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Novel Structure of Optical Add/Drop Filters and Multi-Channel Filter Based On Photonic Crystal for Using In Optical Telecommunication Devices

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Abstract: In this paper, Using a 2D photonic crystal and a novel square ring resonator, several compact and simple structures have been introduced in the present paper to construct optical add/drop filters and multi-channel filter. The difference structures has been designed and simulated by using the proposed square ring resonator and different dropping waveguides. To do analyses, the finite-difference time-domain method and the plane wave expansion have been used. The three add/drop filters can separate the wavelength of 1554 nm with a transmission coefficient of 100 %, quality factor of 1295 and bandwidth of 1.2 nm. The models of structures are simulated by the RSOFT CAD-Layout software. The results, flexibility and simplicity of structures have caused from their used to designing of an optical multi-channel filter with a channel spacing of 1.5 nm. The advantages of this design include the channel spacing, quality factor, transmission coefficient and bandwidth which are suitable for applicability in optical communication systems such as wavelength division multiplexing systems.

Keywords: Photonic Crystal, Add/Drop Filter, Photonic Band Gap, Ring Resonator, PWE, FDTD.

1. INTRODUCTION

The optical network is an optical fiber based network architecture, which can provide much higher bandwidth in the access network compared to traditional copper-based networks. Incorporating wavelength-division multiplexing (WDM) in an optical network allows one to support much higher bandwidth compared to the standard optical network, which operates in the "single-wavelength mode" where one wavelength is used for upstream transmission and a separate one is used for downstream transmission [1]. Today, one of the best options is to take advantage of the benefits of this telecommunication system by using photonic crystals (PCs).

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PCs have been introduced in 1D, 2D and 3D so that the 2D state is commonly used to design optical devices. In the 2D PCs, the refractive index of the environment varies periodically in two directions. According to their properties, PCs can be used to design and implement all optical devices [2, 3]. One of the important properties of PCs lattices is the photonic band gap (PBG). The PBG is a range of wavelengths which are forbidden to propagate through the crystal lattice. The light whose wavelength lies within the PBG can easily move in the linear defect generated in the structure without being dispersed in the structure [3, 4]. This particular feature of PCs allows them to be used in designing and manufacturing micro/nanometer optical devices such as optical add/drop filters [5-9], optical logic gates [10, 11], optical demultiplexers [12-14], optical switches [15], analog-to-digital optical converters [16], optical sensors [17], optical fiber [18], optical splitter [19], and optical modulator [20]. PCs also have unique properties such as low losses, very low group velocity, flexibility in dimension and shape, frequency selection, and the possibility of being implemented in silicon-based optical integrated circuits, and the compatibility with the technology of such circuits [21].

Using PC ring resonators, an optical add/drop filters and multi-channel filter have been proposed in the paper. The proposed structure has been based on ring resonator. The structures consists of input waveguides for sending of Gaussian signal and output waveguides for receiving of separating wavelengths and ring resonator have been used to create difference and better couple light from the input port to the output port [22, 24]. To calculate the photonic band gap in the structure, the plane wave expansion (PWE) method has been used, and the finite-difference time-domain (FDTD) method has been used to examine the permanent state [25, 26].

This paper is formed as follows. In Section 2, analysis methods are discussed. Section 3 focuses on the designing and simulation of structures and finally, the conclusions are presented in Section 4.

2. ANALYTICAL METHOD

In general, the mechanisms of designing the periodic structure such as photonic crystal devices can be divided into several methods. Each of these methods has its own advantages and disadvantages. In general, numerical methods are divided into two main categories: 1. Frequency domain and 2. Time domain. Among the various numerical methods, the following methods can be mentioned:

- Plane wave expansion (PWE) method
- Transfer matrix method
- Finite difference time domain method (FDTD)

- Finite element method (FEM)

From this, PWE method and FDTD method are much more practical and important than others. The intermittent structures, such as photonic crystals, are usually analyzed by solving the Maxwell equations. Analytical and numerical methods are used to apply these equations.

2.1. PWE method

The first step in analyzing these structures is to calculate the structure of the photonic band gap. The analysis of the photonic band gap of these structures is a special and important issue, which one of the common analytical methods in this field is the use of the frequency domain methods, including the PWE method [24]. The PWE method is based on frequency analysis, according to which the wave behavior is modeled in the intermittent environments as the product of a flat wave and an intermittent envelope function. The PWE method is easy to implement and the accuracy of its calculations is suitable for less number of harmonics. The major application of PWE in intermittent structures is to calculate photonic band structure and is always considered as a necessary tool in this field.

The PWE is highly efficient for calculating modes in periodic dielectric structures. Being a Fourier space method, it suffers from the Gibbs phenomenon and slow convergence in some configuration when fast Fourier factorization is not used. It is the method of choice for calculating the band structure of photonic crystals. It is not easy to understand at first, but it is easy to implement. The main advantage of this method is that it produces directly the frequency stop bands, and there is no need to convert the time domain and frequency domain to each other. The disadvantage of this method is that, in addition to being an approximation method, it is not suitable for finite and aperiodic structures [25].

2.2. FDTD method

After obtaining the structure of the photonic band gap, numerical methods are used to analyze the optical devices created using defects in these structures. One of the numerical methods is the FDTD method. The FDTD method is applied extensively using precise meshing as a general and flexible method for analyzing arbitrary structures. The basis of these methods is the discretization of the equations describing electromagnetic fields in a finite area by field approximation in general with the Taylor series [26]. The analysis of three-dimensional photonic crystal structures requires many calculations, much time and memory. Therefore, when a numerical method is selected for analyzing these structures, one of the important options is its ability to be implemented for parallel processing. In the FDTD method, the inversion of the matrices is used. In other words, this method is based on the discretization of space or, alternatively, the continuous replacement with a discrete set of points. This method is very precise and the error factors can be easily identified in the calculations. Due to the fact that this method operates in the time domain, it is also possible to generalize and present the model for nonlinear problems. FDTD is one of the simplest and most comprehensive numerical methods used in a variety of designs.

The starting point for any FDTD solver is the time-derivative parts of Maxwell's equations, which in their simplest form can be written:

$$\frac{\partial B}{\partial t} = -\nabla \times E - J_B \tag{1}$$

$$\frac{\partial B}{\partial t} = +\nabla \times H - J \tag{2}$$

where (respectively) **E** and **H** are the macroscopic electric and magnetic fields, **D** and **B** are the electric displacement and magnetic induction fields, **J** is the electric-charge current density, and $\mathbf{J}_B$ is a fictitious magnetic-charge current density (sometimes convenient in calculations, e.g. for magnetic-dipole sources). In time-domain calculations, one typically solves the initial-value problem where the fields and currents are zero for $t < 0$, and then nonzero values evolve in response to some currents $\mathbf{J}(\mathbf{x}, t)$ and/or $\mathbf{J}_B(\mathbf{x}, t)$ [24].

3. DESIGN AND SIMULATION RESULT

3.1. Design add/drop filters

The structure used to design the optical filter consisted of a square lattice with a refractive index of 3.4 in the air substrate. The refractive index of the structure has changed periodically along the x- and z-axes, and it has been fixed along the y-axis. The radius of the rods has been equal to 106 nm and lattice constant has also been equal to 642 nm. The lattice constant and the radius of the rods have been considered so that the band gap covered the range of the third telecommunication window. The PWE method has been used to obtain the band structure and the photonic band gap, and its results for TM modes have been shown in Fig. 1. According to this figure, the structure has had two PBG frequency ranges TM modes and the frequency range has been equal to $0.265 \leq a/\lambda \leq 0.418$ and $0.688 \leq a/\lambda \leq 0.724$, which has been equal to the wavelength range of $1.387\ \mu m \leq \lambda \leq 2.188\ \mu m$ and $0.809\ \mu m \leq \lambda \leq 0.843\ \mu m$ respectively.

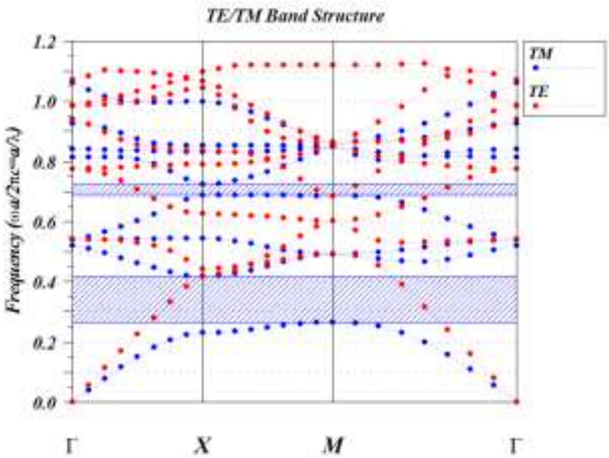


Fig. 1. The band structure of proposed structure.

To construct the optical add/drop filter, two waveguide including the bus waveguide and direct dropping waveguide have been used. To create interference and couple light into the desired outputs, the one ring resonator has been used and it which is square-shaped is sandwich the waveguides. The proposed ring resonator are created by removing a number of PC rods so that the resulting defects take a ring form. The general scheme of the resonator used in structure is shown in Fig. 2. According to figure, the resonator is created by increasing the size of the radius of the inner rods (Ri= 174 nm) along with the scattering rods (Rs= 115 nm) to reduce the refection of light inside the resonator to the corresponding waveguide. The scheme of general optical filter is shown in Fig. 3.

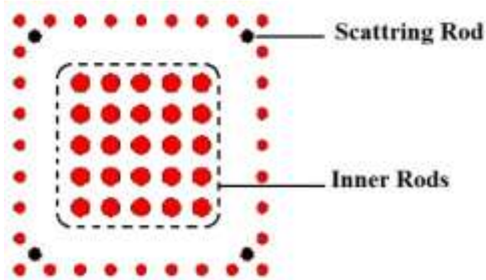


Fig. 2. The proposed of the square ring resonator.

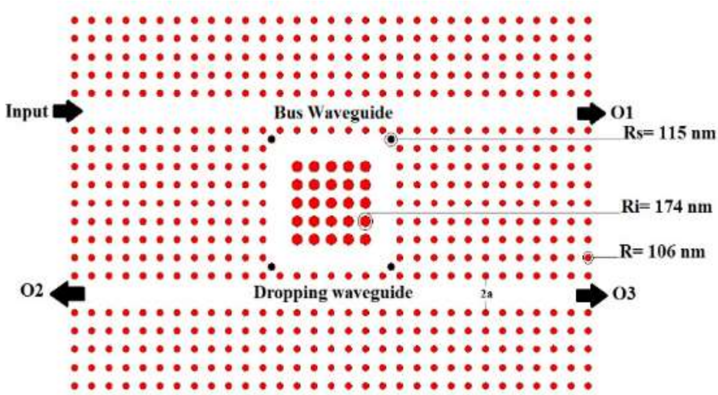


Fig. 3. The schematic of proposed optical add/drop filter.

After designing, a Gaussian light source has been launched into the input and the output spectrum transmitted has been examined, as shown in Fig. 4. According to the figure, the optical filter structure has been capable of the wavelength separation (λ) of 1554 nm with a transmission coefficient of 100%, a quality factor of 1295 nm, and a bandwidth of 1.2 nm. When an optical pulse with such a wavelength is sent to the structure, it is received and separated by the proposed ring resonator and is transmitted to the output O2. The examinations conducted on the structure and the output power have been presented in Fig. 5 (a) and the distribution of the electromagnetic field for various states of add/drop filter designed has been shown in Fig. 5 (b). As shown in figures, when the wavelength 1554 nm enter into the waveguide and is coupled into the ring resonator, filtering and is transferred to the proposed port.

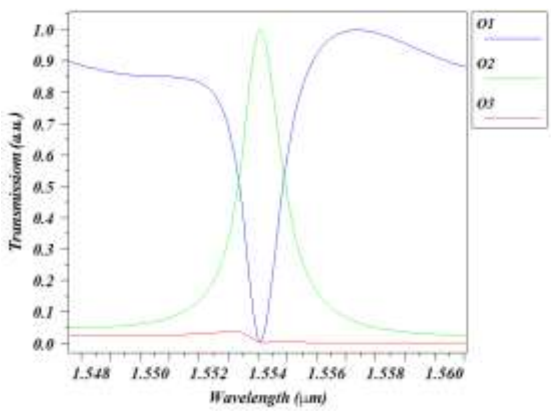


Fig. 4. Output spectrum of the proposed optical add/drop filter with direct dropping waveguide.

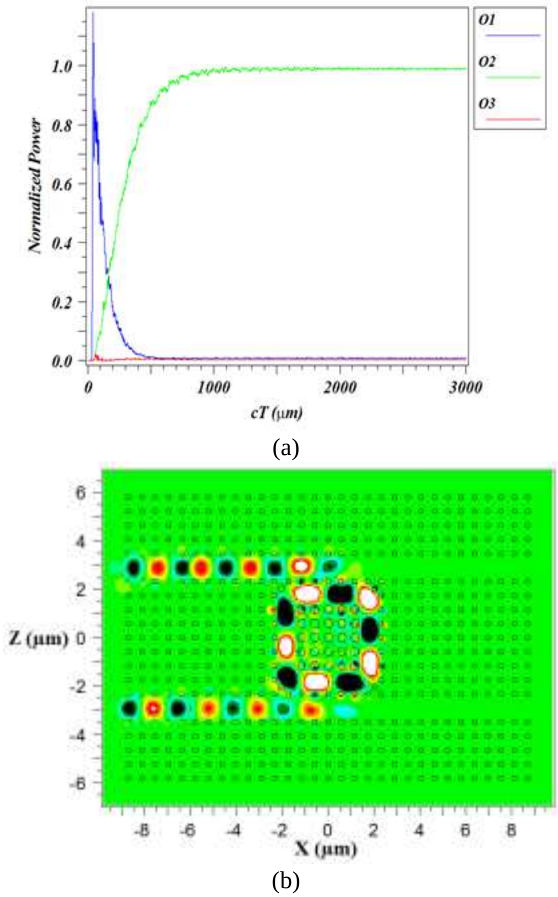


Fig. 5. Optical behavior of optical add/drop filter with direct dropping waveguide in λ=1554 nm, (a) The power transfer diagram, (b) the electromagnetic field distribution.

In the following, by changing in the dropping waveguide has been discussed and this effects on the results of the output spectrum for further functional development has been studied. In such a case, the dropping waveguide is in the indirect mode as shown in Fig. 6. In this case, as in the previous case, the structure has been able to the wavelength separation of 1554 nm with a quality factor of 1295, a bandwidth of 1.2 nm and a transmission coefficient of 100%, as demonstrated in Fig. 7. The examinations conducted on the structure and the output power and the distribution of the electromagnetic field for various states of add/drop filter designed have been shown in Fig. 8.

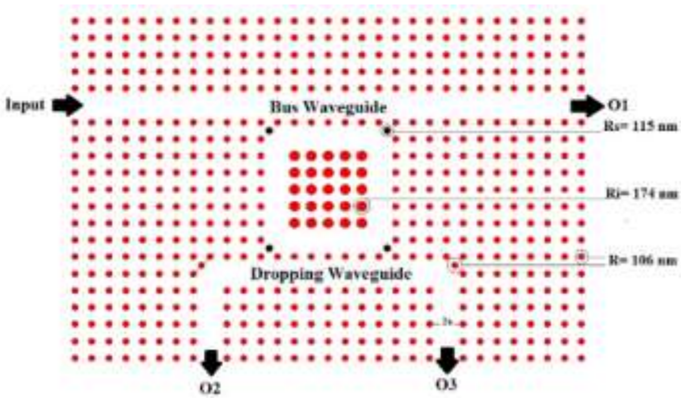


Fig. 6. The schematic of proposed optical add/drop filter with indirect dropping waveguide.

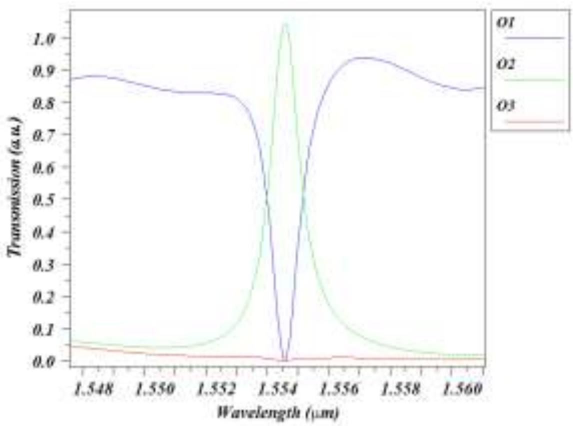
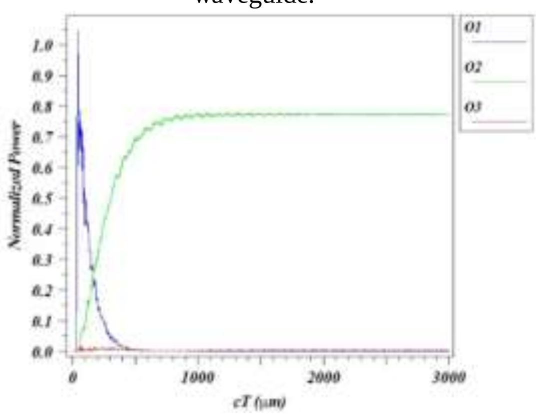
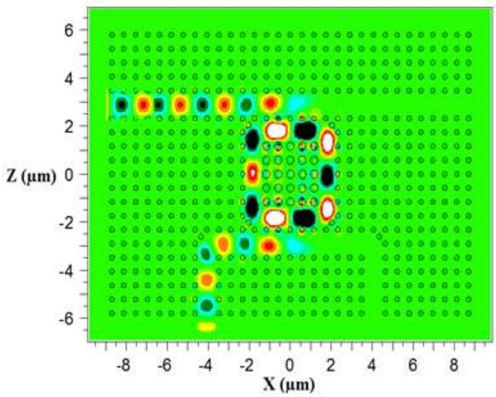


Fig. 7. Output spectrum of the proposed optical add/drop filter with indirect dropping waveguide.



(a)



(b)

Fig. 8. Optical behavior of optical add/drop filter with indirect dropping waveguide in λ=1554 nm, (a) The power transfer diagram, (b) the electromagnetic field distribution.

3.2. Design of an optical multiplexer/demultiplexer

In the following, in order to apply the structure for use in other photonic crystal devices such as optical multiplexer/demultiplexer, optical logic gates, optical biosensor, changes have been made to the indirect dropping waveguide. In this case, the same waveguide has been used. The only difference, the output waveguide has been smaller, more compact and has one output port, as shown in Fig. 9. In this case, as in the previous case, the structure has been able to the wavelength separation of 1554 nm with a quality factor of 1295, a bandwidth of 1.2 nm and a transmission coefficient of 100%, as demonstrated in Fig. 10. The examinations conducted on the structure and the output power and the distribution of the electromagnetic field for various states of add/drop filter designed have been shown in Fig. 11.

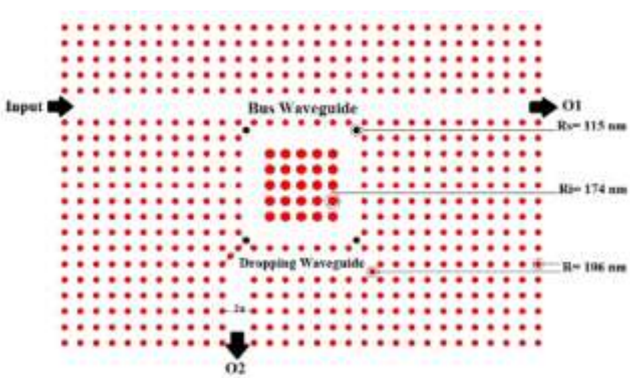


Fig. 9. The schematic of proposed optical add/drop filter with indirect dropping waveguide (one output port).

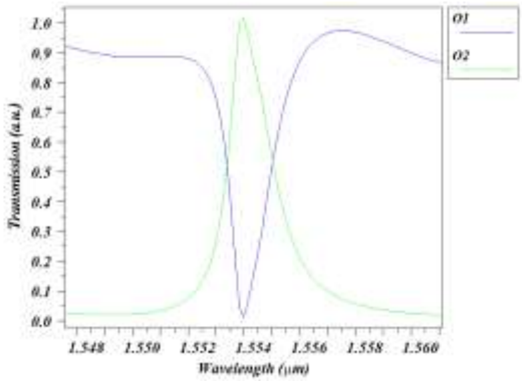
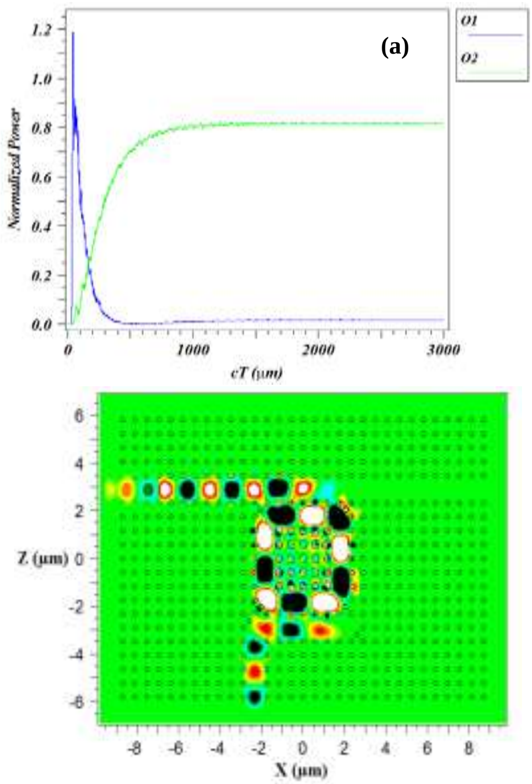


Fig. 10. Output spectrum of the proposed optical add/drop filter indirect dropping waveguide (one output port).



(b)

Fig. 11. Optical behavior of optical add/drop filter with indirect dropping waveguide (one output port) in λ=1554 nm, (a) The power transfer diagram, (b) the electromagnetic field distribution.

Using the given this add/drop filter, a multi-channel drop filter has been designed. In this design of multi-channel drop filter, three proposed square ring resonator, one input waveguide for transmitting input light to square ring resonators and three indirect dropping waveguides for transmit the separated wavelengths have been used, as can be seen in Fig. 12. The radii of the inner rods of ring resonator 169 nm, 174 nm and 179 nm, for the O2, O3 and O4 output channels, respectively.

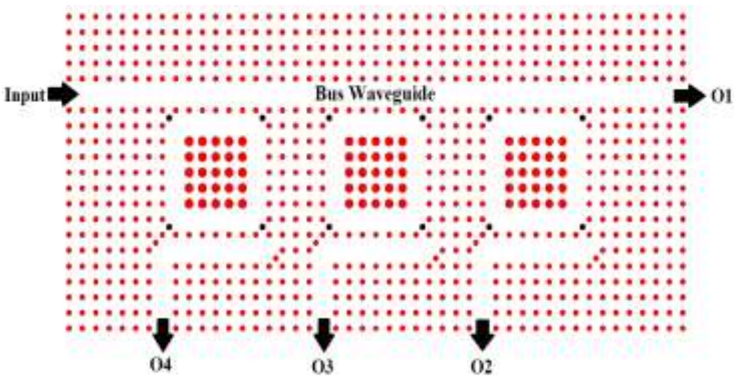


Fig. 12. The proposed multi-channel drop filter with three square ring resonators.

As shown in Fig. 13, the proposed multi-channel filter is able to separate the wavelengths of 1553, 1554.8, 1556.1 nm by the O2, O3 and O4 channel, respectively. The exact values of the quality factor, the transfer coefficient and the bandwidth of each channel are listed in Table 1. According to this table, the given proposed multi-channel filter enjoys very good results especially narrower channel spacing, which justifies highly the application of the structure in optical network such as WDM systems. In addition, due to the high flexibility of the structure, it can be enhanced by the number of telecommunication channels.

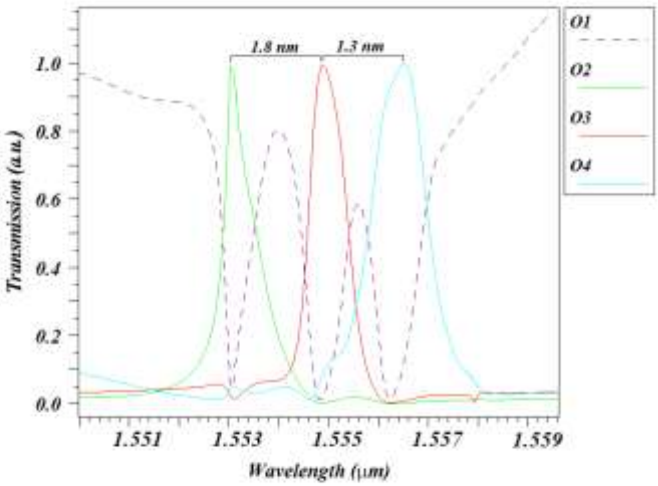


Fig. 13. Output spectrum of the proposed multi-channel add/drop filter with three square ring resonators.

Table 1. Simulation results of the proposed multi-channel add/drop filter.

channel	wavelength (nm)	Band widths (nm)	Quality factor	Transmission (%)
O2	1553	0.4	3882	100
O3	1554.8	0.6	2591	100
O4	1556.1	0.9	1729	100

In this study, using by a square ring resonator, add/drop filters with three different types of dropping waveguide have been designed. The results obtained from this structure show its applicability and suitability in comparison with other structures introduced in this field. These results are presented in Table 2. The results were highly favorable with easy and convenient ring resonator design and structures, which makes suitable for using in other optical devices.

Table 2. Simulation results of the proposed multi-channel add/drop filter.

Reference	Band widths (nm)	Quality factor	Transmission (%)
This paper	1.2	1295	100
This paper	1.2	1295	100
This paper	1.2	1295	100
[5]	1.3	1192	100
[6]	-	205	100
[7]	-	647	100
[8]	-	842	100
[9]	-	1011	99
[23]	1.2	1290	95

- No discuss

4. CONCLUSION

In this paper, using a novel square ring resonator based on photonic crystal, three types of add/drop filters have been designed. Using a square ring resonator with three different dropping waveguides including direct and indirect, add/drop filters have been designed. The given add/drop filters have a transmission coefficient of 100% at wavelength of 1554 nm. Good results, simplicity and flexibility, proposed ring resonator and structures which are compatible with silicon-based technology has been introduced to construct optical multi-channel filter and multiplexer/demultiplexer. The proposed structure can be used in integrated circuits and optical communication systems.

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