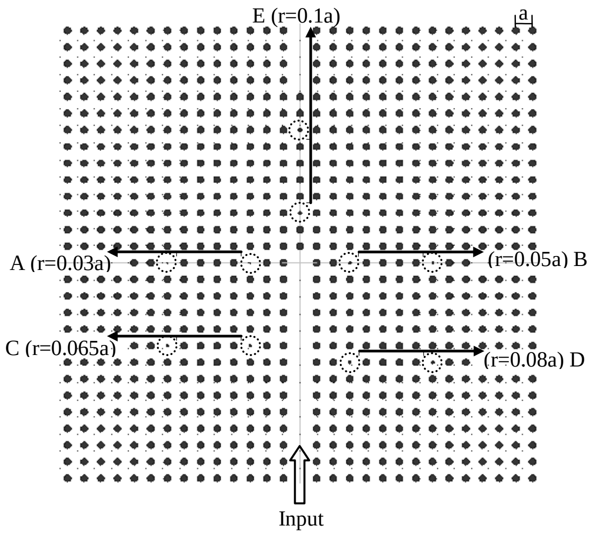


Figure 3. Schematic of the five channel drop filter.

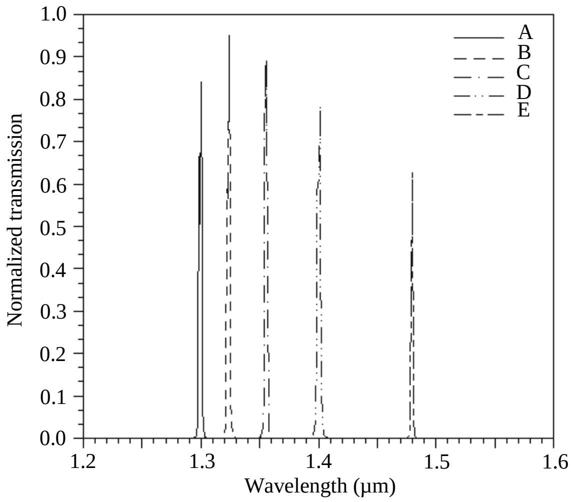


Figure 4. The normalized transmission spectra for ports A (1.3 µm), B (1.3239 µm), C (1.3561 µm), D (1.4 µm) and E (1.48 µm).

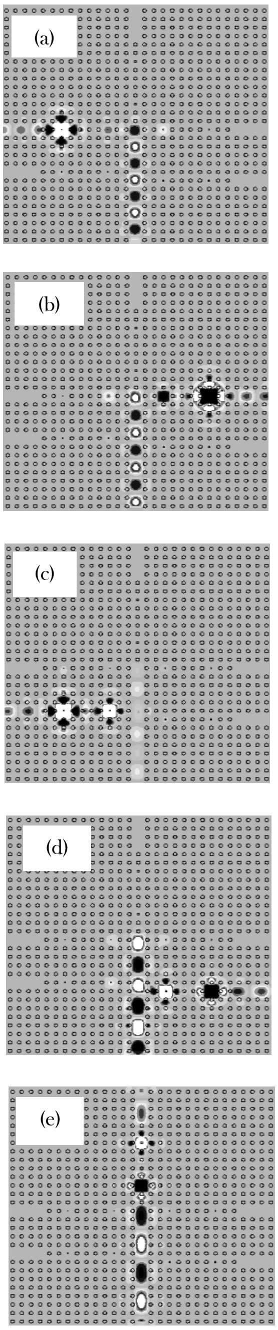


Figure 5. Field distributions at (a) λ=1.3 μm, (b) λ=1.3239 μm, (c) λ=1.3561 μm, (d) λ=1.4 μm and (e) λ=1.48 μm.

3. Simulation and results

The FDTD is one of the most advanced methods today for computation of the field distribution inside the PC based devices which are really optical structures with non uniform dielectric constant distribution.

Different defect cavities are put on the two sides of the bus waveguide to avoid the direct coupling and to reduce the size of the structure. The radius of the defect rods are r=0.03a, 0.05a, 0.065a, 0.08a and 0.1aμm for channels A, B, C, D and E, respectively. Location of each cavity is chosen properly in order to get maximum transmission. Fig.4 shows the normalized transmission of the proposed multi-channel drop filter for TM polarization of incident light. The center wavelengths of the five channels are λ=1.3, 1.3239, 1.3561, 1.4 and 1.48 μm from outputs A, B, C, D and E, respectively. The normalized transmissions of these wavelengths are 83.5, 96.67, 89.67, 78 and 63.5 %, respectively. It is seen from the results shown in Fig. 4 that the proposed multi-channel drop filter can easily separate the light with five different wavelengths simultaneously with high drop efficiency. In order to demonstrate the filter performance, we simulate the field distributions of this filter at the resonance wavelengths as shown in Fig. 5.

4. Conclusion

We have designed a five channel drop filter based on a two dimensional photonic crystal with a square lattice of dielectric rods in air. It was found that the resonant frequency can be flexibly adjusted by just changing the radius of rod defects in the photonic crystal coupled cavity waveguide. The transmission properties of such structure show that the incident light can be successfully filtered to five different ports and high drop efficiency can be achieved. Such structure may offer promising applications for photonic integrated circuits based on PCs and other nanophotonic structures.

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