Design of a New Narrow Band Channel Drop Filter Based on a Photonic Crystal Ring Resonator

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Abstract

In this paper a novel structure for narrow band Channel Drop Filter (CDF) using 2D photonic crystal with a square lattice based on ring resonator is proposed. In this design, an optical ring resonator is embedded between two Horizontal input and output waveguides with 4 orbitals around the center of the resonator so that each orbital consists of 8 rods in which the radius of larger orbital rods is bigger than the radius of smaller orbital rods. The analysis of simulation results showed the proposed filter has the transmission efficiency of 100% at the resonance wavelength of 1550 nm, bandwidth and quality factor are 0.2 and 7753, respectively. This proves that it is a suitable filter for optical communication applications. Ultra-low bandwidth and high transmission efficiency are the most important advantages of the proposed filter in this study. Therefore, it is proved that this filter is usable and suitable for optical communication applications.

Keywords: Photonic Crystal, Channel Drop Filter, Bandwidth, Quality Factor.

1. Introduction

Photonic crystals (PCs) are composite periodic dielectric materials in which Refractive Indexes are periodic in one, two and three dimensions [1, 2]. Photonic crystals are recently used for designing all the optical devices suitable for optical integrated circuits. The first works about photonic crystals (PhCs) have been done by John and Yablonovich in 1987 [3]. Some advantages such as confining light in small regions [4], high speed, high capacity, high performance, long life and compactness [5] made PhCs as a proper option for photonic integration. Besides, the most important practical characteristic of the PhCs is the presence of a wavelength region in which no optical waves can propagate inside the structure called Photonic band gap (PBG) [6]. The PBG region in 2D PhCs is dependent on the refractive index of the dielectric materials, the shape of the rods, the crystal structure, the radius of the rods and the lattice constant of the structure [7]. This special features of the PhCs (i.e. Photonic band gap) enabled designing optical devices in more efficient ways. Optical filters [8], THz filter [9], optical gate [10], optical demultiplexers [11], biosensor [12] and power splitters [13] are some examples of optical devices designed based on PhCs.

Many optical filters based on photonic crystals, suitable for communication application, have been proposed by researchers. Recently, Kumar et al. [14] designed a tunable filter using Si-based one-dimensional photonic crystals in which tuning was achieved by variation of temperature of the Silicon layers.

A tunable optical filter based on a photonic crystal ring resonator was proposed by Rakhshani et al [15] through which tuning the proposed filter was investigated by changing the dielectric constant and radius of different rods. An ultra-narrow band channel drop filter based on a photonic crystal ring resonator with hexagonal lattice having bandwidth of 1nm was proposed by M.R. Almasian [16]. In the following sections procedure of filter designing, simulation and results' analysis are discussed.

2. Design procedure

The proposed structure consists of 2D photonic crystals with square lattice that is comprised of a 23*21array of dielectric rod with refractive index of 3.42 and radius of 0.22a (**nm) that are embedded in the air background with refractive index of 1. Lattice constant of structure (a) is considered to be 520 nm as well. In order to obtain the band structure diagram of the basic structure the plane wave expansion (PWE) method [17] is used.

The band-diagram of the proposed filter is displayed in Fig. 1. As it can be seen in this figure, there are 3 PBGs, 2 PBGs in TM (Transverse Magnetic) mode and one in TE (Transverse Electric) mode. TM PBGs are at $0.270<a/\lambda<0.394$ and $0.522<a/\lambda< 0.548$ and TE PBG is at $0.766<a/\lambda<0.782$. The first PBG is at $1319<\lambda<1925$nm which is suitable for optical communications. Since this PBG is at TM mode, the simulations were done at TM mode as well. The proposed CDF consists of 2 horizontal linear defects as bus waveguides (input port) and drop waveguides (output port) and one ring resonator located between these waveguides. First two waveguides are created by removing two rows of 5 dielectric rods and then to create the ring resonator, a 9*9 array of dielectric rods in the middle of the structure was removed and a ring resonator has been located inside the empty square.

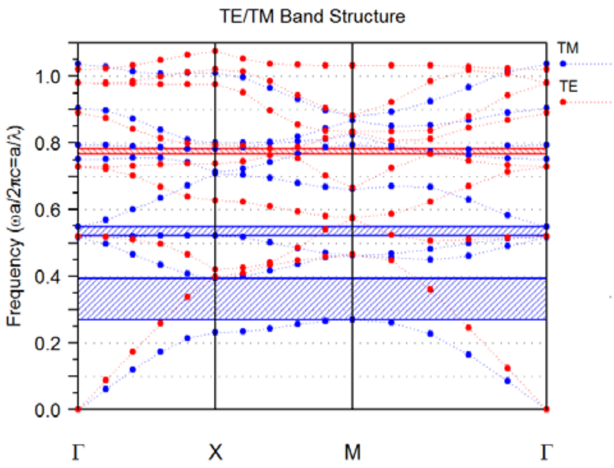

Fig.1. The band structure of the basic PhC

The resonator has 4 orbitals around the center of the resonator and each orbital has 8 dielectric rods as well. The refractive index of rods of the resonator is the same as the basic structure. The distances of the orbitals from the center of the resonator are A1, A2, A3 and A4, respectively, and the radius of the orbital rods is R1, R2, R3 and R4, respectively. The radius of rods and the distance from the center of the resonator are calculated as follows: D1=0.1µm,

A1=D1, A2=1.5*A1,

A3=2.25*A1, A4=3.5*A1,

R1=0.35*D1=0.35, R2=1*D1=0.1,

R3=2.5*D1=0.25, R4=4.5*D1=0.45.

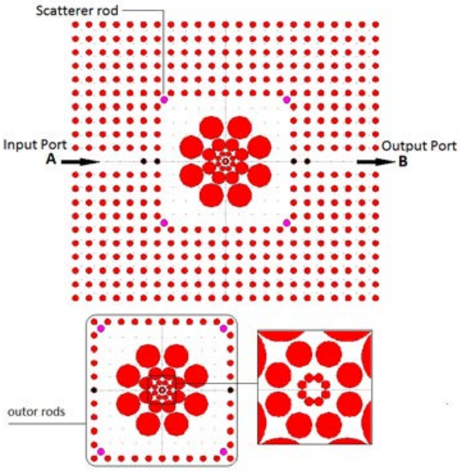

Fig.2. Schematic diagram of the filter

To reduce the effect of opposite propagation modes in sharp corners of the ring, 4 scattering rods (R_s') (indicated by violetcolor) at each corner of the resonator with half lattice constant have been located and their refractive indexes are the same as the basic structure and their radius is 0.911*R. The final structure of the filter is shown in figure.2. In both sides of the resonator between the waveguides and the resonator, two coupling rods were placed and in order to achieve better transmission efficiency, the radius of couplings rods is set to 1.1 * R .

3. Simulation and Results

The transmission characteristics of proposed CDF are calculated using a Finite difference time domain (FDTD) method [18]. The proposed structure has one input port (labeled as A) and one output port (labeled as B) as shown in figure 2. A light source of Gaussian distribution with TM polarization is applied into the input port that records the transmitted power spectral density. According to the value of the radius of resonator rods and their distance from the center of the resonator (as mentioned in previous section), the size of the resonator is determined by changing d1.

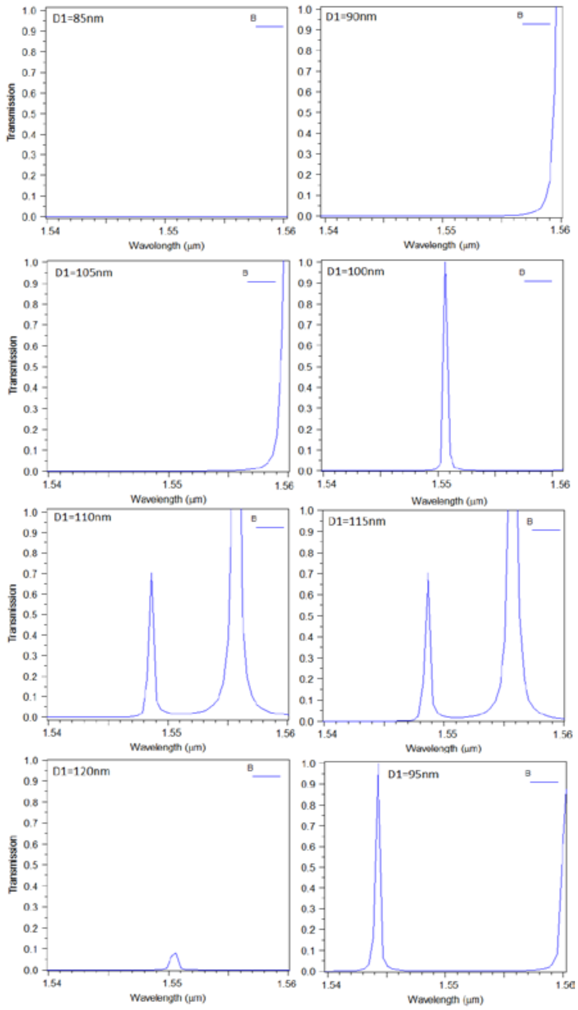

Fig.3. The effect of different d1 on the output spectra by sweeping it in the range of 85-120nm.

Changing the value of d1 leads to changing the value of radius of orbitals around the central as well as overall size of the ring resonator. Fig. 3 shows the effect of different d1s on the output signal by sweeping it in the range of 85–120nm. As shown, the maximum drop efficiency at d1=100 nm and d1=120 nm is achieved, but the bandwidth of the dropped signal for these values are 0.2 nm and 0.25nm, respectively. Hence, d1=100nm is considered as the best value in this stage.

Normalized transmission spectrum of the output port (B) is displayed in Fig. 4. As it can be seen, whole power transfer from the input to the output port through the ring resonator in the present filter is only possible at the resonance wavelength of 1550 nm. Drop efficiency of 100% is achieved at operating wavelength of 1550 nm that has bandwidth and quality factor of 0.2nm and 7753, respectively.

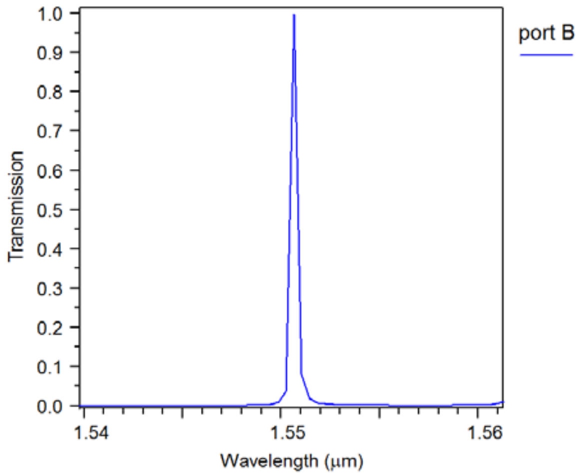

Fig.4.Output spectrum of the proposed filter

Figs. 5(a) and (b) show the electric field distribution of the CDF at the resonance wavelength (1550 nm) and off-resonance (1560 nm) which are attained by applying a continuous light source to the port A. It can be observed that the waves for both wavelengths do not scatter inside the structure due to the PBG effect and only propagate inside the waveguides.

As shown in Figure 5(a), at wavelength of 1550nm optical waves dropped to port B through ring resonator, while figure 5(b) shows that at wavelength of 1560nm the resonance does not occur and these waves could not drop to output port**.** The effect of various items on the output wavelength of the filter is investigated in the following sections.

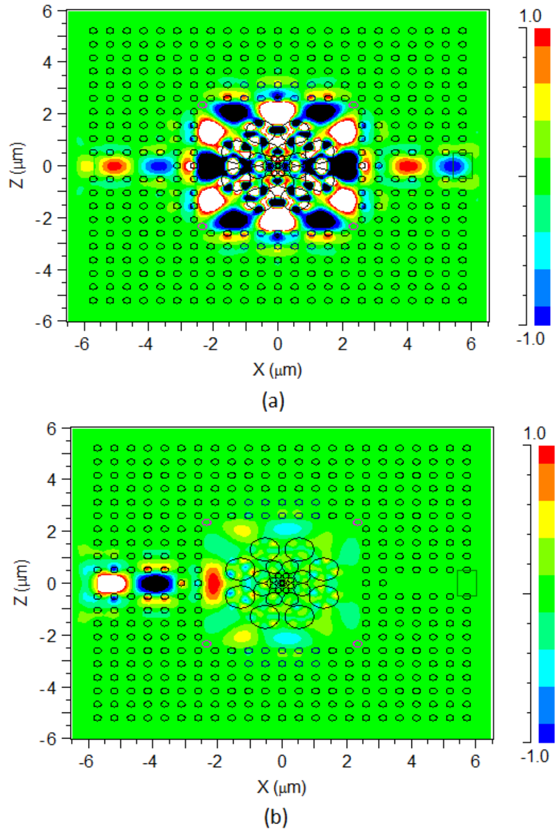

Fig.5.Distribution of optical power at (a) λ=1550 nm and (b) λ=1560 nm

3.1. The effect of adding a rod to the center of the resonator

According to figure (6), a rod with size of R1 is placed in the center of the resonator, and its refractive index is the same as the basic structure. The output wavelength of filter without central rod is compared with that of filter with central rod and it is shown in Table 1.

Its shows that the output wavelength and transmission efficiency remained unchanged while the quality factor decreased. According to obtained quality factor, it can be concluded that a structure without central rod provides better response.

Table 1: Significant parameters of the proposed filter without central rod and with central rod

Filter	λ_0	$\Delta\lambda$	Q	TE[a](%)
with central rod	1550.7	0.2	7753	100
without central rod	1550.7	0.21	7384	100

a: Transmission Efficiency

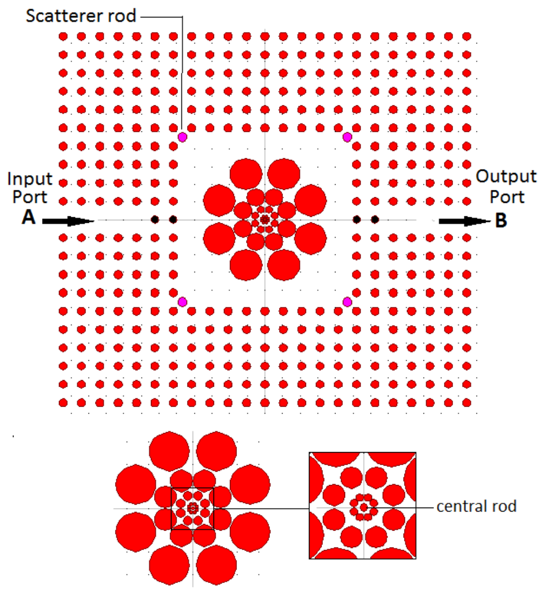

Fig.6. Schematic diagram of the filter with central rod

3.2. The effect of deformation of the outer rods of resonator from square-shaped to octagon-shaped

According to Figure (7-a), the Arrangement of outer rods is changed from square-shaped into octagon-shaped. Filter output spectrum in this new arrangement (octagon-shaped) is shown in the Fig (7-b). As it can be seen, in this case the filter has not appropriate output at wavelength of 1550nm and the filter in the case of resonator with square-shaped outer rods provides more appropriate response.

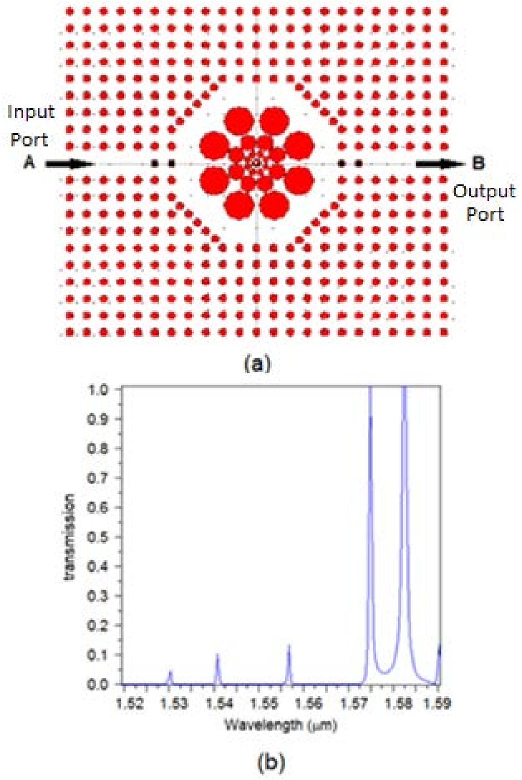

Fig.7. (a) Schematic diagram, (b) Output spectrum of the filter with the octagon-shaped of outer rods

3.3. The effect of deformation of the outer rods of resonator from square-shaped to circle-shaped

According to Figure (8-a), the arrangement of outer rods is changed from square-shaped to circle-shaped. Filter output spectrum in this new arrangement (circle-shaped) is shown in Fig (8-b). As it can be seen, in this case the filter has output at wavelength of 1548nm with transmission efficiency, bandwidth and quality factor of 71%, 3225 and 0.48, respectively, which are not desired in comparison with the results obtained in the case of a resonator with square-shaped outer rods. The details of the filter output wavelength in both cases are shown in Table 2. According to the table, a filter with the square-shaped outer rods provided more suitable output compared with a filter with the circle-shaped outer rods.

Table 2. Significant parameters of the proposed filter with the square-shaped outer rods and the circle-shaped outer rods

Filter	λ_0	$\Delta\lambda$	Q	TE^a(%)
With the square-shaped outer rods	1550.7	0.2	7753	100
With the circle-shaped outer rods	1548.3	0.48	3225	71

a: Transmission Efficiency

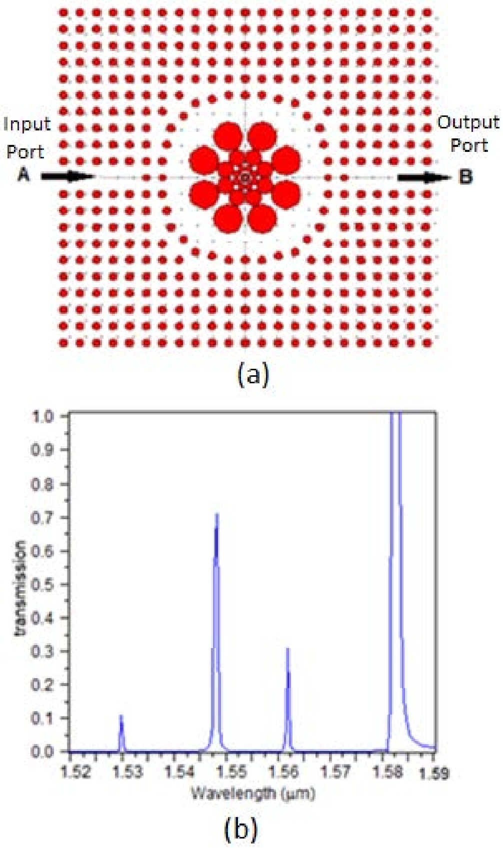

Fig.8. (a) Schematic diagram, (b) Output spectrum of the filter with the circle-shaped outer rods

4. Conclusions

In this paper a novel structure for channel drop optical filter using 2D photonic crystals with a square lattice based on ring resonator is proposed. In this design, an optical ring resonator is embedded between two horizontal input and output waveguides with 4 orbitals around the center of the resonator so that each orbital consists of 8 rods with different sizes in which radius of larger orbital rods is bigger than radius of smaller orbital rods. In order to obtain the band structure diagram of the basic structure, the plane wave expansion (PWE) method is applied and the transmission characteristics of proposed CDF are calculated using FDTD method.

The proposed filter has the transmission efficiency of 100% at the resonance wavelength of 1550 nm and bandwidth and quality factor of this filter are 0.2 and 7753, respectively. The ultra-low bandwidth and high transmission efficiency of the proposed filter made it as a suitable filter for optical communication applications. In this study the effect of different parameters such as adding a rod to the center of the resonator and deformation of the outer rods of resonator from square-shaped to octagon-shaped and circle-shaped on output wavelength of the filter were investigated. The results obtained in the present work showed that due to more favorable output spectrums and more optimal responses, the initial plan of filter with the square-shaped outer rods of resonator is a more appropriate choice compared with the other filters considered in this study.

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