Optica Applicata, Vol. LII, No. 4, 2022
DOI: 10.37190/oa220411

Four channel optical demultiplexer based on L_2 photonic crystal microcavity

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The wavelength demultiplexing is a particularly important function in integrated optics and can be realized using photonic crystals. The aim is to extract accurately the wavelengths in a data flux. In this work, we investigate a new topologies of wavelength demultiplexing based on two-dimensional photonic crystals constituted of dielectric rods spread in a square network. The studied demultiplexer is based on optical filters with optimized parameters in order to extract four different wavelengths in the vicinity of frequencies corresponding to communication windows. It was found that the crosstalk between the structure channels of the demultiplexer are in the range of –19.19 and –44.1 dB and the channel spacing is equal to 0.96 nm. The simulation results presented in this paper are performed and analyzed using the FDTD method.

Keywords: photonic crystal, cavity, waveguide, quality factor, demultiplexer, FDTD, filter, crosstalk.

1. Introduction

The studies conducted during the last decade concerning the use of photonic crystals (PhC) for realizing PhC filters showed that they could offer numerous perspectives. For this reason, this work is devoted globally to the investigations of filters based on two-dimensional photonic crystals (2D PhC) and their use as a filtering and then as a demultiplexing unit. The realization of one-dimensional and two-dimensional photonic crystals is relatively old, but the three-dimensional networks are more recent [1]. However, researchers focused mainly on 2D PhCs since their manufacturing is easier with less cost with respect to 3D structures.

Photonic crystals offer then perspectives to realize optical or electromagnetic devices capable of stocking, filtering and guiding light at the scale of the wavelength in the material.

The optical filtering elements are considered as the most important component of the communication systems. They allow extracting accurate wavelengths from a particular channel in a data flux without affecting the other channels. They are capable of transmitting light in a selective manner for specific wavelengths and block the remaining wavelengths. Therefore, a PCh filter plays a key role in the design and realization of a new generation of demultiplexers [2,3]. Different papers dealt with the photonic crystal demultiplexer: MEHDIZADEH *et al.* [4] have proposed a 4-channel wavelength demultiplexer employing four ring resonators with different geometrical parameters. The channel spacing of the structure is about 3 nm, the minimum transmission efficiency is more than 92%, the overall quality factor is more than 818 and finally the crosstalk levels are better than –18 dB. The next demultiplexer was introduced in 2017 by ZAHEDI *et al.* [5]. The authors investigated a four-channel optical demultiplexer (DMUX) based on two-dimensional photonic crystal. The output wave spectrum was measured for four channels in the range of 1541.5 to 1557.6 nm. The average quality factor of 2567, the average crosstalk of –25 dB, and the transmission coefficient of higher than 97% were obtained. Another demultiplexer was introduced by DELPHI *et al.* [6]. They have proposed a 2-channel and 4-channel optical demultiplexers based on a photonic crystal nano-ring resonator. The 4-channel demultiplexer includes the mean quality factor of 4525, mean channel power transfer factor of 95%, and maximum and minimum channel crosstalk of –19.6 and –40.4, respectively.

Basing on the wavelength demultiplexing properties, we start this manuscript by studying filters based on three main parts. The first part is a linear defect containing an input waveguide formed by removing several motifs. The second part of the filter (the most important) is the resonance cavity created by removing two dielectric rods. The third part is a linear defect containing the output waveguide. We have also studied the influence of some parameters on the filter characteristics such as the cavity reflectivity mirrors, the position and the size of the rods located at the cavity ends. A discussion about the parameters allowing the improvement of the components performance has been undertaken. The goal is to adjust these parameters in order to obtain the best extraction efficiencies and good quality factors. Therefore, the filter optimal configuration is composed of three dielectric rods located between the cavity and the waveguide ($N = 3$) with the position and the size of the rods located at the cavity ends being 0.013 and 0.11 μm, respectively. These results improve significantly the filter characteristics. In this case, extraction efficiency and a quality factor of 96% and 23766 have been obtained, respectively.

Following this study, we perform the numerical simulations of the demultiplexer composed of four optical filters, which are achieved by optical cavities inserted in the waveguides in order to select different wavelengths. These cavities have been created differently by suppressing and modifying some rods to create new channels.

2. Description of the studied structure

Several theoretical and experimental studies have been recently conducted on two-dimensional photonic crystals since it is more difficult to produce three-dimensional photonic crystals. Most of structures with two dimensions are produced from dielectric rods in air or air holes in a dielectric matrix. The intersection of these rods with a perpendicular plane forms a two-dimensional network. Most of research works considered that the electromagnetic wave propagates only in the plane perpendicular to the rods. Different structures have been studied such as the square network [7, 8], the triangular network [9] and the graphite network [10]. In our study, we have chosen a square two-dimensional photonic crystal of 20 × 20 size composed of silicon dielectric rods ($n = 3.46$) arranged on a square lattice in the air ($n_{air} = 1$). The radius of the dielectric rods is about 219 nm and the period is $a = 730$ nm (a is the distance between the center of two adjacent motifs). We have chosen silicon (Si) because it is a promising material especially in the photonics domain. Indeed, its high refraction index and its transparency to communications wavelengths allow the creation of resonators and waveguides with strong confinement of the electromagnetic field. In addition, its technology is well mastered and compatible with the microelectronic technologies. The scheme of the structure is reported in Fig. 1.

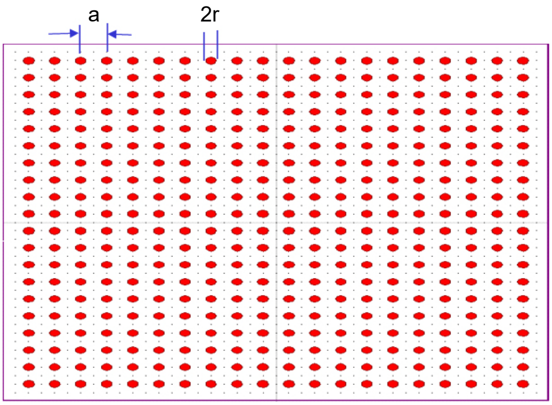

Fig. 1. Schematic structure of 2D PhC formed by square network ($a = 0.73$ μm) of silicon dielectric rods in air.

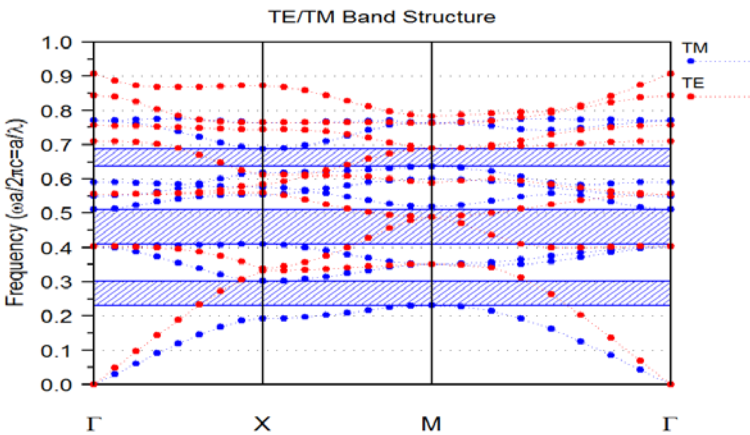

Fig. 2. The band structure of the proposed structure.

Before designing the filter, we first compute the photonic forbidden band of the structure. Band SOLVE of Rsoft photonic CAD simulation tool based on the method of plane waves (PWE) has been used. The diagram of the photonic forbidden band with the values mentioned above is shown in Fig. 2. According to this figure, this structure comprises three BIP in TM mode but no forbidden band appears for the TE polarization. Indeed, the BIPs TE opens generally for connected structures whereas the aperture of BIPs TM is rather favored by disconnected structures as in the case of our structure (pillars in air).

We observe from Fig. 2 that the largest forbidden band of our structure opens from 0.4104 to 0.5086 (a/λ) which corresponds to the interval of wavelengths ranging from 1.4353 to 1.778 μm for a TM polarization, where λ is the wavelength in free space.

3. Study of the photonic crystal filters

The proposed structure is shown in Fig. 3. It is constituted of a square network of silicon dielectric rods immersed in air. The photonic crystals filters are realized mainly using the guide-cavity coupling process. The latter are undertaken in the 2D photonic crystals structure by creating defects: either by a local modification of the index or a change of the size of the crystal motif (defect of substitution), or by shifting one of the motifs (interstitial defect) or the absence of one of the motifs (lacunar defect) or by inserting a different motif (doping).

The studied structure is formed by three main parts. The first part is a linear defect containing an input waveguide which is formed by removing several motifs. The second part of the filter (the most important) is the resonance cavity created by withdrawing two dielectric rods. The third part is a linear defect containing an output waveguide. Two motifs have also been placed in both sides to form the mirrors ($N = 2$). In this filter,

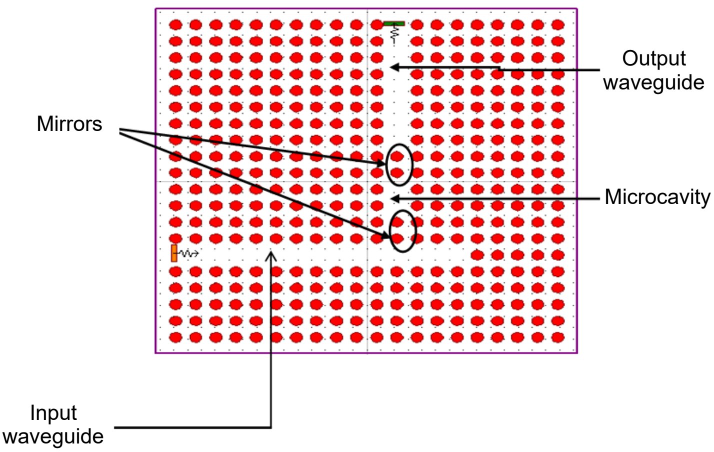

Fig. 3. The schematic diagram of the proposed filter with 2 separation rods between the cavity and the waveguide.

most of the guided wavelengths are reflected to the end of the guide, except the sole of them which will be coupled to the cavity then to the second guide.

3.1. Effect of the reflectivity of the cavity mirrors on *Q*

The evolutions of the quality factor of the filter structure as a function of the different structural parameters have been studied numerically by means of Fullwave of RSoft software. The studied structure shown schematically in Fig. 4(a) has been simulated with different numbers of dielectric rods located between the cavity and the waveguide in order to improve the mirrors reflectivity quality of the cavity.

The transmission characteristics of the filter have been simulated by means of the finite differences technique in the time domain (FDTD) using perfectly matched layers (PML) as absorbing borders.

Figure 4(b) presents the transmission spectrums for $N = 2$, 3 and 4. The peaks improve as the number of rods increases corresponding to the reflectivity increase and

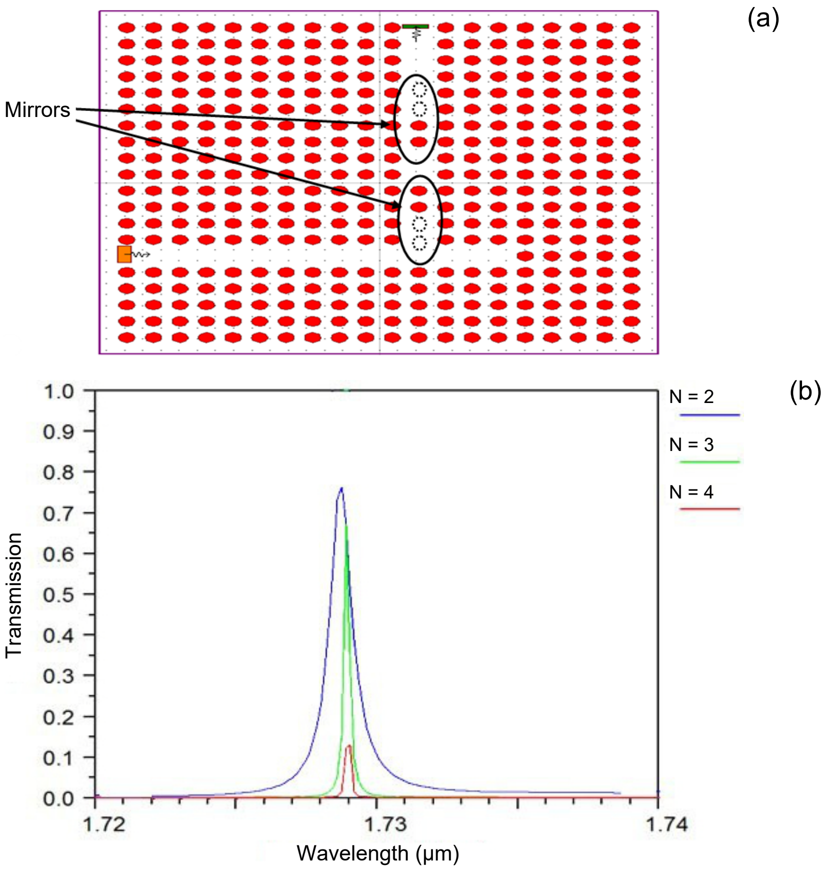

Fig. 4. (a) Photonic crystal filter with 2, 3, 4 separation rods between cavity and waveguide. (b) Transmission spectra of the filter with an increasing number of rods.

Table 1. Variation in wavelength λ and quality factor Q depending on the different numbers of dielectric rods N.

Numbers of dielectric rods	Wavelength λ [μm]	Quality factor Q
$N = 2$	1.7289	1801.1
$N = 3$	1.7291	9271.8
$N = 4$	1.7292	44686

therefore the quality factor. Table 1 provides the theoretical values of the wavelengths as well as the quality factors computed for $N = 2$, 3 and 4.

We can notice that the quality factor increases considerably as N increases because the Q factor will be enhanced when the wall of the cavity is increased, that demonstrates the enhanced confinement effect produced by increasing the number of rods in the input and output channel waveguide and is due to an increase in reflectivity of the photonic crystal mirror. The quality factors present a notable increase with the number of rods. This progression is quite quick until $N = 4$. Contrarily, we observe a decrease in transmission.

With four rods in the proposed filter, we obtain a quality factor of 44686 with a very low uncertainty. In this case, we note a higher value of the quality factor and a low transmission. In order to obtain an optimum quality factor and a high transmission value of the filter simultaneously, we must choose the number of rods in the periodic mirror ($N = 3$). Therefore, we can choose a quality factor of 9271.2 at the resonance mode for $\lambda = 1.7291$ μm with ($N = 3$) as an optimal result because of its relatively high-quality factor and transmission (see Fig. 4(b)).

3.2. Effect of the rods size located at the cavity ends on the quality factor

The rods radius is another important parameter which affects the filter characteristics.

In order to realize a high-Q photonic microcavity, we should reduce the leaky components in the electric field to reduce the radiation loss. Here we try to make confinement gentler. The strategy to obtain gentler confinement is to change the condition for Bragg reflection at the cavity edge. Such reflection is determined by a summation of partial reflections at a series of rods near the cavity edge. For this purpose, the radius r' is varied in the range of 0.09–0.14 μm.

The results are presented in Fig. 5 for different values of radius r'. The computed spectrum in TM polarization shows that the resonance wavelength shifts towards higher wavelengths as r' increases.

Table 2 gives the theoretical values of the filter wavelengths and the quality factors computed for $r' = 0.09$ μm to $r' = 0.14$ μm. The quality factor increases, reaches a maximum then decreases as the radius of the two rods increases. The maximum value of the quality factor is obtained for the optimum radius of $0.12a$ with an uncertainty of 45%. In this case, we observe a higher value of the quality factor Q and a poor transmission (curve in cyan). From these results, we choose $r' = 0.11$ μm as the optimal result be-

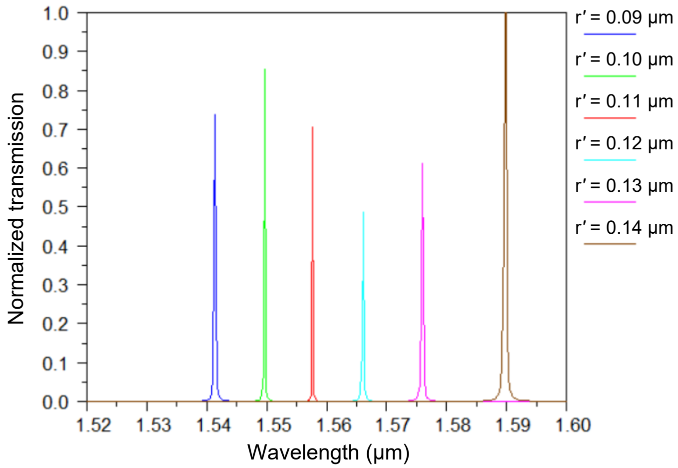

Fig. 5. The output spectra of the proposed filter for different values of r'.

Table 2. Variation of the wavelength λ and the quality factor Q depending on the different values of the radius r'.

Radius r' [μm]	Wavelength λ [μm]	Quality factor Q
0.09	1.5414	16461
0.1	1.5496	18246
0.11	1.5576	22152
0.12	1.5660	22159
0.13	1.5759	15551
0.14	1.5897	7118.1

cause of its relatively high transmission. The quality factor Q computed for this resonance is above 22152.

3.3. Effect of the rods position located at the cavity ends on the quality factor

To improve the quality factor of this structure, the concept presented by Noda *et al.* [11] is applied: the radius of the two rods denoted in blue (Fig. 6(a)) is fixed to its optimal value ($r' = 0.11$ μm). Indeed, the shift of these holes allows a more gradual change in the envelope function at the ends of the cavity and a better confinement of the mode. These rods have been moved towards the exterior of the cavity by a distance ranging between 0.005 and 0.013 μm.

The results are presented in Fig. 6(b) for different values of the shifting d. The computed spectrum in TM polarization shows that when the shift between the two rods increases, the wavelength increases. Indeed, more the shift is important, more the cavity is bigger. The physical origin of this shift is the increase of the effective index of

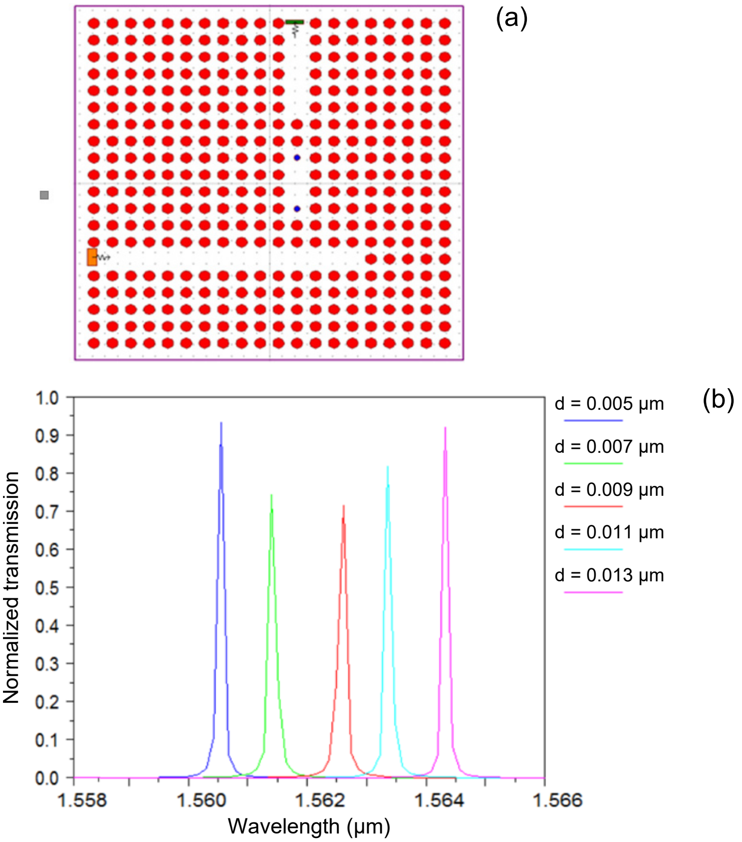

Fig. 6. (a) Photonic crystal filter with the displacement of the two rods marked in blue. (b) The output spectra of the proposed filter for different values of *d*.

Table 3. Variation of the wavelength λ and the quality factor Q depending on the different values of the displacement d.

Displacement d [μm]	Wavelength λ [μm]	Quality factor Q
0.005	1.5604	23170
0.007	1.5614	23407
0.009	1.5626	23524
0.011	1.5634	23727
0.013	1.5643	23766

the cavity. Table 3 provides the theoretical values of the filter wavelengths and the quality factors computed for $d = 0.005$ μm at $d = 0.013$ μm.

The Q factor increases when the shifting of the two rods increases. The maximum computed quality factor (23766) appears at $d = 0.013$ μm for a high transmission. Through this table, we note that the highest Q factor of 23766 is reached when $d = 0.013$ μm for the resonance mode situated at $\lambda = 1.5643$ μm (see Fig. 6(b)).

The reason for the increases of the Q factor with the holes shifting is the envelope function of the electric field profile of the cavity, which approaches the Gaussian function. On the other hand, when the holes are excessively shifted, the electric field penetrates more at exterior of the rods. Then, the optical confinement is done gradually around the rods, whereas the electric field distribution decreases abruptly at the exterior of these latter. Consequently, the envelope function of the electric field profile of the cavity deviates from the Gaussian function.

4. Study of the photonic crystals demultiplexer

The final design structure was produced by bringing all the results from the previous steps together. By combining four different single channel output couplers, each with their own high Q-factor resonators, a four-channel wavelength demultiplexer can be

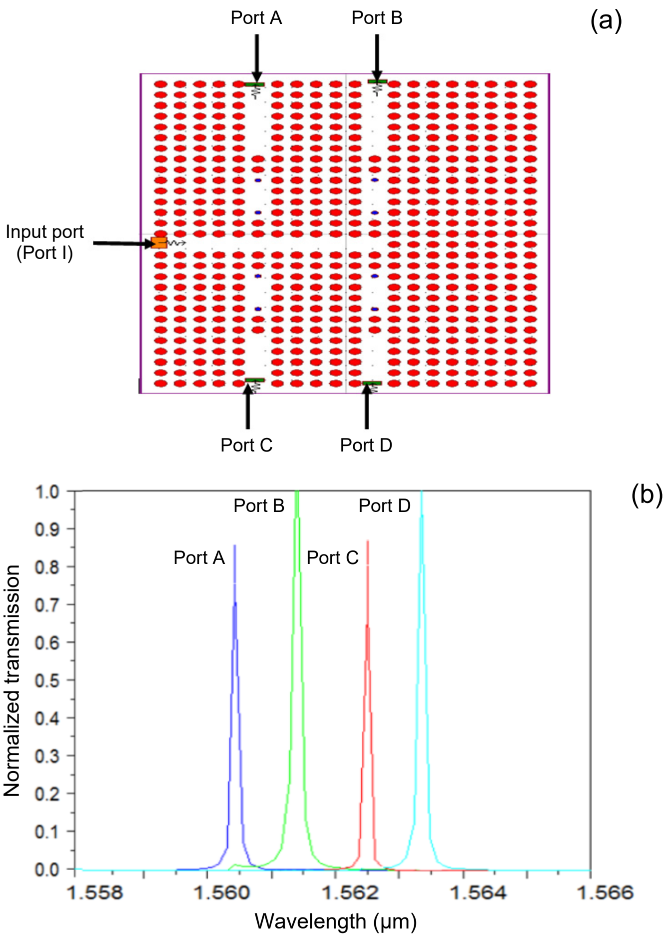

Fig. 7. (a) Schematic diagram of our proposed demultiplexer. (b) The transmission spectra of the demultiplexer at PhC obtained simultaneously in the four output ports.

created (Fig. 7). This figure represents a demultiplexer with the rods radius (denoted in blue) located at the ends of the cavity having the optimal value computed previously ($r' = 0.11$ μm). The positions of the rods are 0.005, 0.007, 0.009, and 0.011 μm.

The considered structure for this demultiplexer is a two-dimensional photonic crystal (2D PhC) constituted of 20 × 29 dielectric rods distributed in a square network as shown in Fig. 7(a).

The device is composed of 5 ports, where port I corresponds to the input signal and ports A, B, C and D are the output ports. The schematic representation of the structure is illustrated in Fig. 7(a). The light is injected via port I through the input waveguide then coupled to the four filters input where it is divided into four channels. Based on previous results, the location of filters is chosen so that it allows an appropriate equilibrium between the coupling efficiency and the degrees of resonance. Figure 7(b) shows the normalized transmission spectrums of the proposed demultiplexer. The resonance wavelengths of A, B, C and D channels are 1.5604, 1.5613, 1.5625 and 1.5633 μm, respectively.

There is also another functional parameter on the demultiplexer such as the quality factor shown in Table 4.

The determination of noise between the different channels is very important for the evaluation of the demultiplexer performance. Every component filter must operate independently without an interaction between the responses. The noise is evaluated by computing an extinguishing rate (ER) defined as [10]

$$\mathrm{ER} = 10\log\frac{\text{Transmission for a specific wavelength at the non-desired output port}}{\text{Transmission for a specific wavelength at the desired output port}}$$

The level of crosstalk (CT) between the structure channels is in the range of –19.19 and –44.1 dB as shown in Table 5. The mean value of the diaphone between output channels is around –31.65 dB.

Table 4. Significant parameters of the proposed demultiplexer.

Port	Wavelength λ [μm]	Quality factor Q	Transmission [%]
A	1.5604	20433	85
B	1.5613	18369	100
C	1.5625	51372	85
D	1.5633	21316	100

Table 5. Crosstalk between output channels of the proposed structure.

	Port A	Port B	Port C	Port D
Port A	/	–19.3	–35.12	–40.13
Port B	–19.19	/	–42.07	–43.66
Port C	–33.65	–27.14	/	–33.82
Port D	–44.1	–36.76	–37.9	/

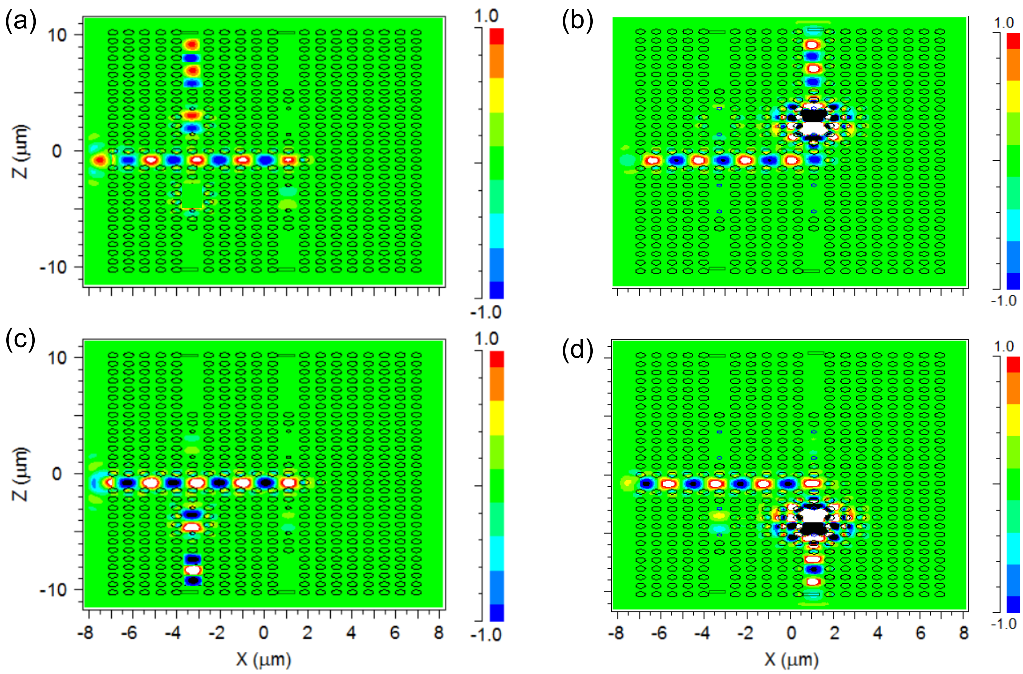

Fig. 8. Field contribution of each wavelength in the photonic crystals demultiplexer: (a) λ = 1.5629 μm, (b) λ = 1.5674 μm, (c) λ = 1.5716 μm, and (d) λ = 1.5759 μm.

The field distributions in the demultiplexer corresponding to the wavelengths of the A, B, C and D outputs are represented in Fig. 8. In this figure, it is clear that the wavelengths 1.5604, 1.5614, 1.5625, and 1.5534 μm are extracted from the input waveguide and transferred to the output waveguide via four cavities.

T a b l e 6. Comparison of the proposed demultiplexer with the other reported ones.

References	Number of channels	Channel spacing [nm]	Average quality factor	Average coupling efficiency [%]	Maximum and minimum of crosstalk (or average) [dB]
[5]	4	3.66	2752.75	97.1	/
[6]	2	7.4	2828	95	–25.07
[6]	4	7.8	4525	95	–19.6 and –40.4
[12]	4	3	2600	95	–19
[13]	4	2	1943	95.8	–18.11
[14]	4	7	3000	97.6	–25
[15]	4	2.75	4164.6.	95.5	–10.5 and –36.5
[16]	4	4.2	2221.13	89	–30.37
[17]	4	5.3	2567	97	–25
[18]	4	3.95	1000	100	–19
[19]	4	2	2600	97.5	–23
Present work	**4**	**0.96**	**20897**	**92.75**	**–44.1 and –19.19 (–31.65)**

By comparing with reported works, our demultiplexer possesses higher quality factor values than those of references [12–19]. The level of diaphone is certainly better than the one obtained in [12–19] (see Table 6).

5. Conclusion

In this paper, we have presented some results and explanations from the study of a filter based on 2D photonic crystals. The effects of some parameters on the filter characteristics such as mirror reflectivity of the cavity, the size and the position of the rods located at the cavity ends have been studied. A part of this work has been devoted to the study of a demultiplexer with four outputs using photonic crystals filters as the fundamental elements for designing this demultiplexer. The designed optical filter has indeed a very favorable transfer coefficient and quality factor. The average transfer coefficient and the quality factor are 92.75% and 20897, respectively. In addition, in this structure, the maximum and minimum values of crosstalk are equal to –19.19 and –44.1 dB, respectively.

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Received January 26, 2022
in revised form March 9, 2022