Quality Factor Enhancement of Optical Channel Drop Filters Based on Photonic Crystal Ring Resonators

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ABSTRACT— In this paper, a channel drop ring resonator filter based on two dimensional photonic crystal is proposed which is suitable for all optical communication systems. The multilayer of silicon rods in the center of resonant ring enables one to adjust resonant wavelength of the ring and enhance power coupling efficiency between ring and waveguide. Refractive index and radius of multilayer rods inside the ring are important factors which help one to enhance the desired output parameters. The proposed structure is capable of presenting high quality factor near 1937 in conjunction with 0.8 nm pass band. The high coupling efficiency 99% is another advantage of the proposed filter.

KEYWORDS: Optical filter, Photonic bandgap, Photonic crystal, Quality Factor.

I. INTRODUCTION

The increasing demand of high-performance systems for metropolitan and access optical communications has led the development of devices and techniques which can employ the high capacity of optical communication in the best manner. Dense Wavelength Division Multiplexing (DWDM) is an effective technique which can use the optimum capacity of a single optical fiber [1] and [2].

Photonic Crystals (PCs) are periodic structures which can control behavior of light. PCs can cause stop bands, namely photonic band gaps (PBGs), for electromagnetic waves (EMs), in which the propagation of optical waves is forbidden [3]. If the periodicity of PCs be broken by some defects, the localization of EM field would be around the defect volume [4]. By creating the defect layer or defect point in the PCs and subsequently breaking their periodicity, a defect mode can be produced inside the PBG. This defect mode leads to a high transmittance in the frequency (or wavelength) domain which can be used for designing a narrow band transmission spectra and high quality factor in a small area. These features made PCs as good candidates in optical communication such as optical filters [5],[6], demultiplexers [7],[13].

Optical channel drop filters (OCDFs) are essential components of photonic integrated circuits (PICs) and DWDM optical communication systems [8]. The first report on photonic crystal ring resonators (PCRRs) was in a hexagonal waveguide ring laser cavity [9]. Since then, significant progress has been made on CDFs in the areas of high spectral selectivity, spectral tunability, quality factor (QF), and pass band ($\Delta\lambda$). The QF is $\lambda/\Delta\lambda$ where λ is wavelength. The passband is the frequency (or wavelength) range of the filter that allows light to pass. In this case, the light power at output port respect to input port is more than 0.5. The quality factor of single ring resonator filters has been enhanced from 160 to over 1000 [10]-[14]. Rakhshani *et al.* proposed a PC-based filter using ring resonator with a QF of 842 [11]. Robinson *et al.* reported a two dimensional PC ring resonator based add-drop filter (ADF) with 13 nm of bandwidth and 114.69 of quality factor [13]. Mehdizdeh *et al*. proposed a structure in which $\Delta\lambda$ and QF values were 4.5 nm and 344 respectively [14].

In this paper, based on completely circular PCRRs, we propose an OCDF which is able to drop different wavelengths. In this structure, average power transmission efficiency (P_{CE}) is approximately 99% in conjunction with 0.8nm for pass band, and quality factor as high as 1937. P_{CE} is the ratio of light power at output port to input light power. These characteristics are highly suitable for full-ring based filters. The overall size of the proposed structure is 432 μm^2 which makes it appropriate for PICs. The paper is further organized as following: in section 2, we will present the proposed structure. In section 3, the results are discussed and finally the conclusion will be provided.

II. THE PROPOSED STRUCTURE

The proposed structure consists of 31 and 21 circular rods in x and z directions respectively. The lattice constant (a) and the radius of basic rods are equal to 797nm and 190nm respectively. The refractive indices of background and silicon rods are 1 and 3.47 respectively. We use Plane Wave Expansion (PWE) method to calculate band structure of the proposed structure. Four PBGs at TM polarization were obtained and displayed in dark area in Fig. 1. It can be seen that the second PBG is in the range of 0.46 <a/ λ < 0.53 (or 1495 < λ< 1732 nm) and is suitable for optical communication applications.

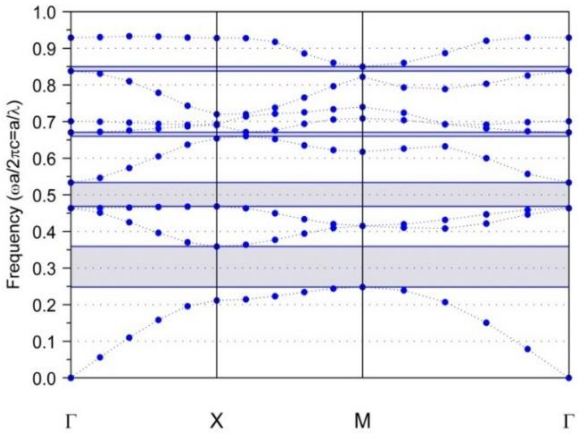
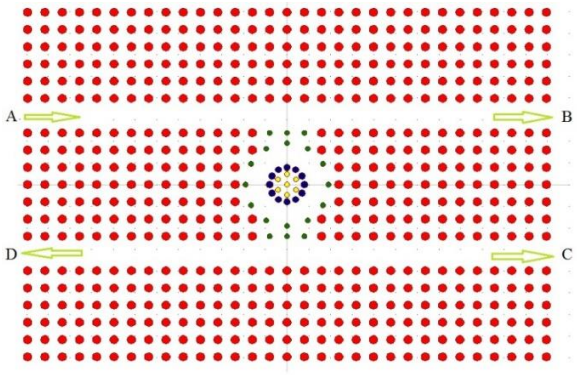


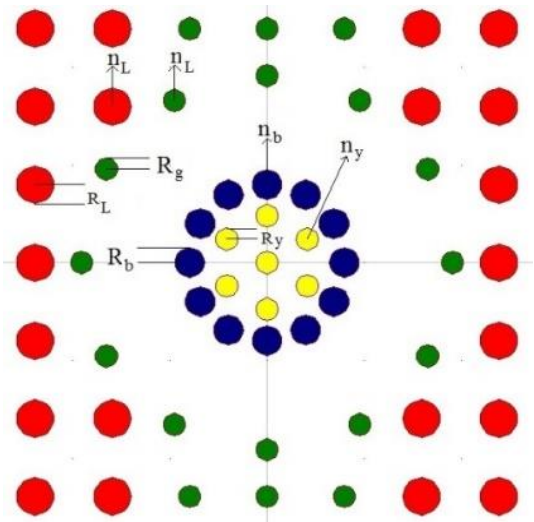
Fig. 1. Bandgap diagram of the proposed structure.

A. *Filter Design*

To manipulate the light, two rows as waveguides and a circle as resonant ring between them are removed as shown in Fig. 2-a. To create the resonator ring, we removed a 5×5 square of rods and then placed a circular multilayer structure included green, blue and yellow rings in center of resulting empty area (Fig. 2-b). The red rods are the basic rods and 12 green rods make the exterior layer which are denoted by R_g as their radiuses and n as their refractive indices. 12 blue rods and 6 yellow rods with same refractive indices, n_b and n_y, form the interior layers which are marked by R_b and R_y as their radiuses respectively.



(a)



(b)

Fig. 2. (a) The schematic diagram of the proposed filter, (b) a macroscopic view of the resonant ring.

In the upper waveguide, the light power is launched at port A and is propagated to port B. If the wavelength of the light is equal to resonant wavelength of the ring, light can drop to the lower waveguide and propagate to ports C and D which are known as forward and

backward dropping respectively. To achieve the appropriate coupling between the waveguides and ring resonators, we matched the rods of the ring resonator with waveguides, where the coupling was exactly happening. By changing the radius of inner rods inside the resonator, the resonant frequency of resonator could be changed. Besides, we chose the refractive indices of the rods which are centered in the ring resonator lower than the major resonator so it could act as a reflector and the light could be confined and be propagated more and more near the surface. By using multilayer rings, light can be confined closer to the surface of the ring. The result of the greater confinement of light near the surface is a higher quality factor [15].

The refractive index and radius of rods in ring resonator are given in Table 1. Generally, we use the letters n and R as refractive index and radius of rods and employ indices L, g, b, and y for lattice (or basic), green, blue and yellow rods respectively.

Table 1. The value of parameters for resonant ring.

Rod	Green	Blue	Yellow
Refractive index	3.58	3.4	3.4
Radius (nm)	114	153	163

B. *Results and Discussion*

In this work, we used RSoft software which employed the finite difference time domain (FDTD) method to simulate the behavior of light waves in the filter. The Gaussian input signal was launched in port A. The output spectrums at ports B, C and D are shown in Fig. 3.

Fig. 3 demonstrates the wavelength 1550nm can be dropped from upper into lower waveguides and propagated toward port C. This means that the proposed ring resonator has been tuned at 1550 nm. One can see P_{CE} at this wavelength is approximately 99% and $\Delta\lambda$ is 0.8 nm. Consequently, QF is obtained 1937 that is suitable in comparison with other works based on PCRR [16]-[22] as given in Table 2.

Figure 4a demonstrates the ring resonator drops incoming light at wavelength 1550nm to the lower waveguide, while it don't at wavelength 1560nm (Fig. 4b). As the both wavelengths are located in the PBG region, they can't scatter in the structure and propagate in the waveguides.

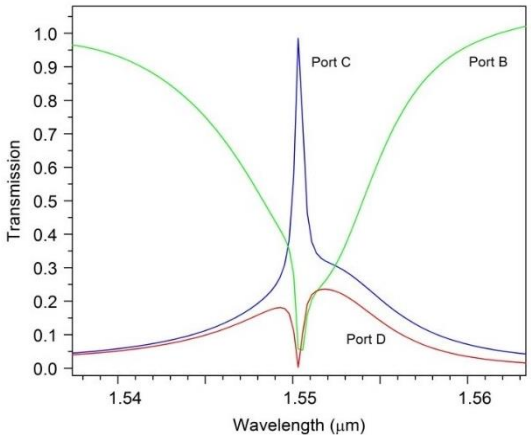


Fig. 3. Output spectra at B, C and D ports.

Table 2. Obtained results compared to other works.

Reference	QF	P_{CE} (%)	$\Delta\lambda$ (nm)
[16]	153	98	9.8
[17]	423	97	3.698
[18]	840	100	1.845
[19]	775	100	2
[20]	196	100	7.9
[21]	221	100	7
[22]	1330	95	1.16
[23]	98	100	19
[24]	283	96.4	5.48
This work	1937	99	0.8

If R_L, the radius of green rods, is changed from 189nm to 193nm, the central wavelength (λ_{ct}) at port C will obtain from 1541nm to 1558nm (Fig. 5). One can conclude as R_L is increasing, the central wavelength at port C becomes longer while pass band and power coupling efficiency are almost constant (Table 3). Besides, the greater R_L results in the higher quality factor.

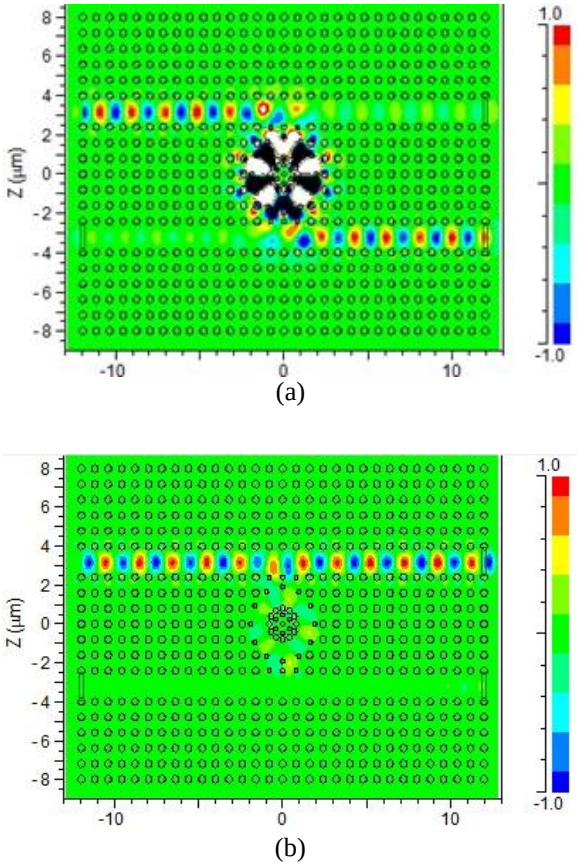


Fig. 4. The calculated electric field distribution inside the structure at two wavelengths (a) 1550 nm, and (b) 1560 nm.

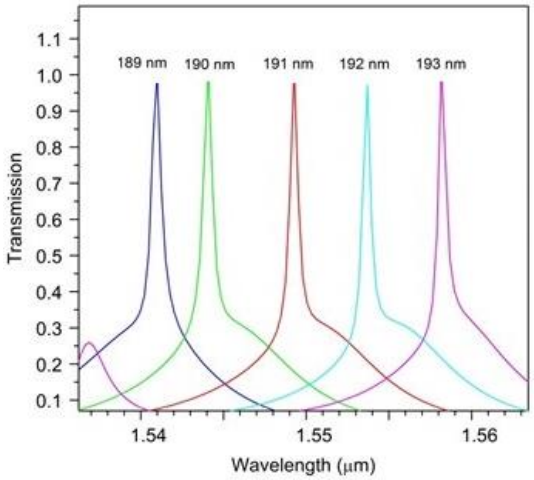


Fig. 5. The output spectrum at port C with different values of R_L.

Figure 6 demonstrates that changing the radius of blue rods (R_b) from 151nm to 155nm shifts λ_{ct} to the upper wavelengths. Although one can obtain 0.5nm for pass band, P_{CE} is reduced to 70% with R_b=155nm. Table 4 shows the details of the output spectrum for different values of R_b.

Table 3. The output characteristics of the filter versus values of R_L.

R_L (nm)	$\Delta\lambda$(nm)	λ_{ct} (nm)	QF	P_{CE} (%)
189	1	1541	1541	99
190	1	1544	1544	100
191	1	1549	1549	100
192	1	1554	1554	97
193	1	1558	1558	100

Simulation results show that the central wavelength at port C shifts to higher wavelengths when the radius of yellow rods (R_y) is increasing (Fig. 7). According to Table 5, one could enhance P_{CE} to 98% and reduce pass band to 0.7nm if 112nm is selected to R_y. The effective refractive index is a key parameter and depends on refractive index and radii of rods. These wavelength shifts are due to change in the effective refractive index. By increasing the radius of rods, the effective refractive index increases so the wavelength shifts toward upper values.

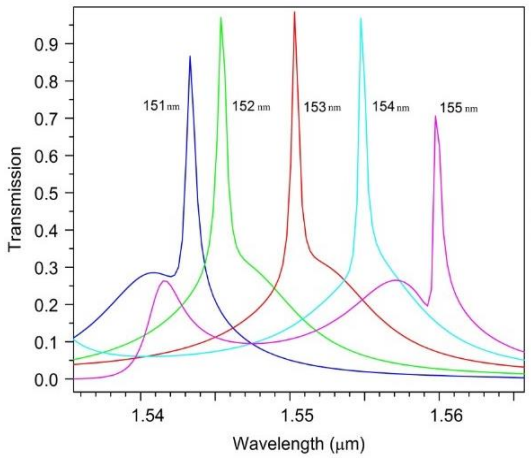


Fig. 6. The output spectrum with different values of R_b.

Table 4. The important parameters of the device with different values of R_b.

R_b (nm)	$\Delta\lambda$ (nm)	λ_{ct} (nm)	QF	P_{CE} (%)
151	0.8	1543	1928	86
152	0.95	1545	1626	97
153	0.8	1550	1937	99
154	0.7	1555	2214	97
155	0.5	1560	3120	70

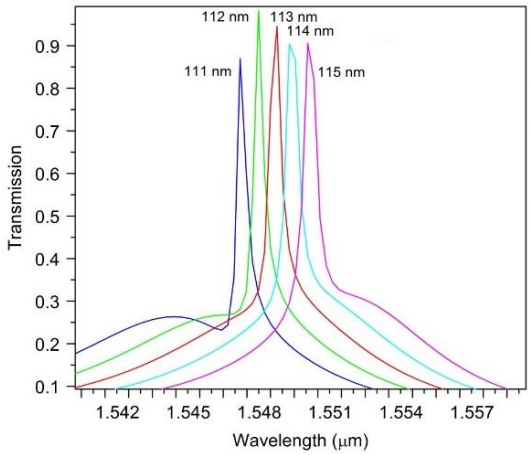


Fig. **7** The output spectrum of the filter for different values of R_y.

As shown in Fig. 8, the more refractive index of the basic rods results in higher central wavelengths at port C while pass band is almost equal to 1nm. One can see in Table 6, P_{CE} is approximately 99% if the refractive index of the basic rods to be 3.5.

Table 5. The output parameters of the filter as a function of R_y.

Ry (nm)	$\Delta\lambda$ (nm)	λ_{ct} (nm)	QF	P_{CE} (%)
111	0.7	1547	2210	87
112	0.7	1548	2211	98
113	0.8	1549	1936	94.5
114	0.75	1550	2066	90.5
115	0.8	1551	1938	90.5

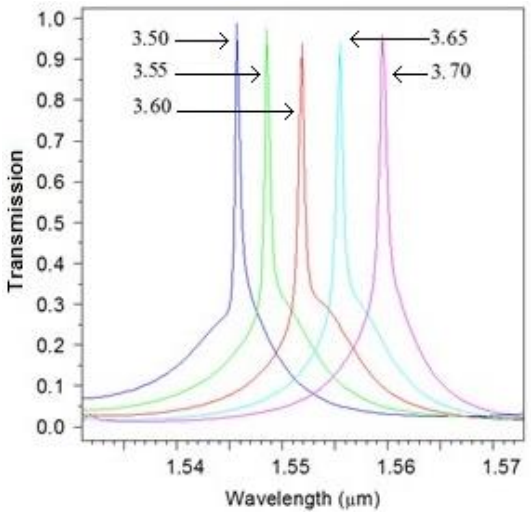


Fig. 8 The light power at port *C* with different values of n_L.

Figure 9 reveals the refractive index of blue and yellow rods is as an effective factor on central wavelength and power coupling efficiency. This figure proves higher central wavelengths are obtained if refractive index of the mentioned rods is raised. As it's shown in Table 7, exact light transmission is occurred from port A to port C when refractive indices of alluded rods are equal to 3.36. In this case, pass band is obtained 1nm.

Table 6. The calculated output parameters of the filter for different values of n_L.

n_L	$\Delta\lambda$ (nm)	λ_{ct} (nm)	QF	P_{CE} (%)
3.50	1	1546	1546	99
3.55	1	1548	1548	98
3.60	1	1552	1552	96
3.65	1	1555	1555	96
3.70	1	1559	1559	98

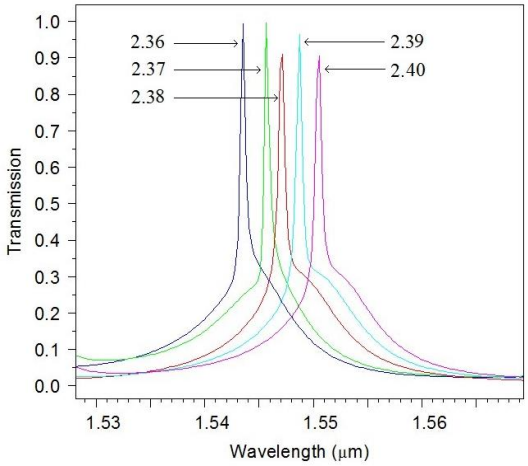


Fig. 9. The output spectra for different values of n_b and n_y.

Table 7. The output parameters of the filter as a function of n_b. and n_y.

$n_{b,y}$	$\Delta\lambda$ (nm)	λ_{ct} (nm)	QF	P_{CE} (%)
2.36	1	1547	1547	99
2.37	1	1549	1549	99
2.38	1	1550	1550	91
2.39	1	1552	1552	96
2.40	1	1554	1554	96

Time response of the proposed filter is shown in Fig. 10. It demonstrates that the delay time for the filter at the output port is about 2 ps.

The results obtained from simulation demonstrate that one should do a tradeoff among output parameters respect to desired application. This makes the proposed filter as a

device with different wavelengths for optical applications.

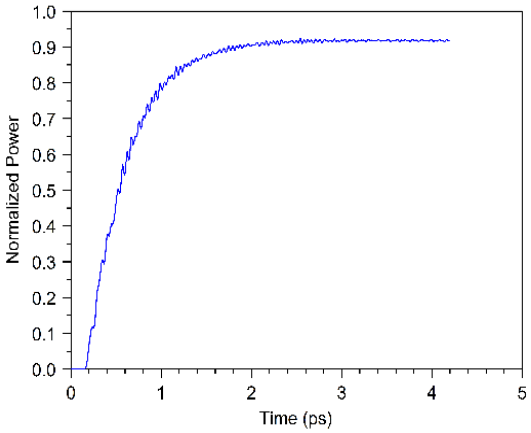


Fig. 10. Time response diagram of the proposed filter.

III. CONCLUSION

A ring resonator based on two dimensional photonic crystal as a dropping filter is proposed to dense wavelength division multiplexing communication systems. The resonant ring consists of three different rods to simplify tuning of resonant wavelength and enhances power coupling efficiency. According to conventional Whispering Gallery Modes theory, we changed the refractive indices of rods inside the ring and propagation of light was forced to be more near the surface of the ring. Close to 99% forward dropping efficiency, quality factor as high as 1937 and pass band of 0.8 nm were obtained in the third communication window.

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