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Transmission and Q-factor improvement in 2D square photonic crystal demultiplexer

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Abstract

Our novel designed structure is a demultiplexer of 2D square photonic crystal (PC) of circular rods embedded in air in which we have created three resonant cavities with different radiuses. So we have three channels based on these cavities which have been implemented to realize the desired demultiplexer structure. The three radiuses of cavities deduce us to obtain three different output resonant wavelengths; it means that this structure drops the desired wavelength depending on the cavity radius. The refractive index n that we will use in this study have a constant value, n = 3.3763. In addition, we had optimized this structure by the variation of the adjacent rods radiuses and positions for each of these cavities. The obtained result is a structure with geometrically three different resonance zones. Then, we were being able to extract three resonant wavelengths characterized by a high transmission power T and Q-factor which the mean values are 91% and 4247 respectively. We denote that this resulting T and Q-factor are higher than those investigated in bibliography.

Keywords: Photonic Crystal; Demultiplexer; 2D-FDTD; Cavity; Q-factor

1. Introduction

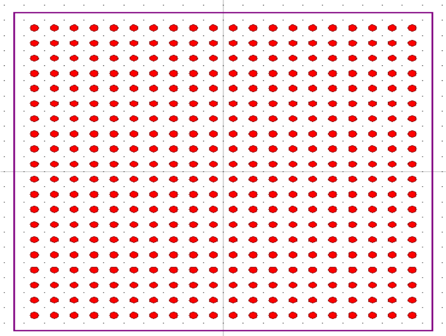
The notion of photonic crystals PCs was proposed for the first time in 1987[1][2][3,4]. The first photonic crystal was made in 1991 [5]. Photonic crystals (PCs) are structures whose refractive index varies periodically in one, two or three dimensions. This periodic medium produces on the light that propagates in the photonic crystal an effect similar to that of the periodic potential on electrons in a crystal. This periodicity induced the presence of allowed and prohibited energy band [1][6,7,8]. A photonic band gap (PBG) corresponds to an energy interval where the propagation of light is prohibited in certain directions of this crystal [1]. It is this property that makes PCs interesting for many applications. For the reason that the PCs control the light on dimensions of the order of magnitude of the wavelength in the material, that these structures became the most suitable for optoelectronics. PCs offer a very high power transmission and a better Q-factor, furthermore, PCs became the axis of several researches such as the modification of the forms of cavities as well as their adjacents (cavity L2) [9]; cavity infiltration [10], and even introduce changes in position and size of this one (cavity L3)[11]. The control of the light makes these structures good candidates for the realization of the optical devices. By introducing defects in the 2D lattice, we have a potential applications of 2D PBGs [12,13]: realization of very small size resonant cavities, waveguides , selective filters, optical fibers [1] , add-drop filters [14], power splitters [15,16], channel drop filters[17,18],multiplexers and demultiplexers[1][19].This may offer promising applications for photonic integrated circuits (PICs) on a semiconductor substrate. A particularly important function of integrated optics that could be achieved with photonic crystals: wavelength division multiplexing (WDM) which need some basic functions such as filters, modulators, sources, photodetectors and demultiplexers[20].These demultiplexers are based on the use of photonic crystals for linear and point defects and are capable to select a channel with a specific wavelength. The demultiplexing process consists in extracting one selected wavelength from one waveguide and sending it to another one through a resonant cavity [21]. That means, the resonant frequency is localized from the input waveguide in the resonant cavity and then transmitted to the output waveguide. This cavity can be used as frequency selecting device. Features like independent polarization, low crosstalk, high spectral resolution and compactness are needed for these devices [22]. In the bibliography, we find a multitude of topologies, such as using line defect PCs waveguides [22,23], directional coupling[24,25]ring resonators[26], coupled cavity and PCs waveguides[27]. In this paper, we will present a add-drop demultiplexer structure implanted in three different zones with specific characteristics for each. The cavities radiuses have been adjusted to r1=0.04*a r2= 0.06*a and r3=0.08*a as well as the adjacent rods and their positions: r-adjacent=0.26μm, 40nm,r-adjacent2=0.24μm, 20nm,r-adjacent3=0.18μm,0nm respectively. The structure geometry optimization is required; it leads to increase the Q-factor and transmission efficiency. Also, this adjustment aims to adjust the output wavelength, so this is called the tuning of dropped wavelengths. As a result, each of these zones will extract one wavelength, from where we have the demultiplexing process. These resonant wavelengths are detected by the monitors placed in the output ports B1, B2, B3. This optimization is of great importance as we will demonstrate it below. The 2D-FDTD method has been used as a numerical tool for calculation [1][28,29] as well as the Plane Wave Expansion method (PWE) which is suitable for modeling [30] and ofcorse the Perfectly Matched Layer (PML) for the absorbing boundaries in electromagnetism [31,32].

2. Design of the photonic crystal demultiplexer

In this study; we present a 2D photonic crystal in a square lattice of dielectric rods in air, Fig.1(a).The refractive index n=3.3763; constant lattice a=0.58µm[33] and rods radius=0.18*a[34].With 20x20 perfect square lattice of our 2D-PC,we denote the existence of a large photonic band gap at the normalized frequency range of 0.309-0.445. In other words, this corresponds to the spectrum of 1.312 µm to 1.877 µm for TE polarization (magnetic field parallel to the axis of dielectric rods) Fig.1(b). On the other hand, there is no gap for TM modes with this refractive index contrast and relatively small r/a. The first reduced PBG is considered for designing PC-Demultiplexer as it covers the second and third windows in optical region.

In [35], we presented three resonators implanted in the previous structure. The created defect consists in the modification of the cavity rod radius, so it is set at r=0.08*a, r1=0.04*a and r2=0.06*a. On the other hand and likewise for the adjacent rods of cavities, the radiuses

(a)



(b)

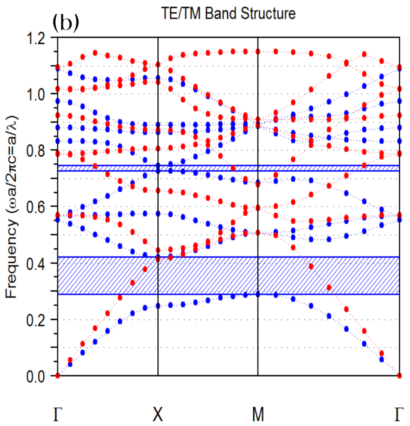


Figure 1. (a) Schematic of a 2D square photonic crystal, (b) Band diagram of 20 ×20 square lattice without defects by PWE method.

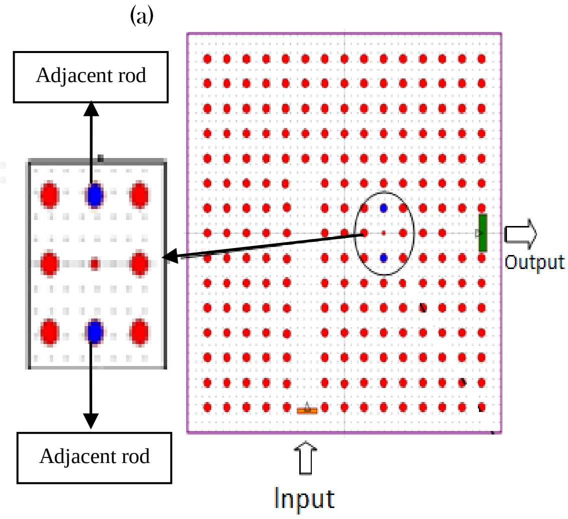
were set at 0.18*a, 0.26*a, 0.24*a respectively. So, we had in the output guide six wavelengths which have been extracted. This happened by the presence of the coupling phenomenon between the two waveguides, and the resonant cavity.

3. Simulation results

Now, to optimize our structure, Fig.2(a), we have changed the positions of the adjacent rods, so we have optimized the displacement d-rods to get the values of 40nm, 20nm and 0nm (no displacement).The resulted wavelengths are shifted to the higher values, and their Q-factors became more important as it will be shown later. According to Fig.2(b), we denote the corresponding transmission power efficiency for cavity radius r=0.08*a and d-rods=0nm, T=89.95% and Q-factor Q=5600 for λ=1.6399µm.

The waveguides and the resonant cavity coupled at their resonant wavelength to trap electromagnetic energies. It is a process of acquiring resonant wavelength from the bottom and sending it to the left and right by the ring resonators.

(a)



(b)

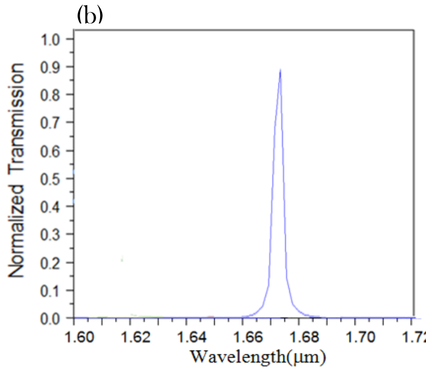


Figure 2. (a): Typical resonator with one output port. (b): Optimized transmission response for the resonator of cavity radius: r=0.08*a and d-rods=0nm.

Two other zones were created for the same purpose and in the same way. So for r=0.04*a and r=0.06*a, we had set the positions of adjacent rods d-rods=40nm and 20nm respectively. Here, there is a shift of the output wavelengths to the right sides. So, the resulted wavelengths are shifted to the higher values. The output resonant wavelengths are λ(r1)=1.6296, λ(r2)=1.6328 while the corresponding power efficiencies and Q-factors are T=97% , T=85% and Q1=8344,Q2=8400 respectively. The resulted resonant wavelengths are removed after their passage from the input waveguide, to the output waveguide and this through the resonant cavities. The output waveguide from which we received the three resonant wavelengths and the input waveguide were coupled to the resonant cavities to trap the electromagnetic energies.

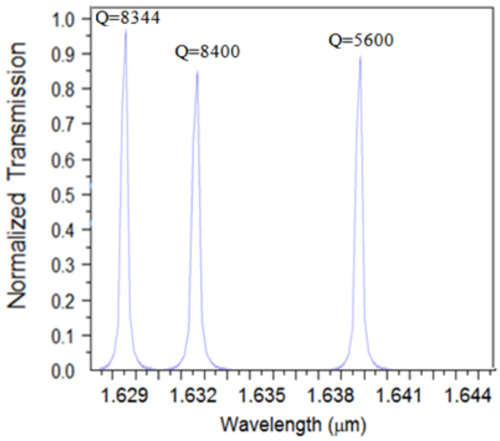


Figure 3. Optimized transmission response for the three resonators, from the left for: d-rods=40nm, 20nm and 0nm.

We can denote in Fig.3 that we have the optimized cases concerning the optical power transmission of the structure, Fig.2(a) for the three zones. The resonators work for the tunability of the wavelengths when we see their displacement from the left to the right with the increase of the cavity size.

In this paper we present a optimized structure design which consists of a 2D square photonic crystal demultiplexer with 20x20 perfect square lattice in X and Y respectively. As described above, three resonators each with its d-rods positions property, so from the smaller cavity size to de bigger, we have d-rods1 = 40nm, d-rods2 = 20nm and d-rods3 =0nm, Fig.4. The time step is chosen to 0.01 while for the collection of the normalized transmitted spectral power density, we have placed three ready power monitors at the output ports Bn in the end of each output waveguide, Bn: (B1, B2, B3). Port A in the lower side of the input waveguide receive the polarized transverse electric (TE) of input Gaussian signal. The finite difference time domain (2D-FDTD) method algorithm is used as a numerical calculation tool while the perfectly matched layers (PML) of Beranger as absorbing boundaries. Q-factor is evaluated as:

$$Q = \lambda/\Delta\lambda \qquad (1)$$

Where λ and Δλ are central wavelength and full width at half power of output respectively. We can see on Fig.5 the normalized transmitted power through the output ports Bn after having simulated the structure illustrated on Fig.4. The full results: resonant wavelengths, Q-factor and the output transmission response efficiency T with properties of each zone are presented in the Table1 below. The output resonant wavelengths are λ1=1.6296 µm, λ2 =1.6328 µm and λ3=1.6399 µm from the smaller to the bigger cavity radius. What we can notice is that the transmission efficiency and the Q-factor have reached important values, T1=93.7%, T2= 80% andT3= 83.4% while Q-factor1 =8148, Q-factor2 =8339, Q-factor3 =5557 respectively. The mean value of the transmission efficiency and Q factor are 85.7% and 7348 respectively. In [36-38],the Q factor varied between 296 and 5101. We therefore note that we have obtained a higher mean Q-factor with our optimized structure when we compare it with those of bibliography.

Table1: Transmissions and Q-factors for the resonant wavelengths

Cavity's r (µm)	r-adjacent: (µm)	λ(µm)	T	Q-factor
r1=0.04*a	0.26*a	1.6296	93.7%	8148
r2=0.06*a	0.24*a	1.6328	80%	8339
r3=0.08*a	0.18*a	1.6399	83.4%	5557

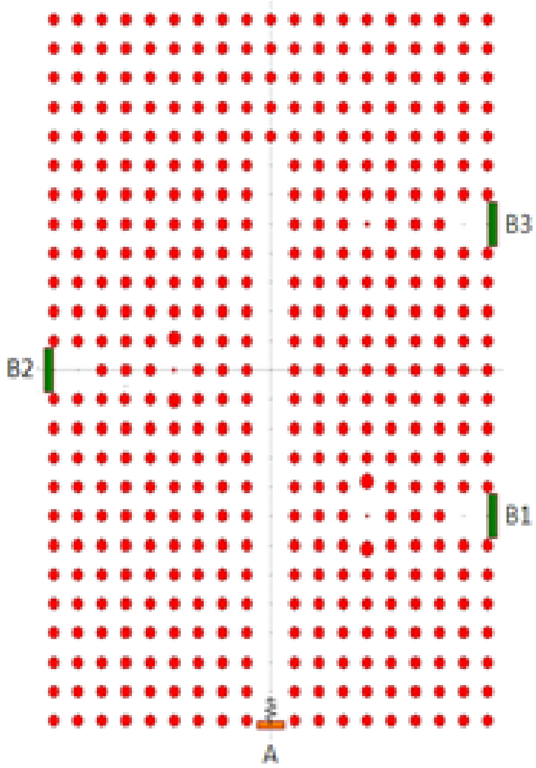


Figure 4. Schematic of the proposed structure

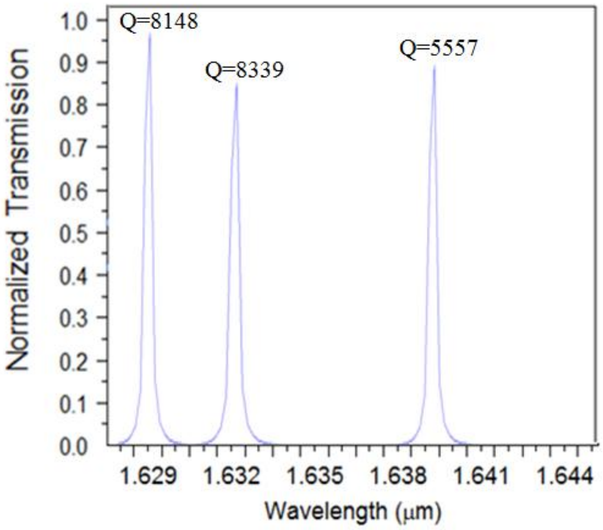


Figure 5. Optimized optical power transmission of the demultiplexer.

Finally, Fig.6(a),(b) shows the electric field distribution of the optimized proposed structure and the off–resonant case . Firstly, our output resonant wavelength is removed from the input waveguide and then sended into the output waveguide through the resonant cavity, Fig.6(a). So, this cavity produces in each zone a coupling phenomenon which allows the propagation of selected wavelength. In the other hand, Fig.6(b) shows us the case examined for λ =1.645 µm without any coupling phenomenon. Fig.6(a) as the two other zones in our structure, shows clearly that the resonant wavelengths each in its own area, reach its Bn output ports with high transmission power and quality factor Q-factor.

(a)

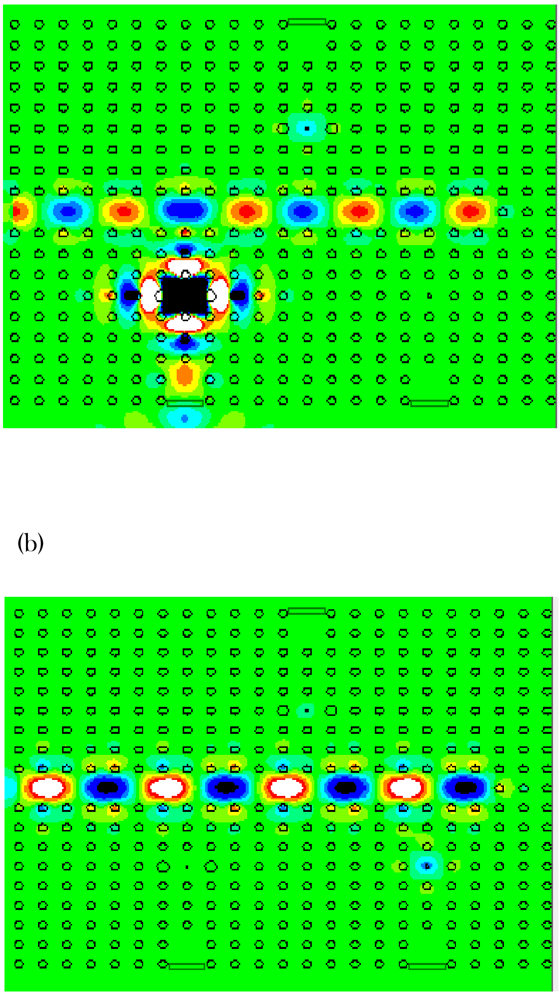


Figure 6. Electric field distributions of the structure for (a): on-resonant wavelength λ1=1.6127 µm, (b): for off-resonant wavelength λ=1.645 µm.

The comparison of this study with some recent works is presented in Table 2.

Table 2: Comparing our results with some previous works

Works	Maximum spectral width Δλ(nm)	Footprint (µm^2)	Minimum T (%)	Q-factor	Largest Crosstalk (dB)
[36]	0.9	752.64	95	2225	-30
[37]	7.5	129.96	88	296	-26.072
[38]	0.35	199.63	87	5101	-30.71
Our work	0.2	159.79	85	8339	-28.025

3. Conclusion

In this study, we have presented a structure of 2D photonic crystal demultiplexer in a square lattice. This was optimized by the introduction of the changes on its geometric properties. With three zones of different cavities, adjacent rods sizes and their positions, we could note the improvement brought to the efficiency of transmission as well as to the quality factor Q-factor. Resonant wavelengths have been tuned each time the cavity and the adjacent rods radiuses as well as their positions are varied. So the mean value of transmission efficiency and Q-factor are 85.7% 7348 respectively, which are more important than those presented in bibliography [36-38]. For photonic integrated circuits (PICs), this structure is of great value and it is also promising for nanotechnology.

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