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Channel drop filter based on photonic crystal ring resonator

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Photonic crystal ring resonators are promising candidates for realizing all optical filters with acceptable transmission efficiency and quality factor values. In this paper, by putting a hexagon-shaped structure at the middle of on 7 × 7 square cavity we created a ring resonator structure and designed a channel drop filter. The drop wavelength of our filter is at 1550.4 nm, with transmission efficiency and quality factor equal to 94% and 707, respectively. Our structure is composed of dielectric rods immersed in air. Because in this kind of structures the dominant band gap is in TM mode, all of our simulations have been done in TM mode. The total footprint of our filter is 199.4 μm^2, which makes it suitable for all optical integrated circuits.

Keywords: photonic crystal, optical filter, ring resonator, quality factor.

1. Introduction

Considering the ever increasing trend toward optical communication networks based on fiber optics communications, we understand the significant importance of all optical devices. The optimum goal for optics and photonics engineers is having a complete optical network without any electronics. Reaching this goal needs all optical devices such as optical filters, optical demultiplexers, optical switches, *etc*. Optical filters are one of the most important building blocks of optical communication networks, which play a crucial role in wavelength division multiplexing (WDM) technologies. Optical filters can be used for separating nearly spaced optical channels from each other in WDM applications.

Currently photonic crystals (PhCs) are the best candidates used for designing all optical devices suitable for integrated optical circuits. PhC are regular arrays of dielectric materials with periodic refractive index distribution [1]. The periodic nature of these structures results in a special frequency region in the band structure diagram of them, in which the propagation of optical waves is prohibited. These frequency regions are called photonic band gap (PBG) [2, 3]. Optical filters [4–6], optical demultiplexers [7–11], optical switches[12, 13], optical logic gates [14, 15], *etc.*, are some examples of optical devices designed based on PhCs.

Photonic crystal ring resonators (PhCRR) are composed of two waveguides, namely bus and drop waveguides and a resonant ring located between them. At a certain wavelength – resonant wavelength – optical waves in the bus waveguide will drop to the drop waveguide through the resonant ring. DJAVID *et al.* [16] proposed a T-shaped channel drop filter (CDF) based on PhCRRs and investigated the effect of different parameters on switching wavelength. They found that dielectric constants of the inner rods and coupling rods are suitable parameters for tuning the filter. Multichannel-drop filter using PhCRR is the most recent work done by DJAVID and ABRISHAMIAN [17]. YOUCEF MAHMOUD *et al.* [18–20] proposed another channel drop filter based on X-shaped ring resonator structure.

The rest of the paper is organized as follows: in Section 2 we discussed the design procedure of the demultiplexer, in Section 3 we proposed the simulation results, and finally in Section 4 we concluded from the our work and results.

2. Filter design

The fundamental platform used for designing the proposed filter is 33 × 21 square lattice of dielectric rods immersed in air. The effective refractive index of dielectric rods is 3.46. And the radius of dielectric rods is $R = 0.185a$, where a is the lattice constant of the PhC structure. The band structure diagram of the PhC with aforementioned values is depicted in Fig. 1. Figure 1 shows that our structure has two PBGs in TM mode (dark blue area). These TM PBGs are in $0.295 < a/\lambda < 0.44$ and $0.73 < a/\lambda < 0.75$ range. Only the first PBG in TM mode is wide enough for covering the sufficient wavelengths

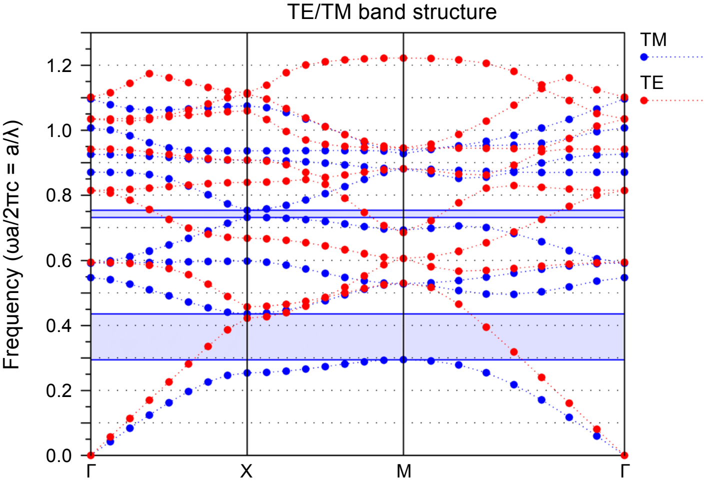

Fig. 1. The band structure of the fundamental structure.

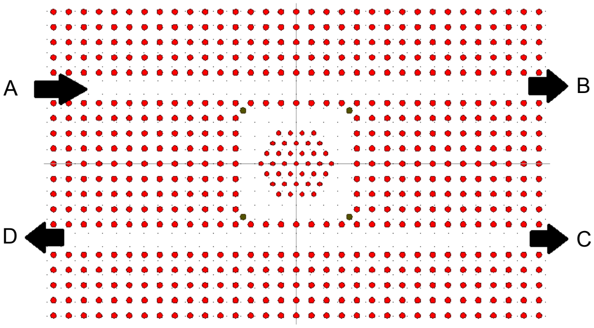

Fig. 2. The final sketch of the proposed filter.

for optical communication applications. In order to have maximum compatibility with optical communication ranges, we choose the lattice constant to be $a = 548$ nm. So the suitable PBG of our initial PhC structure will be in 1245 nm $< \lambda <$ 1875 nm range in TM mode, therefore all the simulations will be done in TM mode.

Our proposed CDF is composed of three main parts: two line defects as bus waveguide (the upper one) and drop waveguide (the lower one) and a resonant ring located between the waveguides. For creating the resonant ring, first we removed a 7 × 7 square of rods and then placed a hexagon-shaped structure in the middle of the resulted empty square area as the core of the resonant ring. The core structure of the ring is different from the fundamental structure. Its lattice type is hexagonal. The radius of core structure rods is $R = 0.185A$, where $A = 0.775a$ is the lattice constant of the core structure. The refractive index of the core structure is the same as the fundamental structure.

Similar to any other PhCRR-based CDF our proposed structure has four ports: input port A, forward transmission port B, forward drop port C and backward drop port D. Optical waves enter the structure through port A and exit it from port B, however at the desired wavelength, the optical waves drop to the drop waveguide through the resonant ring and travel toward port C. We introduced four scattering rods at the corners of the square for improving the transmission efficiency and the performance of the resonant ring. These scattering rods are shown in green color to be distinguished from other rods. The radius and the refractive index of these scattering rods are the same as the fundamental structure. The final sketch of the proposed PhCRR-based CDF is shown in Fig. 2.

3. Simulation and results

Finite-difference time-domain (FDTD) [21] is used for studying optical properties of the proposed CDF. FDTD can be used for obtaining the distribution patterns of optical waves and the transmission properties of PhC-based devices. We used both methods in our designing procedure. Obtaining accurate results from FDTD simulations requires choosing proper values for mesh sizes and time step of the FDTD calculations. Therefore we choose mesh sizes to be $\Delta x = \Delta z = a/16$. Considering $a = 548$ nm in our structure, we have $\Delta x = \Delta z = 34.5$ nm. In addition, the time step value will be obtained using Courant condition

$$\Delta t \le \frac{1}{c\sqrt{(1/\Delta x)^2 + (1/\Delta z)^2}}$$

where c is the velocity of light in free space. So we have $\Delta t = 0.024$.

Obtaining accurate results from FDTD calculations requires 3D simulations which are very complex and time consuming; therefore we used the effective refractive method to reduce 3D simulations to 2D one with minimum errors [22]. The other crucial parameter that we should consider in our simulations is the boundary condition, for this purpose we used perfectly matched layer (PML) [21] boundary condition surrounding our structure. The thickness of PML is assumed to be 500 nm.

The output spectrum of the CDF is shown in Fig. 3. The normalized transmissions of the CDF at ports B, C and D are depicted with separated curves. Figure 3 shows that optical waves in all the wavelengths will go toward port B except at $\lambda = 1550.4$ nm in which optical waves will drop to the drop waveguide and travel toward port C; we have no output wave at port D. The drop efficiency of the structure is 94% at $\lambda = 1550.4$ nm and the bandwidth is 2.2 nm. So the quality factor ($Q = \lambda_0/\Delta\lambda$) is 704. The distribution of the optical wave inside the structure for two different wavelengths is shown in Fig. 4. Figure 4 shows that at $\lambda = 1550.4$ nm the optical waves due to the dropping effect of the resonant ring will drop to the drop waveguide and travel toward port C. However at $\lambda = 1560$ nm, optical waves will not drop to the drop waveguide and only will travel toward port B because their central wavelengths do not coincide with the drop wavelength of the structure. At the following, we are going to investigate the effect of different parameters on the filtering behavior of the proposed CDF.

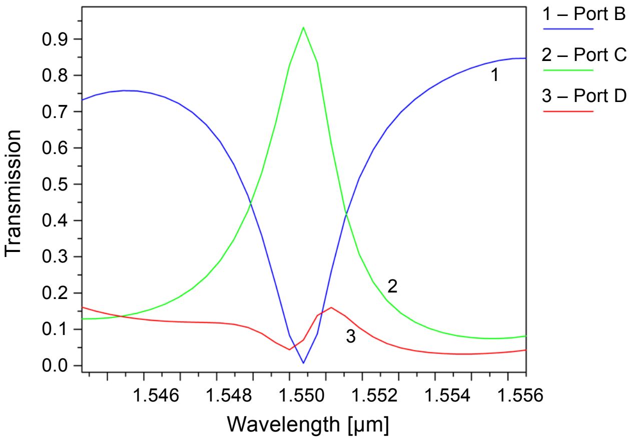

Fig. 3. The output spectrum of the CDF.

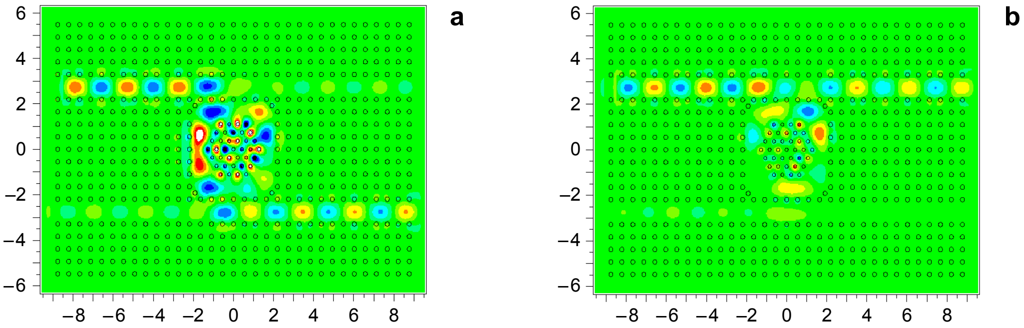

Fig. 4. Distribution of optical power at $\lambda = 1550.4$ nm (**a**) and $\lambda = 1560$ nm (**b**).

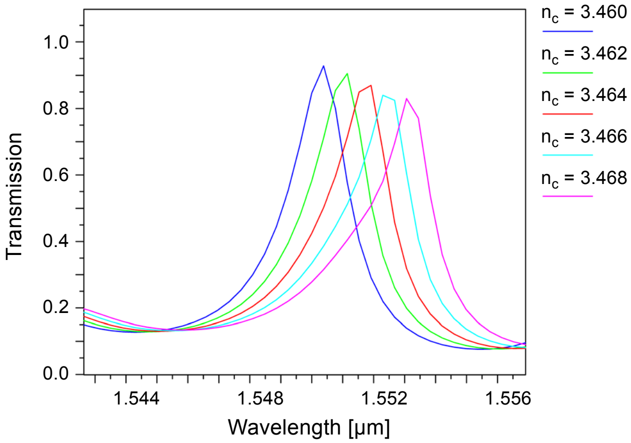

Fig. 5. The output spectra of the filter for five different values of core refractive indices.

The first parameter we are going to investigate is the refractive index of core rods (inner rods of the resonant ring). In order to separate the effect of refractive index from other parameters, we assume that the refractive index of the other parts of the filter are constant. Then, we obtain the output spectra of the filter for different values of core refractive index. The output spectra of the filter for five different values of core refractive indices are shown in Fig. 5. According to Fig. 5 by increasing the refractive index of the core (n_c), we observe a red shift in the output wavelength of the proposed filter.

Table. Significant parameters of the proposed CDF for different values of core refractive index n_c.

n_c	λ [nm]	$\Delta\lambda$ [nm]	Q	Transmission efficiency [%]
3.460	1550.4	2.2	704	94
3.462	1551.1	2.4	620	91
3.464	1551.8	2.6	596	87
3.466	1552.4	2.8	554	84
3.468	1553.2	2.8	554	83

The detailed specification of the output wavelengths for different refractive indices is listed in the Table.

The output spectra of the filter for different refractive indices of outer rods and scattering rods are shown in Figs. 6 and 7, respectively. These figures show that changing the refractive index of these parts of the filter has no effect on the output wavelength of the filter. Considering the results obtained from investigating the effect of refractive index on the optical behavior of the proposed filter, one can see that the output wavelength of the proposed filter mainly depends on the refractive index of the core structure. And it is very sensitive upon the variation of the core refractive index, such that by slightly changing the refractive index of the core, we observe severe variation in the output wavelength of the proposed filter. This property can be used for designing

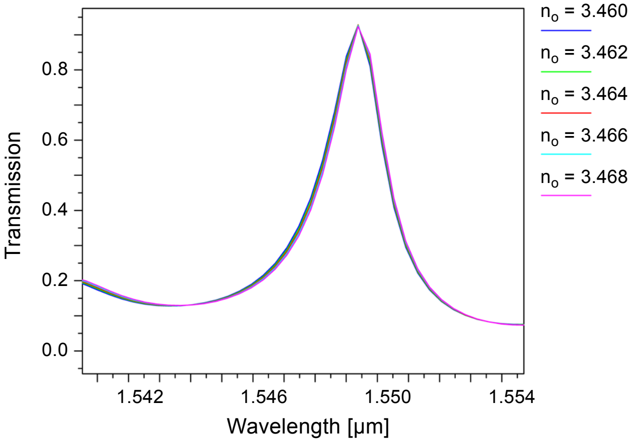

Fig. 6. The output spectra of the filter for refractive indices of outer rods.

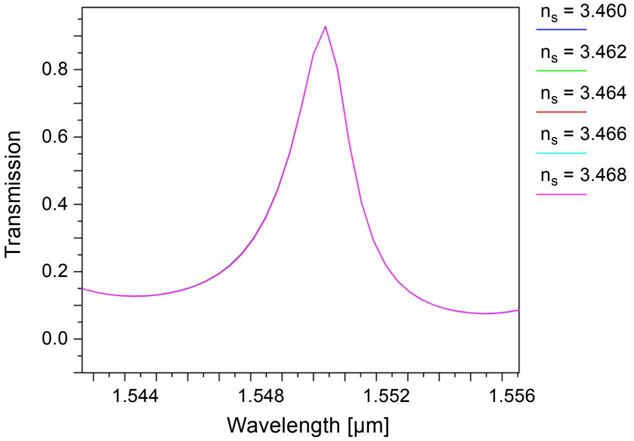

Fig. 7. The output spectra of the filter for refractive indices of scattering rods.

optical switch and optical gates, which can reduce the required optical power for performing the switching action. The proposed filter has better quality factor and more compact dimensions compared with previously proposed works [18–20, 23–25].

4. Conclusion

In this paper we proposed a channel drop filter based on PhCRR. We employed a hexagon-shaped structure as the core of our ring resonator. Our proposed filter has a resonant wavelength at 1550.4 nm with transmission efficiency equal to 94%. The bandwidth and quality factor of the filter is 2.2 nm and 704, respectively. The total footprint of the filter is 199.4 μm^2, so it is suitable for integrated optical circuits. We studied the impact of different parameters on the output wavelength of the filter. The results obtained from our simulations show that the resonant wavelength of the filter depends on the refractive index core structure. Increasing the refractive index, results in a red shift in the output spectra of the filter.

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