Novel Design of Four-Channel Wavelength Division Demultiplexer Based on Two-Dimensional Photonic Crystal Ring Resonators

Imane Chergui, Faiza Bounaas and Amel Labbani

October 24, 2022

Novel design of four-channel wavelength division demultiplexer based on two-dimensional photonic crystal ring resonators

Imane Chergui
Laboratoire Hyperfréquences et Semiconducteurs (LHS)
Departement d'Electronique
Faculté des sciences de la Technologie
Université Frére Mentouri
Constantine1, Algérie
imanechergui1995@gmail.com

Faiza Bounaas
Laboratoire Hyperfréquences et Semiconducteurs (LHS)
Departement d'Electronique
Faculté des sciences de la Technologie
Université Frére Mentouri
Constantine1, Algérie
faiza.bounaas@student.umc.edu.dz

Amel Labbani
Laboratoire Hyperfréquences et Semiconducteurs (LHS)
Departement d'Electronique
Faculté des sciences de la Technologie
Université Frére Mentouri
Constantine1, Algérie
labbani.amel@umc.edu.dz

***Abstract*— In this study we investigated four-channel optical demultiplexer using two dimensional photonic crystal ring resonators with a square lattice structure. The numerical simulation results show that the output transmission efficiency and the quality factor are 99.45%, and 1613, respectively. The crosstalk between -11.16 dB and -33.93 dB was attained. The finite difference time domain and plane wave expansion methods were chosen to demonstrate the performance of the considered device. The total size of the structure, is about 269 μm^2 which is suitable for optical integrated circuits (PICs) and appropriate for WDM (wavelength division multiplexing) technologies.**

Keywords—photonic crystal, crosstalk, demultiplexer, FDTD, quality factor

I. INTRODUCTION

Due to the significant advantages of optical communication networks, such as high bandwidth, high speed, immunity, etc., they received significant attention. The ideal objective for optics and photonics engineers is to create an optical network entirely devoid of electronics. Therefore, all-optical equipment such as optical filters, demultiplexers, optical switches, and so on are required to achieve this purpose. Demultiplexers based on the photonic crystal are important parts of optical communication networks and are a key part of wavelength division multiplexing (WDM) technologies.

Photonic crystals (PhCs) are now the most promising choices for designing all-optical devices suited for integrated optical circuits. PhCs are regular arrays of dielectric materials with a periodic dispersion of refractive indexes. Due to their periodicity feature, these structures have a specific frequency zone in their band structure diagram where optical wave transmission is forbidden. These frequency ranges are photonic band gaps [1, 2]. According to this property many devices based on PhCs has been designed such as optical logic gates [3, 4], switches[5, 6], sensors[7-9], filters[10-12], demultiplexers[13-15], etc.

A four-channel demultiplexer is suggested in this article.Five waveguides and four-ring resonators in a 2DPhC are utilized to produce the proposed device. We will employ the finite difference time domain and plane wave expansion methods to calculate the spectrum of the output transmission. The suggested structure is suitable for photonic integrated circuits and WDM systems.

II. BASIC DESIGN

Our objective in this section is to investigate an optical filter. The proposed device is based on two-dimensional (2D) PhC formed by a cubic lattice of silicon rods with a refractive index of 3.5 embedded in air background, as depicted in fig.1. The radius of the dielectric rods is R = 0.19a, and a is the lattice constant. The plane Wave Expansion (PWE) approach is used to compute the photonic band diagram of the specified structure. As shown in fig. 2, the normalized frequency is obtained from 0.2948 to 0.4402(a/λ), which covers the optical communication domain.

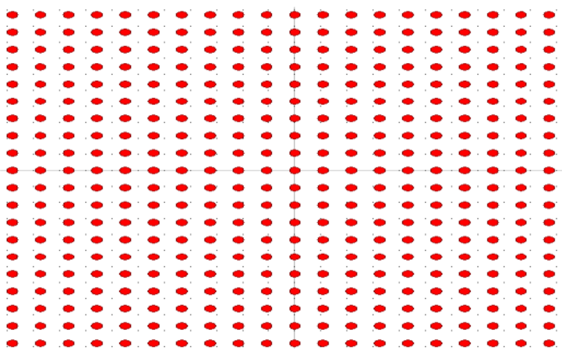

Fig. 1. Schematic of 2D PhC basic structure

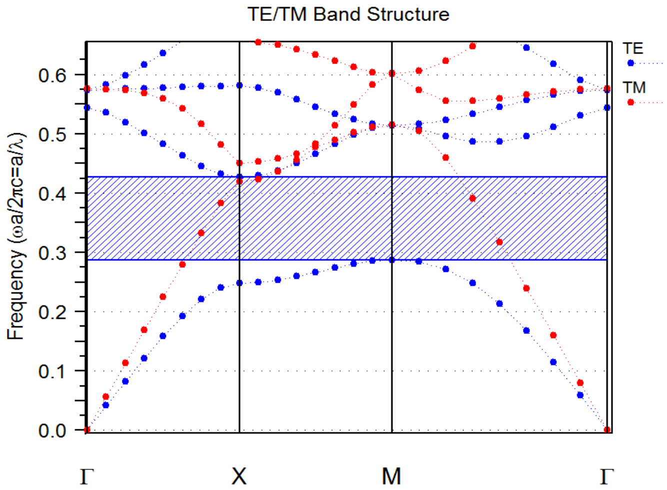

Fig. 2. The scatter diagram of the basic structure

The finite difference method in the time domain for two dimensions (2D-FDTD) was used for the filter simulations. The FDTD method's lattice size (x, z) has been set to a/16. To have a stable results, the time step Δt must be chosen based on equation (1) :

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

Where Δt is the time step, c is the speed of light in vacuum and Δx and Δz are the mesh sizes in both x and z directions.

III. FILTER DESIGN

In this section, we proposed an optical filter based on ring resonator. The ring with square shape is situated between two linear waveguides. The rods situated within the ring resonator are named inner rods. Their radius *rs* are set to 0.085 *a*. In Fig. 3, the right inset shows a bigger picture of the square ring and the parameter *rs* of the inner rod.

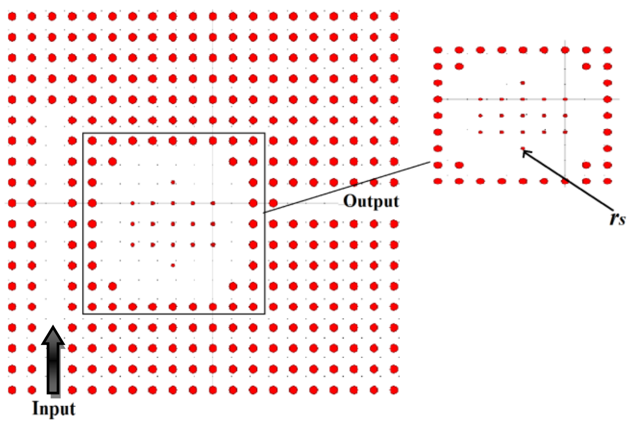

Fig. 3 the suggested filter structure

The time domain simulation of the proposed filter is shown in fig.4. Our results show that the maximum transmission efficiency and quality factor obtained at resonant wavelength λ = 1554.1 nm equals 99.9% and 3883.2, respectively.

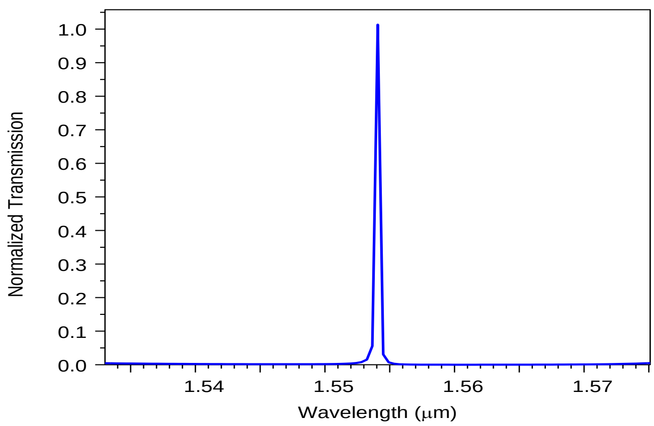

Fig. 4. The output spectrum of the proposed filter when rs=0.085×a .

In this part, we varied the radius of inner rods that affects the normalized transmission spectrum. We changed the inner rods (*rs*) from 0.0835*a*, to 0.85*a*, with an increment step of 0.0005*a*. We observed that different radius equal to 0.0835*a*, 0.084*a*, 0.0845*a* and 0.85*a* can select different resonant wavelengths of λ = 1550 nm λ = 1551.6 nm λ = 1552.8 nm and λ = 1554.1 nm, respectively. Fig.5 shows that an increase in *rs* results in red shift in the resonant wavelength.

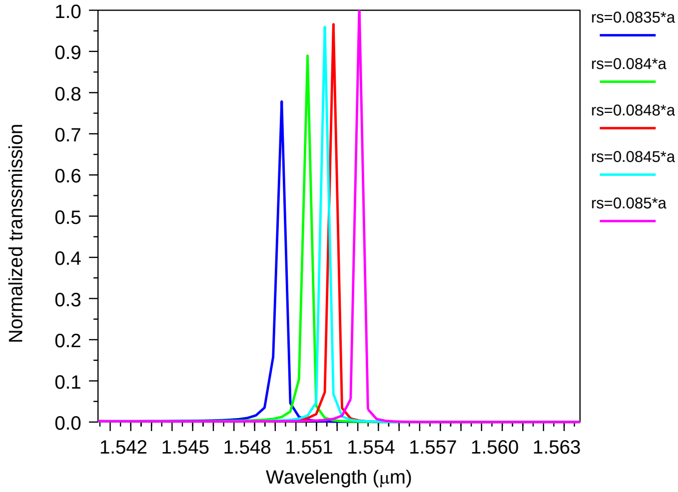

Fig. 5 Output spectrum of the filter for four various values of *rs*

IV. DEMULTIPLEXER DESIGN

In this part, we investigated four channel demultiplexer based on two dimensional photonic crystal. In our design, we used four ring resonators and two linear waveguides. The radius of the inner rods of the channels 1, 2, 3 and 4 are 0.08*a*, 0.085*a*, 0.09*a* and 0.095*a*, respectively. The final sketch of the structure is shown in fig.6. The output spectra of the demultiplexer are shown in Fig. 7. As illustrated the figure, this device can separate four channels with central wavelengths equal to λ_1 = 1499 nm, λ_2 = 1516.2 nm λ_3 = 1524 nm and λ_4 = 1536.9 nm. To prove the performance of the proposed demultiplexer, the steady-state electric field distribution is calculated for the four wavelengths. The obtained results are illustrated in Fig.8. Table 3 shows the comparison between the suggested demultiplexer and some recently published articles

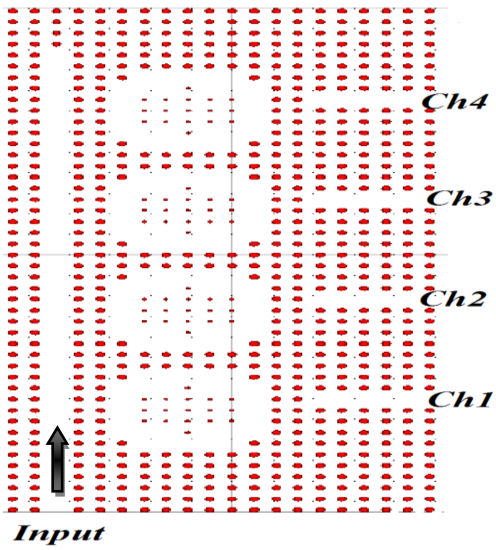

Fig.6 Sketch of the proposed demultiplexer

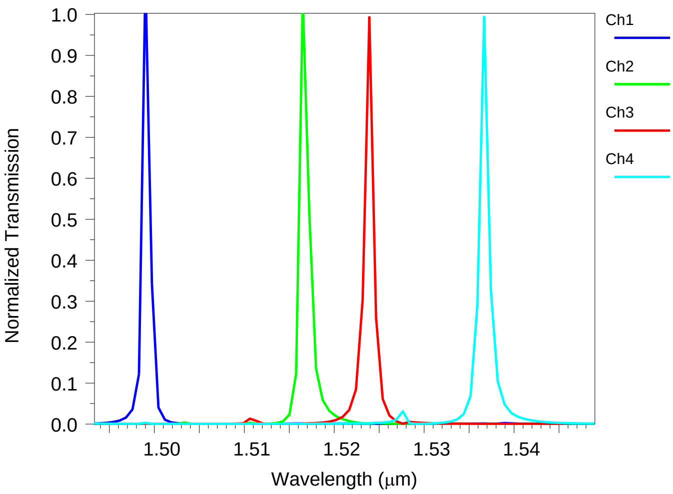

Fig.7. The output spectrum of the suggested demultiplexer

TABLE 1: WAVELENGTH, TRANSMISSION POWER AND QUALITY FACTOR RES OF THE PROPOSED DEMULTIPLEXER.

Wavelength (nm)	Transmission efficiency %	Quality factor
1499	100	1873.75
1516.2	100	1514
1524	98.83	1.530
1536.9	99	1537

TABLE 2: CROSSTALK VALUES OF THE SUGGETED DEVICE (DB).

Channel	1	2	3	4
1	_	-18.35	-15.14	-11.16
2	-14.93	_	-20.45	-20.07
3	-30.65	-24.65	_	-25.71
4	-27.16	-33.93	-31.94	_

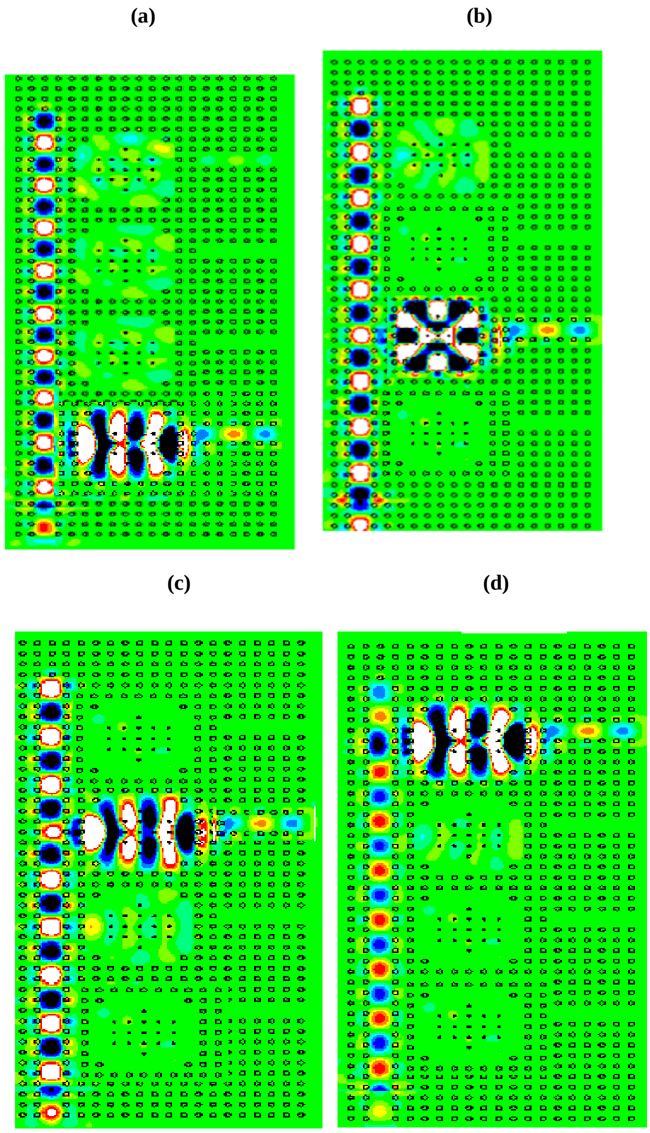

Fig.8. Optical field distribution for T- shaped dimultiplexer with various wavelengths (a) λ_1 = 1499.1 nm, (b) λ_2 = 1516.2 nm (c) λ_3 = 1524.2nm, (d) λ_4 = 1536.8nm.

TABLE 3. COMPARISON OF OUR RESULTS WITH SOME PREVIOUS STUDIES

Reference	Transmission efficiency %	Quality factor	Crosstalk (dB)
[16]	96	1000	− 35
[17]	91.48	1342.835	/
[18]	98	1319	-28
Our work	99.45	1613	-22.54

IV Conclusion

In this study, we proposed a novel design of compact demultiplexer based photonic optical demultiplexer ring resonator. We demonstrate that by selecting an appropriate radius of the inner rods of the ring resonator, high transmission efficiency and high-quality factor were attained. The output transmission efficiency achieved is approximately 99.9%, localized at 1554.1 nm. The numerical simulation results show that for different radii of the inner rods *rs* equal to 0.08*a*, 0.085*a*, 0.09*a* and 0.095*a*, can select different resonant wavelengths of λ_1 = 1499 nm, , λ_2 = 1516.2 nm, λ_3 = 1524 nm and λ_4 = 1536.9 nm, respectively. The total footprint of the device is 269 μm^2, which is very compact and suitable for optical integrated circuits (PICs) and could be used in WDM technologies.

REFERENCE

[1] J. D. Joannopoulos, P. R. Villeneuve, and S. Fan, "Photonic crystals," *Solid State Communications,* vol. 102, pp. 165-173, 1997.

[2] K. Sakoda and K. Sakoda, *Optical properties of photonic crystals* vol. 2: Springer, 2005.

[3] T. S. Mostafa, N. A. Mohammed, and E.-S. M. El-Rabaie, "Ultra-high bit rate all-optical AND/OR logic gates based on photonic crystal with multi-wavelength simultaneous operation," *Journal of Modern Optics,* vol. 66, pp. 1005-1016, 2019.

[4] K. Goswami, H. Mondal, P. Das, and A. Thakuria, "Realization of ultra-compact all-optical logic AND Gate based on photonic crystal waveguide," in *Advances in Communication, Devices and Networking*, ed: Springer, 2022, pp. 61-68.

[5] M. Radhouene, M. Najjar, M. K. Chhipa, S. Robinson, and B. Suthar, "Design and analysis a thermo-optic switch based on photonic crystal ring resonator," *Optik,* vol. 172, pp. 924-929, 2018.

[6] R. Rajasekar, K. Parameshwari, and S. Robinson, "Nano-optical switch based on photonic crystal ring resonator," *Plasmonics,* vol. 14, pp. 1687-1697, 2019.

[7] B. Tebboub, A. Labbani, and F. Brik, "A Label-Free Biosensor for Protein Detection Based on Ring Slots in a Photonic Crystal," *Journal of Russian Laser Research,* pp. 1-8, 2022.

[8] F. Bounaas and A. Labbani, "High sensitivity temperature sensor based on photonic crystal resonant cavity," *Progress In Electromagnetics Research Letters,* vol. 90, pp. 85-90, 2020.

[9] F. Bounaas and A. Labbani, "Optimized Cancer Cells Sensor Based on 1D Photonic Crystal Vertical Slot Structure," *Progress In Electromagnetics Research C,* vol. 117, pp. 239-249, 2021.

[10] F. Ghasemi, S. R. Entezar, and S. Razi, "Graphene based photonic crystal optical filter: Design and exploration of the tunability," *Physics Letters A,* vol. 383, pp. 2551-2560, 2019.

[11] M. Hosseinzadeh Sani, A. Ghanbari, and H. Saghaei, "An ultra-narrowband all-optical filter based on the resonant cavities in rod-based photonic crystal microstructure," *Optical and Quantum Electronics,* vol. 52, pp. 1-15, 2020.

[12] M. Y. Mahmoud, G. Bassou, and A. Taalbi, "A new optical add–drop filter based on two-dimensional photonic crystal ring resonator," *Optik-International Journal for Light and Electron Optics,* vol. 124, pp. 2864-2867, 2013.

[13] H. Alipour-Banaei, S. Serajmohammadi, and F. Mehdizadeh, "Optical wavelength demultiplexer based on photonic crystal ring resonators," *Photonic Network Communications,* vol. 29, pp. 146-150, 2015.

[14] V. Fallahi, M. Seifouri, S. Olyaee, and H. Alipour-Banaei, "Four-channel optical demultiplexer based on hexagonal photonic crystal ring resonators," *Optical Review,* vol. 24, pp. 605-610, 2017.

[15] C. Liu, Z. Tang, H. Dong, D. Song, Z. Luo, X. Ling, and S. Cao, "Wavelength division demultiplexing by photonic crystal waveguides with asymmetric corrugated surfaces," *Chinese Optics Letters,* vol. 8, pp. 761-763, 2010.

[16] M. R. Rakhshani, "Compact eight-channel wavelength demultiplexer using modified photonic crystal ring resonators for CWDM applications," *Photonic Network Communications,* vol. 39, pp. 143-151, 2020.

[17] A. Berry, N. Anand, S. Anandan, and P. Krishnan, "High-Performance Eight-Channel Photonic Crystal Ring Resonator–Based Optical Demultiplexer for DWDM Applications," *Plasmonics,* vol. 16, pp. 2073-2080, 2021.

[18] B. Mohammadi, M. Soroosh, A. Kovsarian, and Y. S. Kavian, "Improving the transmission efficiency in eight-channel all optical demultiplexers," *Photonic Network Communications,* vol. 38, pp. 115-120, 2019.