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Optical filter based on photonic crystal

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In the present paper, a novel structure for designing all optical filter based on photonic crystal structure is proposed. The filter is capable of selecting optical signals at wavelength of 1550 nm and the total footprint is less than 118 μm^2.The transmission efficiency and bandwidth were obtained as 92% and 0.9 nm, respectively. After designing the filter, the impact of different parameters on the filtering behaviour of the structure has been studied. Simplicity of design and ultra-compact dimensions is the most significant characteristics of the filter.

Keywords: Photonic crystal, Optical filter, Defect, Finite difference time domain method

1 Introduction

Currently optical communication networks are one of the best solutions used in data transmission across very large distances while keeping high bit rates. In order to have full advantage of optical communication networks, an all optical network is needed, which is composed of full optical devices such as optical filters, optical de-multiplexers, optical switches, etc. Optical filters play a crucial role in such networks and can be used to remove noise and unwanted signals from the original channel. They are also employing in wavelength division multiplexing (WDM) systems for designing optical de-multiplexers.

Photonic crystals (PhCs) are regular arrays of dielectric materials in which the distribution of the refractive index is periodic. This periodicity of the refractive index creates a wavelength region in the band structure of the PhC, in which the propagation of electromagnetic waves including optical waves is forbidden, this wavelength region is called Photonic Band Gap[1,2] (PBG). The ability of controlling light in ultra-small dimensions makes them suitable candidates for designing all optical devices designed using photonic crystals.

The simplest PhC based filter can be realized by introducing a defect layer inside a 1D photonic crystal structure, which results in a very sharp defect mode inside the PBG of the original PhC structure that can be used as a narrow band filter[3]. If we replace the defect layer via quantum well we will have a multichannel filter[4].Another way of realizing multichannel filter based on 1DPhC is replacing dielectric layers by superconducting PhC, in these structures there is no defect layer[5]. It has been shown that by combining two defective 1DPhC, one with negative refractive index defect layer and the other with positive refractive index defect layer we will have a narrow band and narrow transmission angle filter[6]. Other kind of filters based on 1DPhCs is the reflection or band reject filters like anti-UVB filter[7]. All of these aforementioned filters are based on 1D PhCs. 1D PhCs do not have complete band gaps so their optical behaviour is very sensitive upon the incident angle of the input light.

Beside 1D structures, 2D PhCs due to their complete band gaps are not sensitive upon the incident angle of input light. Different mechanisms have been proposed to design optical filters based on 2DPhCs. One way of realizing optical filter in 2DPhCs is putting a resonant cavity between input and output waveguides[8]. It has been shown that the resonant wavelength of the cavity can be controlled by changing the effective length of the resonant cavity. Using quasi crystal structures is another way of realizing optical filters[9] based on 2DPhCs. The most common mechanism used to design 2DPhC based filters is ring resonators[10]. Different kinds of ring resonators have been proposed most recently[11-13]. In these structures, the resonant wavelength depends on the refractive index and dimensions of the resonant ring[14].

In the present paper, an optical filter based on 2D photonic crystal structure is proposed. The wavelength selecting mechanism of the proposed filter is based on a resonant cavity with reduced radius of the rods. High transmission efficiency, ultra-compact dimension and simplicity of design are the most significant advantages of the filter.

2 Filter Design

In order to design the proposed structure, we use 2D PhC as the basic platform, which is composed of square lattice dielectric rods immersed in air medium. The PBG region of the basic platform should be adjusted according to the optical communication wavelength (1550-1600 nm) range. In 2D PhCs, PBG depends on the refractive index of dielectric rods and ratio of the radius[15] of dielectric rods (r) to lattice constant (a) of PhC. The variation of PBG region versus refractive index and radius to period ratio are shown in Fig. 1. The PBGs in TE and TM modes are shown via red and blue colored areas, respectively (Fig.1). It is observed that PBG regions in TM mode are dominant and by increasing the refractive index the PBGs shift towards lower normalized frequencies and the gaps are being widen. Also, by increasing the r/a ratio the PBGs shift towards lower normalized frequencies too.

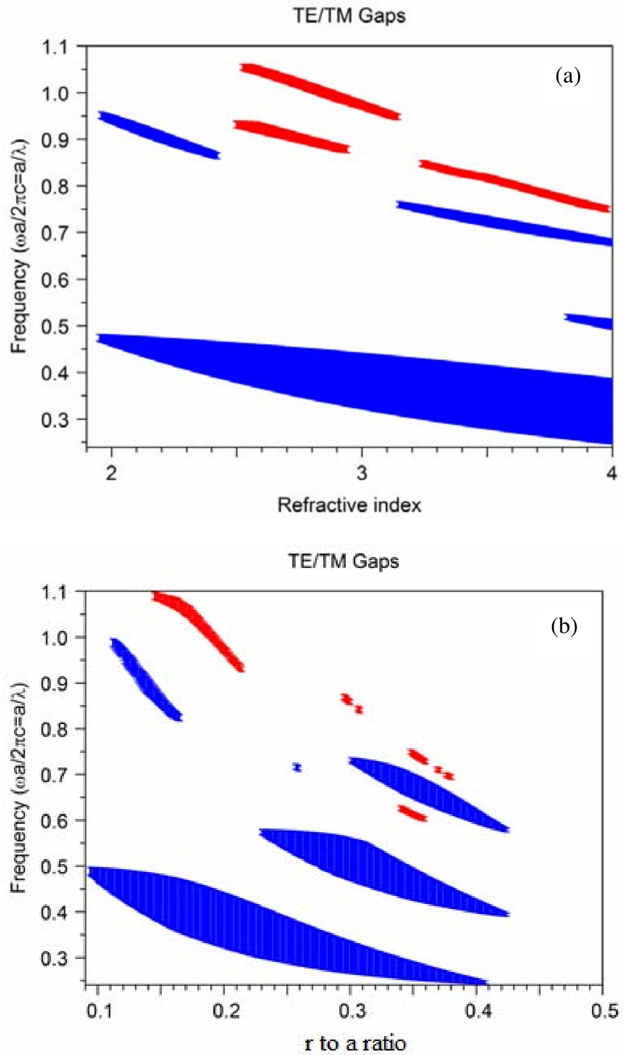

Fig. 1 — Variation of PBG region versus (a) refractive index and (b) radius to period ratio

In the basic platform, the number of dielectric rods in x and z directions are 21 and 15, respectively. The effective refractive index of dielectric rods is 3.47. The radius of rods to period ratio is 0.2. The band structure diagram for this PhC is shown in Fig. 2. This structure has two PBGs in TM mode that is shown by dark area in the band structure of the PhC. It is observed from Fig. 2 that the first PBG is in the range of $0.28<a/\lambda< 0.42$.Considering a=558 nm, the PBG will be at1328 nm $<\lambda<$1992 nm.

To design the proposed filter, first we create a line defect by removing 16 rods in X direction, which works as the input waveguide of the filter as shown in Fig. 3. Then, by reducing the radius of 3 rods in Z direction close to the input waveguide, we created the reduced resonant defect. Finally, 8 rods in the Z direction were removed to create the output waveguide of the filter. The reduced defect rods are shown with blue color and their radiuses (R_d) are equal to 60 nm. The dielectric rods on left and right sides of the defect rods are shown in red colour, their radia R_s are 120 nm. These rods are shifted towards the centerline of the resonant defects by L. The initial value of shift is zero.

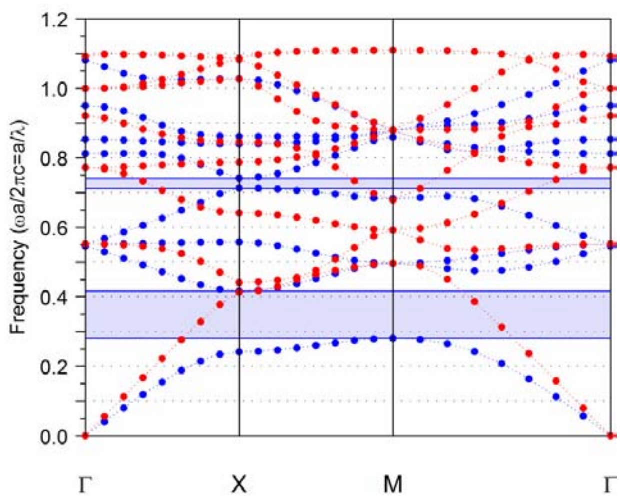

Fig. 2 — Band structure of the basic PhC

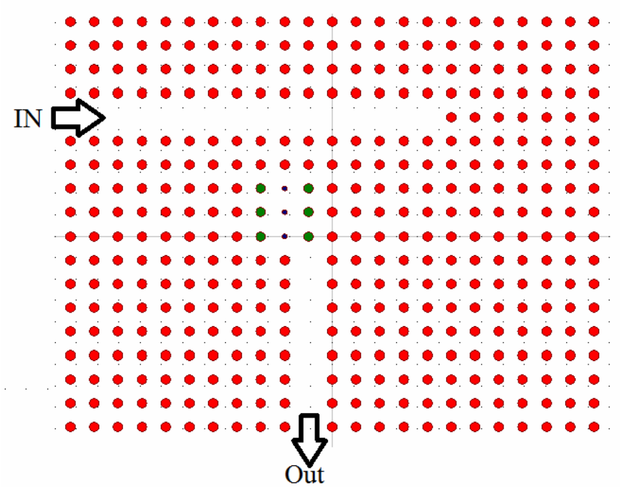

Fig. 3 — Final sketch of the proposed filter

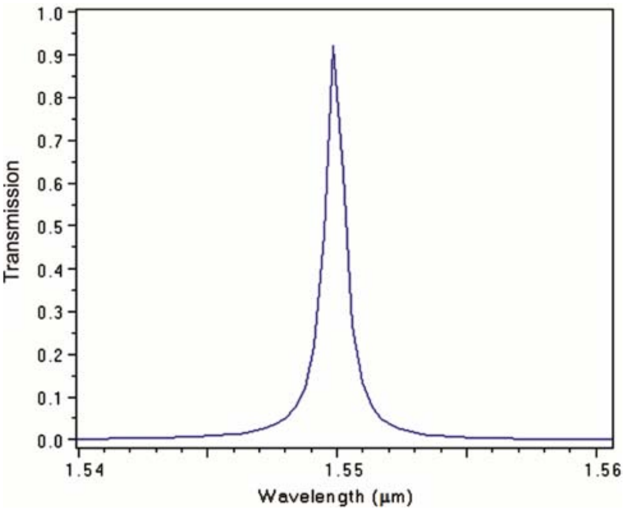

Fig. 4 — Output spectrum of the filter

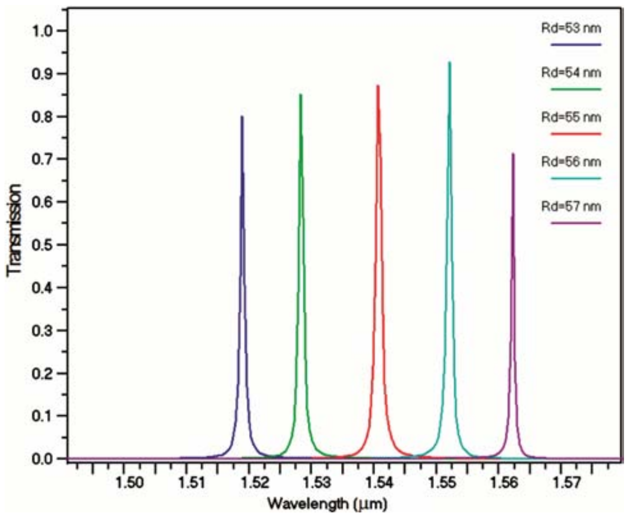

Fig. 5 — Output spectra of the filter for different values of R_d

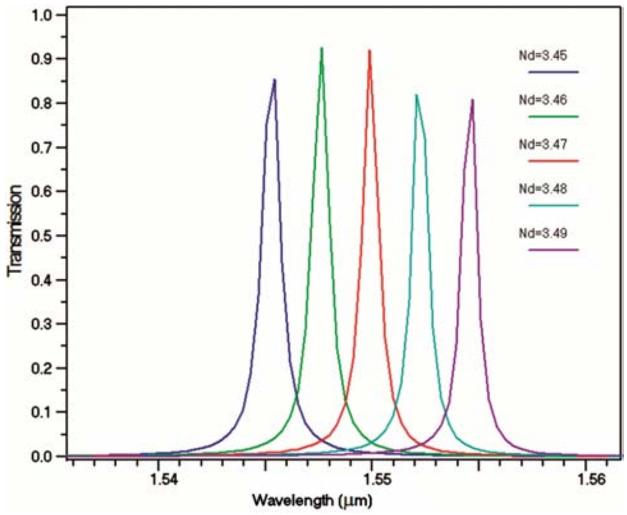

Fig. 6 — Output spectra of the filter for different values of N_d

3 Simulation and Results

By employing Fullwave simulation tool of RSoft photonic CAD software, the proposed filter is simulated. Fullwave studies the propagation of light inside PhC based devices using finite difference time domain (FDTD) method[16]. Figure 4 shows the output spectrum of the filter which only selects the wavelength of 1550 nm, the bandwidth ($\Delta\lambda$) is 0.9 nm and the Q-factor ($Q=\lambda_0/\Delta\lambda$) is 1722. The transmission efficiency of this filter is 92%. It is also investigated, how much the output wavelength of the filter is sensitive upon structural parameters.

The output spectrum of the structure for different values of R_d-radius of defect rods-is shown in Fig. 5. By increasing R_d, output wavelengths are shifted to longer wavelengths, because the resonant wavelengths increase. Such that for R_d=53, 54, 55, 56, and 57 nm the output wavelengths are 1519, 1529, 1541, 1552 and 1562 nm, respectively. The detailed

Table 1 — Significant parameters of the proposed filter for different values of R_d

R_d	λ (nm)	$\Delta\lambda$ (nm)	Q	*T. E.** (%)
53	1519	0.8	1899	80
54	1529	0.8	1911	87
55	1541	0.9	1712	88
56	1552	0.9	1724	93
57	1562	0.9	1736	71

*Transmission efficiency

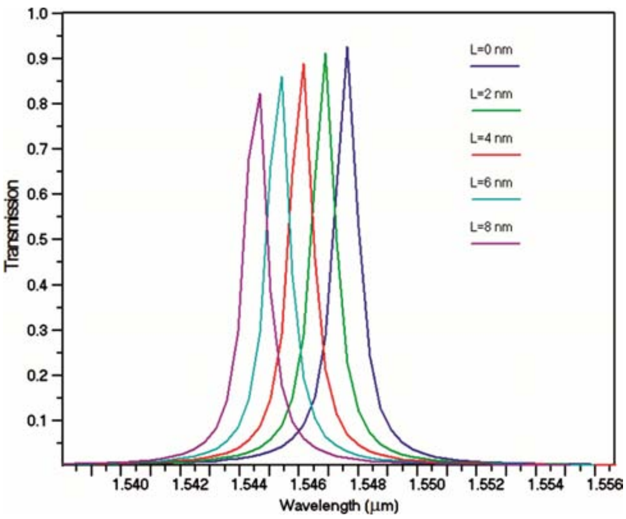

Fig. 7 — Output spectra of the filter for different values of L

Table 2 — Significant parameters of the proposed filter for different values of N_d

N_d	λ (nm)	Δλ (nm)	Q	*T. E.** (%)
3.45	1545	1	1545	86
3.46	1548	0.9	1720	93
3.47	1550	0.9	1722	92
3.48	1552	1	1552	82
3.49	1555	1	1555	80

*Transmission Efficiency

Table 3 — Significant parameters of the proposed filter for different values of L.

L	λ (nm)	Δλ (nm)	Q	*T. E.** (%)
0	1547.6	0.9	1720	93
2	1546.8	0.9	1719	91
4	1546.1	0.9	1718	89
6	1545.3	0.9	1718	86
8	1544.6	0.9	1717	82

*Transmission efficiency

specifications of the output wavelengths for different values of R_d are listed in Table 1.

The output spectrum of the structure for different values of N_d-refractive index of defect rods-is shown in Fig. 6. By increasing N_d, the resonant wavelength is also increased and shifts output wavelength to higher values. It has been shown for N_d =3.45, 3.46, 3.47, 3.48, and 3.49 nm the output wavelengths are 1545, 1548, 1550, 1552 and 1555 nm, respectively. The details of the output wavelengths for different values of N_d are listed in Table 2.

Figure 7 shows output wavelengths of the proposed filter for different values of L. As the value of L increases, the resonant wavelength becomes shorter and then output wavelength shifts to shorter value. One can see λ=1547.6, 1546.8, 1546.1, 1545.3 and 1544.6 nm are obtained for L=0, 2, 4, 6, and 8 nm, respectively. Other parameters of the filter are given in Table 3.

4 Conclusions

In the present paper employing a reduced defect cavity inside a 2D photonic crystal, an optical filter is proposed. The total footprint of the filter is less than 118 μm^2. The proposed filter had transmission efficiency and quality factor equal to 92% and 1722. Using numerical methods such as PWE and FDTD, we obtained the optical properties of the proposed structure and investigated the effect of different parameters on the output wavelength of the filter. The results demonstrated that by increasing the radius and refractive index of defects output wavelength became longer, however increasing value of L-horizontal shift of side rods toward cavity center line-resulted in a shift for the output wavelength to shorter wavelengths.

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