*Progress In Electromagnetics Research M, Vol. 69, 107–114, 2018*

# Nine Channels Wavelength Division Demultiplexer Based upon Two Dimensional Photonic Crystal

**Sanaa Ghezali[1], Fatima Tayeboun[1, *], and Kada A. Meradi[2]**

**Abstract**—The article analyzes a nine-channel Wavelength Division Demultiplexer based on a two-dimensional photonic crystal lattice. In the design of the device, defects and air holes are shifted in the resonant cavities: by changing characteristics such as radii of defects, distance between them and position of defects. A compact optical filter circuit is designed with a 1 nm channel spacing. The properties of these devices are investigated using finite-difference time-domain method. The resonant wavelengths of nine channel demultiplexers are 1481.4, 1503.7, 1526.6, 1538.4, 1550.3, 1562.3, 1574.7, 1587.2 and 1612.9 nm. The value of transmission efficiency for channels was obtained in 79–96% range. In addition, the maximum value of crosstalk and average quality factor for channels were calculated −11.3 dB and 2000, respectively. The overall size of the structure is small (11.3 μm × 15.3 μm) which is suitable for photonic integrated circuits and optical communication network applications.

## 1. INTRODUCTION

For realizing ultra-compact optical devices, one needs structures which can control the propagation of light waves inside very small space and waveguides. Due to their photonic band gap (PBG) region, photonic crystals (PhCs) have excellent ability to confine and control the light waves inside compact waveguides [1, 2]; therefore, they are very promising structures to design compact optical devices such as multiplexers [3, 4] and demultiplexers [5–8].

An optical demultiplexer is a device, which has the property of adding or dropping given wavelength channels from a multi-wavelength network. In recent years, various configurations have been proposed for performing filtering behavior based on PhC structures. Defect structures, resonant cavities coupled waveguides and ring resonators are some examples of proposed filtering mechanisms [9–14].

Number of output channels, transmission efficiency, quality factor, crosstalk and channel spacing are the most crucial characteristics of PhC-based demultiplexers. Recently, many attempts have been focused on improving the aforementioned characteristics. For instance, a five-channel demultiplexer has been proposed by horizontally cascading five single channel drop filters with different lattice constants; in this structure, the channel spacing was around 8 nm [15]. Another similar demultiplexer was created by cascading multiple add-drop filters with different lattice constants; the add-drop filters operation was based on contra-directional coupling and standing wave resonators. The authors claimed that this demultiplexer is able to separate 12 channels with 10 nm channel spacing [16].

Rakhshani and Birjandi [17] cascaded three PhC ring resonator-based channel drop filters with different refractive indices to realize a four-channel demultiplexer. In this structure, the channel spacing was about 6.1 nm with bandwidth and average transmission efficiency being 2.75 nm and 95%, respectively. Crosstalk and footprint were obtained as −24.44 dB and 294.25 μm$^2$, respectively. Alipour-Banaei et al. [18] proposed a resonant defect structure for designing an eight-channel demultiplexer, and

*Received 3 April 2018, Accepted 28 May 2018, Scheduled 13 June 2018*
* Corresponding author: Fatima Tayeboun (tayebounfatima@yahoo.com).
[1] University Djillali Liabes, Sidi-Bel-Abbes 22000, Algeria. [2] Institute of Science and Technology, University of Ain Temouchent, BP 284 RP, 46000, Algeria.

the channel spacing was about 1 nm. The minimum transmission efficiency and the largest crosstalk were 40% and −8 dB, respectively.

Considering the above-mentioned demultiplexers, in this paper we aim to overcome the drawbacks of the previously proposed structures, such as increasing the number of output channels, decreasing the bandwidth, channel spacing and crosstalk, and improving the transmission efficiency and quality factor. So we proposed a novel defective resonant cavity structure to realize the proposed demultiplexer.

This paper is organized as follows. In Section 2, we discuss the WDDM structure design procedure and describe the calculated photonic band gap. Simulation and results of the demultiplexer are discussed in Section 3, and finally, in Section 4 we conclude our work.

## 2. PHOTONIC CRYSTAL GEOMETRY

The proposed Wavelength Division Demultiplexer (WDDM) makes use of a two-dimensional triangular lattice of air holes in a dielctric medium for good confinement and manipulation of light. The demultiplexer is designed with $22 \times 30$ rods in $X$ and $Z$ directions. The radius of air rods is $R = 130$ nm, and the refractive index of dielctric is 3.46.

Plane-wave expansion (PWE) [19] is a method which is used to solve the Maxwell's equation by formulating an eigenvalue problem. The modes of PCs are in the concept of eigen-solutions of the wave equation with an inhomogeneous and periodic structure. It solves the problem in time harmonic forms with no dispersive media. This method is used to calculate the PBG and propagation modes of the PhCs structure.

In our structure, a wider PBG extends from $0.27 < a/\lambda < 0.44$ for TM polarization (in which the magnetic field is in the propagation plane and the electric field is perpendicular), where $\lambda$ is the wavelength in free space whose corresponding wavelength range is from 1481.4 nm to 1612.9 nm. Figure 1 shows the band structure diagram of PhC.

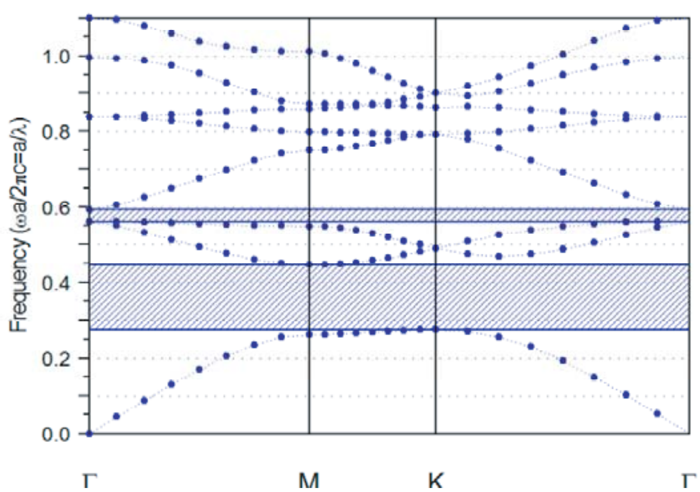



**Figure 1.** Band structure of triangular lattice photonic crystal of TM polarized light.

In this structure, we employed a high quality factor defective resonant cavity as the wavelength selecting part of the demultiplexer. As shown in Figure 2(a), the defective resonant cavity is composed of three central air rods as core rods with reduced radius; the radius of the core rods is $Ri$ where $i$ is the number of channel. The central rods are shown in a different color to be distinguished from other rods.

At upper and lower sides of core rods, we have other rods constructing the upper and lower walls of the cavity. In order to control the width of the resonant cavity, we reduced the radius of $n$ rods on $R_0$. The resonant wavelength of the proposed cavity depends on $Ri$ and parameter $n$.

By removing 10 air rods from the central line of the air rod array (Figure 2(b)) and 25 air rods inclined 60°, we created input waveguides. Then, nine output waveguides at right sides of the

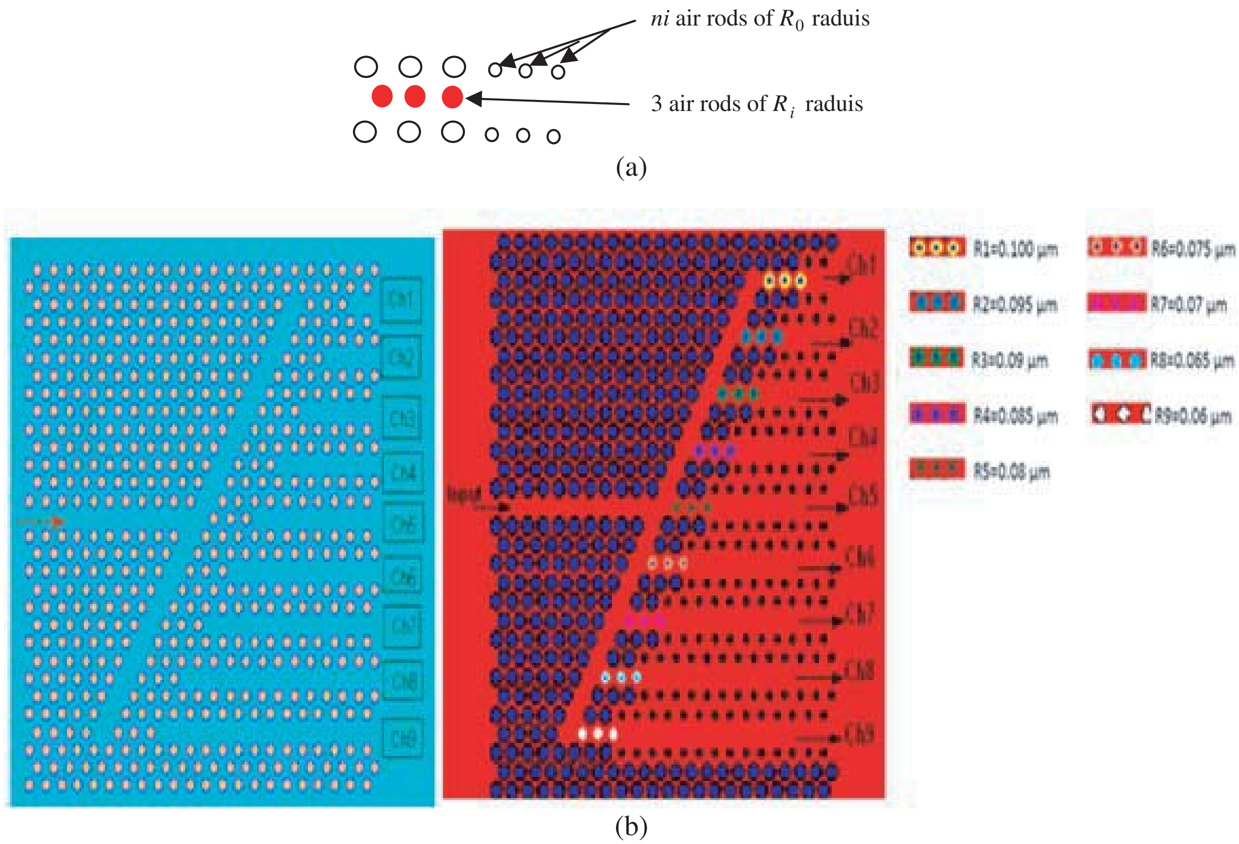



**Figure 2.** (a) Schematic diagram of the proposed defective resonant cavity. (b) Simulated structure.

input waveguide were created. Finally, we put resonant cavities between input waveguides and output waveguides. In order to separate nine channels with different central wavelengths, the resonant cavities should have different resonant wavelengths.

So the structural parameters of cavities $Ri$ and $ni$ should be chosen different from each other. Therefore, for all defective resonant cavities, the values of $R_0$ are similar and equal to 52.5 nm. See Table 1 for chose different $ni$ and $Ri$ values for every defective resonant cavity.

**Table 1.**

| *Number of channel i* | $ni$ | $Ri$ |
|---|---|---|
| *Channel 1* | 2 | $R1 = 0.1\,\mu\text{m}$ |
| *Channel 2* | 4 | $R2 = 0.095\,\mu\text{m}$ |
| *Channel 3* | 5 | $R3 = 0.09\,\mu\text{m}$ |
| *Channel 4* | 7 | $R4 = 0.085\,\mu\text{m}$ |
| *Channel 5* | 8 | $R5 = 0.08\,\mu\text{m}$ |
| *Channel 6* | 10 | $R6 = 0.075\,\mu\text{m}$ |
| *Channel 7* | 11 | $R7 = 0.07\,\mu\text{m}$ |
| *Channel 8* | 13 | $R8 = 0.065\,\mu\text{m}$ |
| *Channel 9* | 14 | $R9 = 0.06\,\mu\text{m}$ |

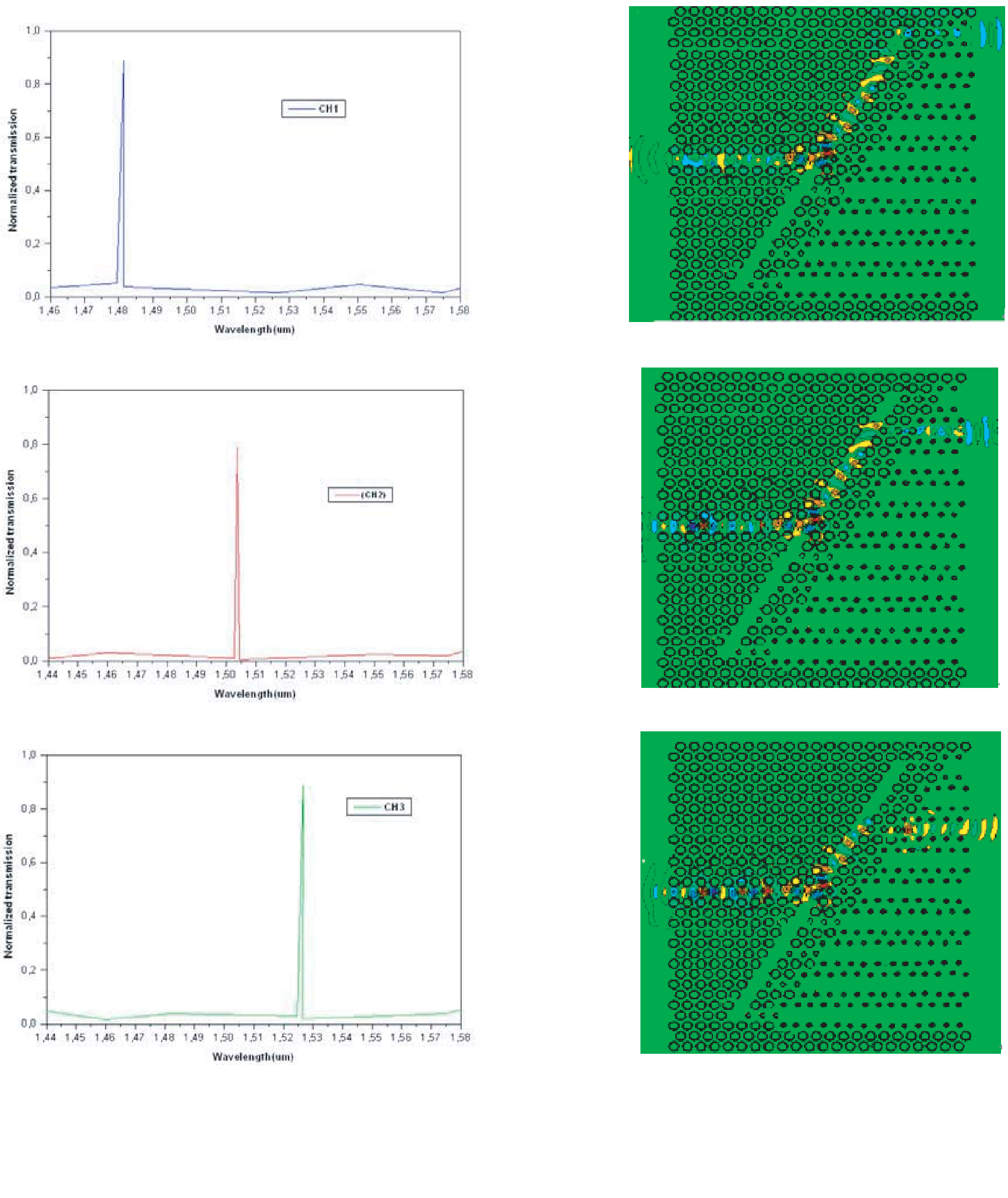
## 3. SIMULATION AND ANALYSIS

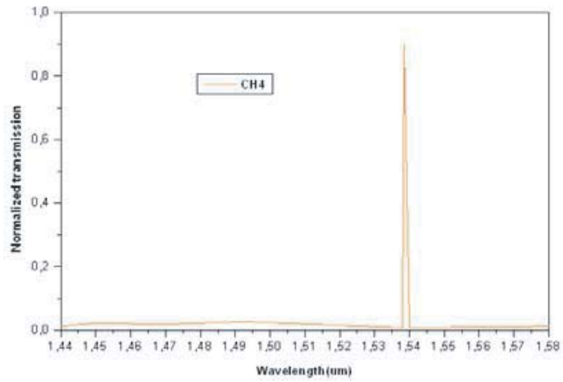
The finite-difference time-domain (FDTD) method [20] is a method to simulate the electromagnetic devices for all ranges of frequencies from the microwave to the optical regime. It is one of the most important computational techniques for analysing the electromagnetic waves propagating through PhC devices. It is simple, attractive, accurate and efficient to discretise Maxwell's equations.

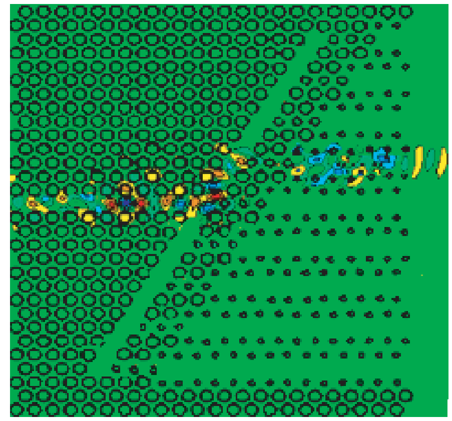
The output spectra of the proposed resonant cavity for different values of *ni* and *Ri* are depicted in Figures 3(a) and (b). As one can see, by increasing *ni* the resonant mode shifts toward upper wavelengths. However, increasing *Ri* will shift the resonant modes toward lower wavelengths.

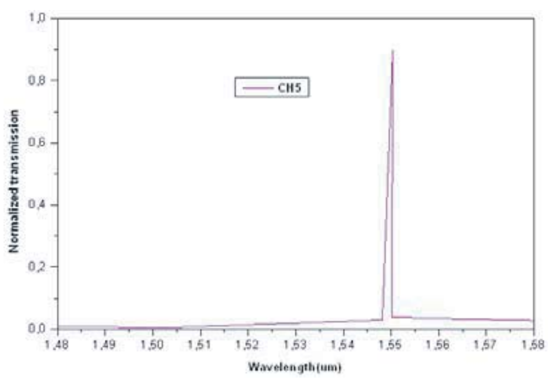
The obtained maximum and minimum transmittances are 96% and 79%, respectively, and the minimum transmission of 79% occurs at the wavelength of 1.503 μ, while the maximum transmittance in the order 96% occurs at the wavelength of 1.562 μ. Due to different interferences of light at the end of the input waveguide, light is transmitted through different waveguides as shown in Figure 3(b).

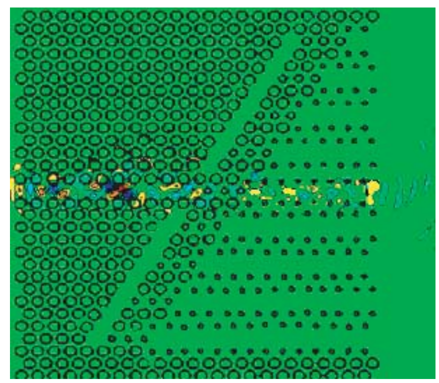
As can be observed in Figure 3, different wavelengths are dropped into different waveguides with high transmittance and low reflectance. The separation between adjacent channels is about 20 nm, well fitted for WDM systems. The divergence in the spacing can be explained in terms of dispersion of the

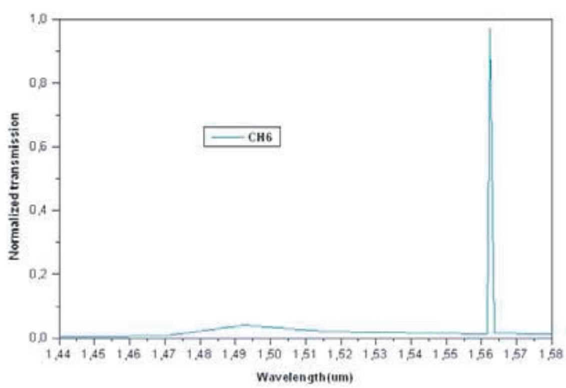


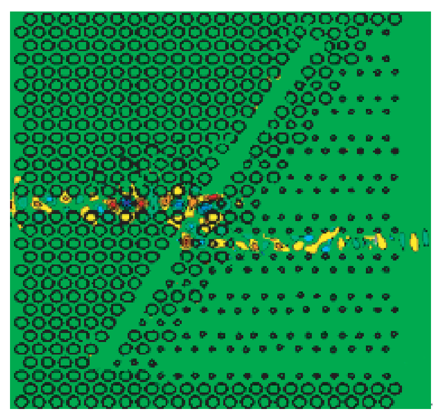

CH4
Normalized transmission
Wavelength (um)

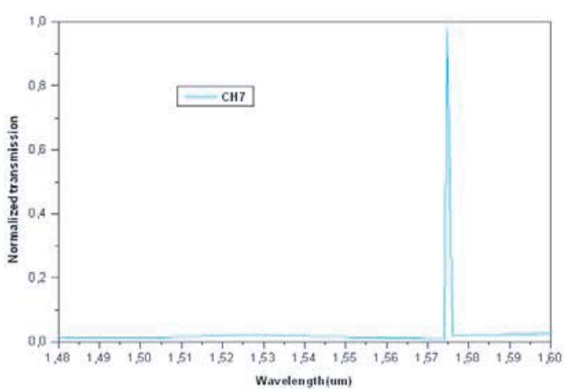


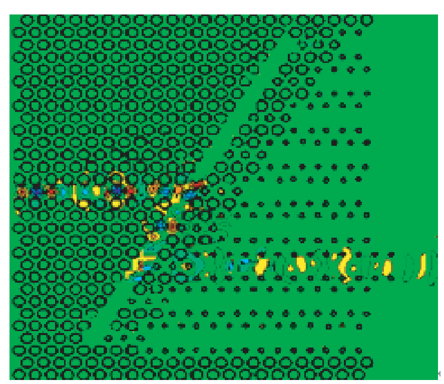

CH5
Normalized transmission
Wavelength (um)

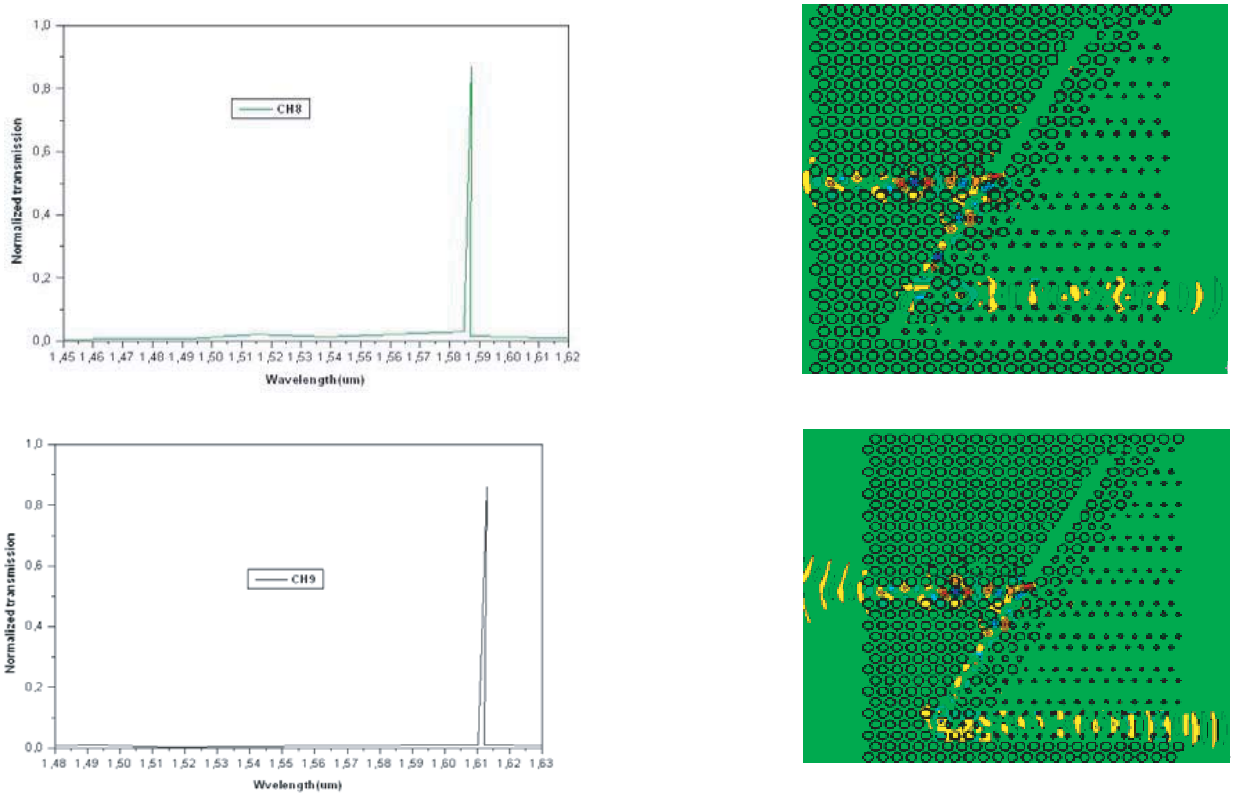



CH6
Normalized transmission
Wavelength (um)




CH7
Normalized transmission
Wavelength (um)






(a) (b)

**Figure 3.** (a) Output spectral nine channel transmission separately. (b) Distribution of the magnetic field Hz separatel.

photonic crystal and finite mesh sizes.

Another crucial parameter in optical demultiplexers is quality factor, which is calculated by $Q = \lambda/\Delta\lambda$ where $\lambda$ is the central wavelength of the channel, and $\Delta\lambda$ is the bandwidth of the channel. According to the aforementioned relationship, smaller bandwidths lead to higher quality factors. In the proposed structure, the minimum and maximum bandwidths are 0.45 and 1 nm, respectively; therefore, the minimum and maximum quality factors are 1481 and 3471, respectively. The proposed structure has better quality factor values than in previous works [e.g., 9–14, 21–25]. The reduced rods will result in destructive interference between the low amplitude resonant modes, which contributes to the lower mode cancelation mechanism [26] and, as a result, creates narrow band modes and high $Q$-factor values. The complete specifications of the proposed demultiplexer are listed in Table 2.

Another critical point in wavelength division demultiplexer design is crosstalk.

The crosstalk calculation $X$ is defined as follow:

$$X_{\mathrm{dB}} = 10\lg\frac{1-A}{1-A_i}.$$

where $A$ is the transmission maximum value of resonant cavity of one channel at the resonant frequency. $A_i$ represents the transmission value of the other adjacent channels at the same resonant frequency.

The resolution of demultiplexer increases when crosstalk decreases.

In Table 3, an acceptable crosstalk between outputs is shown changing from −11.3 dB to −38 dB. This is a main distinction for the proposed structure. In this table, crosstalk is named as $X_{tij}$, in which $i$ and $j$ vary from 1 to 9. $X_{tij}$ shows the effect of crosstalk of output $j$ in the $i$th output. ($i$ and $j$ indices are row and column in Table 2, respectability).

For example, $Xt_{12}$ shows the amount of crosstalk of output 2 in output 1.

**Table 2.** Simulation results of nine wavelength division demultiplexer.

| channel | $\lambda$ (nm) | $\Delta\lambda$ (nm) | $Q$ | Transmission |
|---|---|---|---|---|
| 1 | 1481.4 | 1 | 1481 | 88% |
| 2 | 1503.7 | 0.9 | 1670 | 79% |
| 3 | 1526.6 | 0.6 | 2544 | 89% |
| 4 | 1538.4 | 1 | 1538 | 89% |
| 5 | 1550.3 | 1 | 1550 | 90% |
| 6 | 1562.3 | 0.45 | 3471 | 96% |
| 7 | 1574.7 | 1 | 1574 | 95% |
| 8 | 1587.2 | 1 | 1587 | 86% |
| 9 | 1612.9 | 0.7 | 2304 | 85% |

**Table 3.** Crosstalk amounts ($X_{tij}$) of the proposed structure (dB).

| Channel | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | $---$ | $-1.3$ | $-18$ | $-25$ | $-28$ | $-27$ | $-26$ | $-26$ | $-28$ |
| 2 | $-16$ | $---$ | $-14$ | $-22$ | $-23$ | $-25$ | $-25$ | $-25$ | $-26$ |
| 3 | $-16$ | $-19$ | $---$ | $-13$ | $-17$ | $-21$ | $-23$ | $-25$ | $-22$ |
| 4 | $-27$ | $-25$ | $-17$ | $---$ | $-12$ | $-22$ | $-24$ | $-23$ | $-22$ |
| 5 | $-27$ | $-31$ | $-18$ | $-17$ | $---$ | $-18$ | $-20$ | $-23$ | $-19$ |
| 6 | $-32$ | $-31$ | $-23$ | $-25$ | 13 | $---$ | $-18$ | $-20$ | $-19$ |
| 7 | $-35$ | $-33$ | $-29$ | $-27$ | $-25$ | $-17$ | $---$ | $-17$ | $-18$ |
| 8 | $-38$ | $-36$ | $-33$ | $-31$ | $-26$ | $-24$ | $-24$ | $---$ | $-17$ |
| 9 | $-38$ | $-38$ | $-34$ | $-35$ | $-31$ | $-25$ | $-19$ | $-17$ | $---$ |

Finally, the overall foot print of the proposed structure is about $18\,\mu\text{m}^2$ making it smaller than previously proposed structures [9, 22].

## 4. CONCLUSION

In this paper, we propose a novel defective waveguides structure based on 2D photonic crystal to perform wavelength selection. It is shown that by changing the size of the border and the three holes in each waveguide, the selective wavelength will be changed. So we employed nine waveguides with different widths and created a nine-channels demultiplexer. The dominant characteristics of the proposed demultiplexer are high quality factor values — the quality factor is more than 3400 — and very low crosstalk, which is between $-11.3$ and $-38$ dB. Transmission efficiency of the proposed structure ranges between 79 and 96%.

## REFERENCES

1. Sakoda, S., *Optical Properties of Photonic Crystals*, Springer, Berlin, 2001.
2. Wu, Z., K. Xie, and H. Yang, "Band gap properties of two dimensional photonic crystals with rhombic lattice," *Optik*, Vol. 123, 534–536, 2012.
3. Mahmoud, M. Y., G. Bassou, A. Taalbi, and Z. M. Chekroun, "Optical channel drop filters based on photonic crystal ring resonators," *Opt. Commun.*, Vol. 285, 368–372, 2012.
4. Yusoff, M. H. M., H. A. Hassan, M. R. Hashim, and M. K. Abd-Rahman, "Hybrid photonic crystal 1.31/1.55 μm wavelength division multiplexer based on coupled line defect channels," *Opt. Commun.*, Vol. 284, 1223–1227, 2011.

5. Alipour-Banaei, H., F. Mehdizadeh, and S. Serajmohammadi, "A novel 4-channel demultiplexer based on photonic crystal ring resonators," *Optik*, Vol. 124, 5964–5967, 2013.
6. Djavid, M., F. Monifi, A. Ghaffari, and M. S. Abrishamian, "Heterostructure wavelength division multiplexers using photonic crystal ring resonators," *Opt. Commun.*, Vol. 281, 4028–4032, 2008.
7. Bernier, D., X. Le Roux, A. Lupu, D. Marris-Morini, L. Vivien, and E. Cassan, "Compact low crosstalk CWDM demultiplexer using photonic crystal superprism," *Opt. Express*, Vol. 42, 17260–17214, 2008.
8. Yusoff, M. H. M., H. A. Hassan, M. R. Hashim, and M. K. Abd-Rahman, "Hybrid photonic crystal 1.31/1.55 μm wavelength division multiplexer based on coupled line defect channels," *Opt. Commun.*, Vol. 284, 1223–1227, 2011.
9. Robinson, S. and R. Nakkeeran, "Photonic crystal ring resonator based add-drop filter using hexagonal rods for CWDM systems," *Optoelectron. Lett.*, Vol. 7, 0164–0166, 2011.
10. Meradi, K. A., F. Tayeboun, S. Ghezali, et al., "Design of a thermal tunable photonic-crystal coupleur," *Journal of Russian Laser Research*, Vol. 32, No. 6, 572–578, 2011.
11. Robinson, S. and R. Nakkeeran, "PCRR based add drop filters using photonic crystal ring resonators," *Optic-Int. J. Light Electron Optic*, 2012.
12. Shih, T.-T., Y.-D. Wu, and J.-J. Lee, "Proposal for compact optical triplexer filter using 2-D Photonic crystals," *IEEE Photon. Technol. Lett.*, Vol. 21, 18–21, 2009.
13. Vegas Olmos, J. J., M. Tokushima, and K. Kitayama, "Photonic add-drop filter based on integrated photonic crystal structures," *J. Sel. Top. Quantum Electron.*, Vol. 16, 332–337, 2010.
14. Wang, C.-C. and L.-W. Chen, "Channel drop filters with folded directional couplers in two-dimensional photonic crystals," *Physica B*, Vol. 405, 1210–1215, 2010.
15. Cheng, S. C., J. Z. Wang, L. W. Chen, and C. C. Wang, "Multichannel wavelength division multiplexing system based on silicon rods of periodic lattice constant of hetero photonic crystal units," *Optik*, Vol. 121, 1027–1032, 2011.
16. Manzacca, G., D. Paciotti, A. Marchese, M. S. Moreolo, and G. Cincotti, "2D photonic cavity based WDM multiplexer," *Photonic Nanostruct.-Fundam. Appl.*, Vol. 5, 164–176, 2007.
17. Rakhshani, M. R. and M. A. M. Birjandi, "Design and simulation of wavelength demultiplexer based on heterostructure photonic crystals ring resonators," *Physica E*, Vol. 50, 97–101, 2013.
18. Alipour-Banaei, H., F. Mehdizadeh, and M. Hassangholizadeh Kashtiban, "A novel proposal for all optical PhC-based demultiplexers suitable for DWDM applications," *Opt. Quant. Electron.*, Vol. 45, 1063–1075, 2013.
19. Johnson, S. G. and J. D. Joannopoulos, "Block-iterative frequency domain methods for Maxwell's equations in a plane wave basis," *Opt. Express*, Vol. 8, 173–190, 2001.
20. Gedney, S. D., *Introduction to Finite-Difference Time-Domain (FDTD) Method for Electromagnetics*, Morgan and Claypool, Lexington, 2006.
21. Qiang, Z., W. Zhou, R. A. Soref, "Optical add-drop filters based on photonic crystal ring resonators," *Opt. Express*, Vol. 15, 1823–1831, 2007.
22. Rashki, Z. and M. A. Mansouri Birjandi, "New design of optical add-drop filter based on triangular lattice photonic crystal ring resonator," *Tech. J. Eng. Appl. Sci.*, Vol. 3, 441, 2013.
23. Robinson, S. and R. Nakkeeran, "Investigation on two dimensional photonic crystal resonant cavity based bandpass filter," *Optik*, Vol. 123, 451–457, 2012.
24. Drouard, E., H. T. Hattori, C. Grillet, A. Kazmierczak, X. Letartre, P. Rojo-Romeo, and P. Viktorovitch, "Directional channel drop filter based on a slow Bloch mode photonic crystal waveguide section," *Opt. Express*, Vol. 13, 3037–3048, 2005.
25. Shanthi, K. V. and S. Robinson, "Two-dimensional photonic crystal based sensor for pressure sensing," *Photonic Sensors*, Vol. 4, No. 3, 248–253, 2014.
26. Johnson, S. G., S. Fan, A. Mekis, and J. D. Joannopoulos, "Multipole cancellation mechanism for high $Q$ cavities in the absence of a complete photonic band gap," *Appl. Phys. Lett.*, Vol. 78, 3388–3391, 2001.