



# Optical Channel Drop Filter Design Based on PCRR and Micro Cavity Resonator

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## Abstract

Optical channel drop filter (OCDF) plays a key role in optical communication networks for filtering the individual wavelength among the group of channels in wavelength division multiplexing systems. There are several channel drop filters with different design mechanisms available in the literature, but those structure dimensions are not compact enough for the photonic integrated applications. Hence, in this paper, a compact and efficient OCDF is developed in the triangular lattice PC structure based on diamond-shaped photonic crystal ring resonator (PCRR) mechanism combined with micro cavity resonator (MCR). The developed OCDF is analysed for different operating wavelengths by considering the different positions of MCR around the main PCRR. Based upon the position of the MCR around PCRR, the three dropping wavelengths such as 1540 nm, 1550 nm, and 1570 nm are observed at the output waveguides with 100% dropping efficiency. Then the structural and performance parameter comparison is done between the proposed and existing structures in terms of device dimension, dropping efficiency, and quality factor. It is depicted through the results that the quality factor and the device dimension are better than that of the existing structures for 1550-nm wavelength.

**Keywords** Photonic crystal · Optical channel drop filter · Ring resonator · Cavity resonator · Photonic band gap

## Introduction

The unique properties of photonic crystal (PC) structure have introduced various researches in the field of optics. With the help of photonic band gap (PBG) engineering [1], the PC structure provides the facility to build numerous optical devices such as optical switches [2], optical encoders/decoders [3, 4], optical multiplexer/demultiplexer [5], optical logic gates [6], and optical channel drop or add/drop filters [7–20]. The channel drop filters (CDFs) are the essential component used for selecting/filtering the desired resonant wavelength applicable in wavelength division multiplexing (WDM) systems. In the literature, a variety of optical channel drop filter (OCDF) structures based on different design mechanisms have been proposed. The various design mechanisms include coupling waveguides, optimized point and

line defects, resonant cavities, defective multilayers, ring resonators, and multi-cavity coupled ring resonators. The mechanisms like ring resonators and resonant cavities are preferred more than that of the other designs because of their effective wavelength selectivity due to resonant coupling nature. Recently, Zohreh Rashki et al. [7] have proposed a OCDF based on flower-shaped PCRR using cubic lattice structure. They analysed the resonant wavelength and output efficiency by varying the refractive index of whole rods and inner rods. From the analysis, it is observed that the higher values of refractive index resulted in shift to higher wavelengths. Next, Hamed Alipour Banaei et al. [8] have suggested a T-shaped filter based on 12 fold quasi crystal ring resonator to obtain a smooth output spectrum. They obtained 90% maximum transmission efficiency and a quality factor value of 387 with the filter size of about  $242.4 \mu\text{m}^2$ . Later, the same authors [9] have proposed another CDF based on hexagon-shaped ring resonator. Here, they used four scattering rods to increase transmission efficiency. With this structure, they obtained the maximum transmission efficiency up to 94% with the quality factor value of 704. Their filter size is about  $199.4 \mu\text{m}^2$ . Then, an elliptical-shaped ring resonator-based channel drop filter built using square lattice

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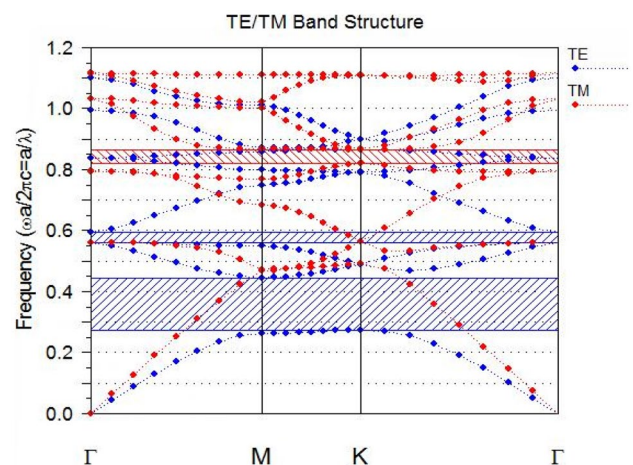
structure is proposed by Hamed Alipour-Banaei et al. [10]. Their structure yields 100% dropping efficiency and a quality factor of 647. They also analysed the filter performance for vertical, double, and triple ring configurations and found that the better quality factor value is obtained for the triple ring configuration. Later, Hamed Seif-Dargahi et al. [11] have proposed an ultra-compact CDF based on a resonant cavity with four scattering rods. They also observed the increase in the refractive index of the dielectric rod results in a shift to the longer wavelengths of the filter. Their filter size is less than  $76 \mu\text{m}^2$ . Followed by this design, Saba Rezaee et al. [12] have proposed a new filter based on H-shaped photonic crystal resonator. They analysed the shift in a resonant wavelength corresponding to the different values of the refractive index and the radius of the dielectric rods separately. The transmission efficiency and the quality factor obtained for their structure are about 100% and 221 respectively. Though the structure yields maximum efficiency, the quality factor seems to be less which can be improved further. Later, Rahima bendjelloul et al. [13] have proposed a new T-shaped CDF based on the PCRR mechanism. They studied the shift of the output wavelengths with respect to the variation of the structural parameters. The dropping efficiency of their structure is about 100% and a quality factor of 502 with the filter size of  $189.66 \mu\text{m}^2$ . Next, Mayur K. Chhipa et al. [14] have proposed the filter design which obtains 99% dropping efficiency with a low-quality factor around 192 at 1511-nm resonant wavelength. Their structure size is about  $123 \mu\text{m}^2$ . Then, Juan Zhang et al. [15] have proposed a nested dual-loop resonant ring-based add-drop filter and analysed the dropping wavelengths by varying the refractive index and the radius of inner and other rods. Their structure yields a maximum dropping efficiency of 98%. Followed by this design, A. Tavousi et al. [16] designed PC-based all circular ring resonator for optical filtering, in which the dropping efficiency lies between 76 and 100% and the crosstalk between  $-10$  to  $-50$  dB has been obtained. Most recently, R. Rajasekar and S. Robinson [17] have proposed a new trapezoid-shaped photonic crystal ring resonator-based channel drop filter with the resonant wavelength of 1543 nm. Their structure yields a dropping efficiency of 100% and a quality factor value of about 514.33. In addition to all of these existing structures, few channel drop filter designs based on X-shaped ring resonator have been proposed and investigated by various researchers [18–20]. However, most of the existing designs have introduced additional structure complexity in terms of maximum position alteration of dielectric rods inside the ring resonator which makes it difficult in the fabrication process. Hence, the ring resonator could be designed in such a way to make the fabrication process easier as well as to satisfy the minimum needs of the filter characteristics. From the existing structures, it is inferred that the better quality factor and efficiency are obtained only

through complex design structures. Hence, in this paper, an effort has been made to develop a new OCDF with diamond-shaped ring resonator with a simple design principle that results in maximum dropping efficiency and the acceptable quality factor value. Further, the position of MCR is varied to investigate the different dropping wavelengths of the proposed filter structure.

The remaining paper is organized as follows. “Proposed OCDF Structure” discusses the structural design of the proposed channel drop filter. “Simulation Results and Discussion” gives a detailed analysis of the performance investigation of the proposed filter. Finally, “Conclusion” concludes the paper.

## Proposed OCDF Structure

The two-dimensional (2D) photonic crystal structure considered for the design of OCDF is composed of  $25 \times 19$  triangular lattice of dielectric rods with an effective index of 2.46. To begin with the design of the channel drop filter, the photonic band diagram for the basic PC structure with the lattice constant ( $a$ ) of 541 nm with the rod radius ( $r$ ) of  $0.2a$  is investigated without introducing any defect. Here, the PBG calculation is carried out through the plane wave expansion (PWE) numerical analysis method under the Bandsolve simulation tool. The PWE method is used to obtain an accurate solution for the dispersion properties of the proposed PC structure. The band gap diagram of the proposed PC structure is shown in Fig. 1 that shows the band gap region for both TE and TM modes. The two blue crossed line regions represent the TE band gap, whereas the red crossed line region represents the TM band gap region. The wide photonic band gap is shown for TE polarization



**Fig. 1** Dispersion diagram of TE/TM modes of triangular lattice PC structure

which is in the range of  $0.275 < a/\lambda < 0.445$ , and their corresponding wavelength ranges from 1.258 to 2.03  $\mu\text{m}$ . Then the TM band gap lies in the range of  $0.821 < a/\lambda < 0.864$  which has the wavelength ranging from 0.65 to 0.68  $\mu\text{m}$ . Among these two ranges, the former range of wavelength is adopted for communication systems. Hence, the TE polarization is utilized for the numerical analysis of the proposed filter structure.

The proposed OCDF is realized by introducing simple defects in the fundamental PC structure. Initially, line defects are made by removing the row of dielectric rods to create the bus/input waveguide and drop/output waveguide as shown in Fig. 2. Then, the ring resonator is formed by removing the column of dielectric rods around the diamond ring shape. The dielectric rods present inside the resonator are with the rod radius ( $r_r$ ) around 135 nm. The MCR consists of one dielectric rod with rod radius ( $r_m$ ) which plays a vital role in the selection of dropping wavelength at the output port.

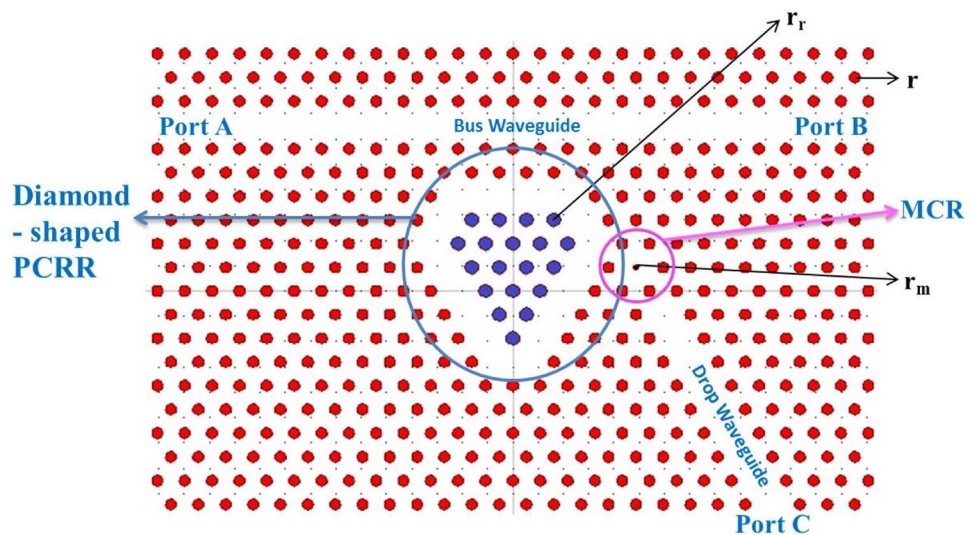
This general OCDF structure consists of three ports: Port A represents the input port, port B indicates the transmission output port, and port C is the output/channel drop port. The diamond-shaped ring resonator with a micro cavity resonator exists between the input port and output channel drop port to select the desired dropping wavelength using resonant coupling phenomenon. So far in the literature, only the effects of parameters such as refractive index and radius of the dielectric rods are varied to study the different dropping wavelengths. There are no works reported to analyse the effect of changing the position of MCR in the output dropping wavelength. Hence, the proposed OCDF structure is investigated for selecting the different resonant wavelengths by changing the position of the MCR around the PCRR. It is seen from Fig. 3 that the three types of structures with three

different positions of MCR are designed to drop three different resonant wavelengths ( $\lambda_1, \lambda_2, \lambda_3$ ). In the first structure, the MCR is placed at the end of the ring resonator as shown in Fig. 3a, with the MCR rod radius ( $r_{m1}$ ) for the perfect dropping of the resonant wavelength  $\lambda_1$ . Then in structure-II, the MCR is placed at the right top of ring resonator as shown in Fig. 3b, with the MCR rod radius ( $r_{m2}$ ) to drop the wavelength of  $\lambda_2$ . Next in structure-III, the position of the MCR is shifted to right down of ring resonator as shown in Fig. 3c, with the dielectric rod radius of MCR ( $r_{m3}$ ) to select the dropping wavelength of  $\lambda_3$ . In all these three structures, the entire structural parameters are maintained the same as discussed above except the MCR rod radius.

### Simulation Results and Discussion

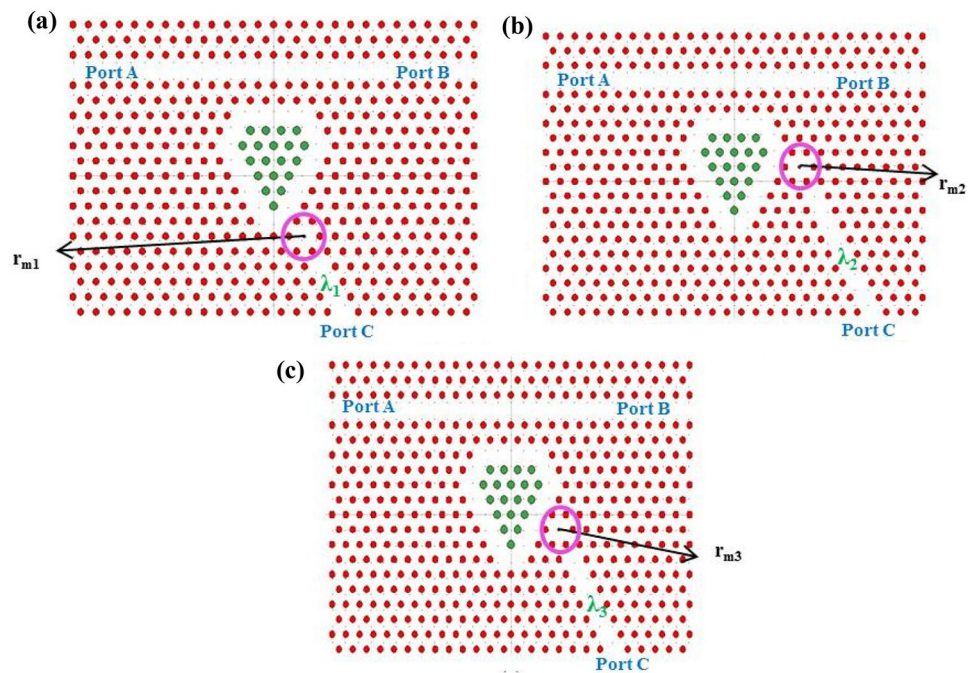
The performance investigations of the proposed OCDF structures are studied by the finite difference time domain (FDTD) numerical method. FDTD method is used for the electromagnetic transmission analysis of the filter by conducting fast Fourier transform (FFT) of the field distribution to acquire its transmission spectrum. Perfectly matched layers (PML) with the thickness of (500 nm) is used as boundary conditions to absorb the reflected signals. The grid size chosen for full wave simulation in the X direction is  $a/32$  and the estimated time step ( $\Delta t$ ) is about 0.011067. The time step value should not exceed the stability limit to perform the FDTD simulation. The estimated memory size to perform the simulation is about 33.7 MB. Gaussian signal with TE polarization is used as the input source signal with 1-mW power is applied at the input port (A) for analysing the transmission characteristics of the filter. The input light signal launched at the input port A is dropped/coupled to the output waveguide through the ring resonator

**Fig. 2** Proposed optical channel drop filter design





**Fig. 3** Proposed optical channel drop filter: (a) Structure I—MCR at Position 1, (b) Structure II—MCR at Position 2, and (c) Structure III—MCR at Position 3



and MCR once it attains the evanescent mode coupling phenomenon. The wavelength scanning of the proposed OCDF structures is done by applying the Gaussian input signal with multiple wavelengths ranging between 1525 and 1560 nm. Power monitors are placed at the two output ports (B and C) to collect the normalized transmission power spectral density.

Generally, the resonant wavelength drop of the structure is determined mainly by choosing the proper design values such as radius of the whole rods, the refractive index of the material, and the rods present inside the ring resonator and the cavity resonator. Most importantly, the rods of the ring resonator play a crucial role in selecting the dropping wavelength (i.e. wider spectral selectivity) to the output waveguide. Hence, in the proposed structure, the radius of the ring resonator rods is chosen as 135 nm to drop the wavelengths that fall under the C band. From this range of wavelength, the precise wavelength selection (i.e. narrow spectral selectivity) is further made by selecting the suitable radius value of the micro cavity resonator rod. Usually, the determined wavelength through the basic structure is shifted to longer/shorter wavelengths by changing either the lattice constant or radius or refractive index of the rods. But in this paper, the shifts in the resonant wavelengths are studied by changing the position of the MCR around the PCRR.

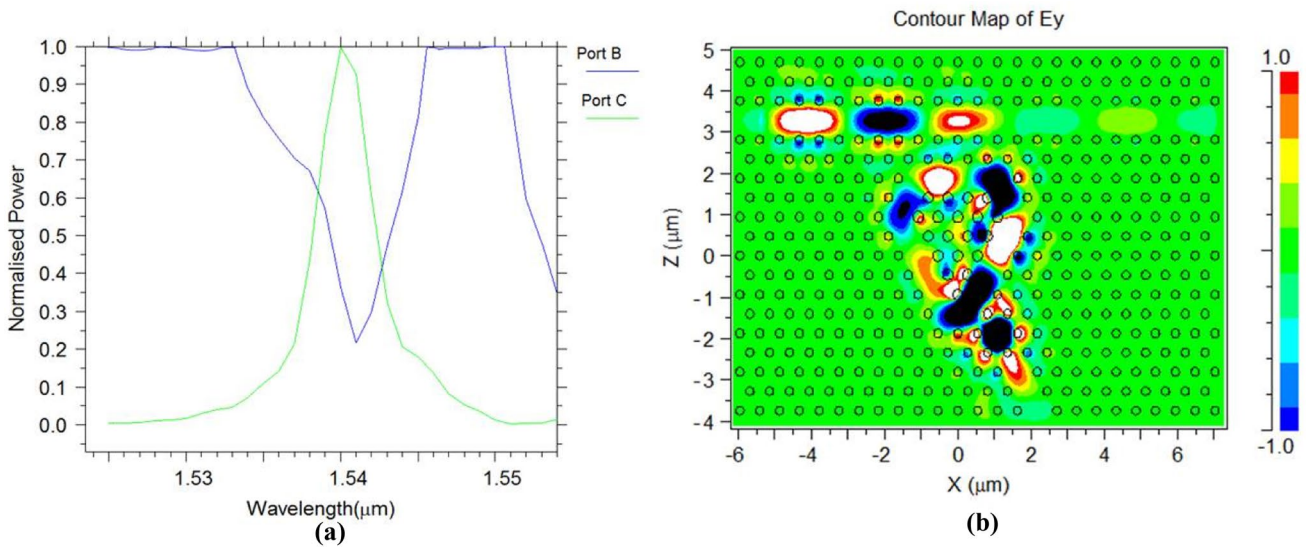
The working mechanism of the channel drop filter is analysed by the resonant tunnelling process that takes place in both the ring resonator and micro cavity resonator. Initially, the OCDF structure-I is subjected to the FDTD analysis by applying the input light signal with the range of wavelength from 1525 to 1550 nm at port A. Among this range

of multiple wavelengths applied at the input, only the resonant wavelength 1540 nm ( $\lambda_1$ ) is completely dropped to the output channel port C which is seen in Fig. 4a. That is, only the resonant wavelength ( $\lambda_1$ ) corresponding to the defect rod radius ( $r_{m1} = 46.35$  nm) of MCR is coupled to the drop port C, whereas the other wavelengths are reflected back to the transmission port B. The electric field distribution of the structure-I for the resonant wavelength  $\lambda_1$  is shown in Fig. 4b, where it can be observed that the resonant coupling phenomenon that takes place at ring resonator and micro cavity resonator results in the transmission of the wave to the drop port.

Similarly, the wavelength scanning for the OCDF structure-II is made with the MCR rod radius of ( $r_{m2} = 46.55$  nm) for the wavelength range from 1530 to 1565 nm. From Fig. 5a, it is observed that the resonant wavelength of 1550 nm ( $\lambda_2$ ) is dropped at the output port C, whereas the other wavelengths are reflected back to the transmission port B. The electric field distribution of the corresponding dropping wavelength  $\lambda_2$  is shown in Fig. 5b.

Then the simulation results of the OCDF structure-III are shown in Fig. 6. Here, the MCR rod radius ( $r_{m3} = 45$  nm) is chosen for the perfect drop of the resonant wavelength ( $\lambda_3$ ). From Fig. 6a, it is observed that the resonant wavelength of 1570 nm ( $\lambda_3$ ) is dropped in the output port C with a 100% dropping efficiency. The electric field distribution of the corresponding dropping wavelength  $\lambda_3$  is shown in Fig. 6b.

Table 1 summarizes the structural and performance parameters of the proposed OCDF structures. It is observed



**Fig. 4** OCDF structure-I: (a) Resonant wavelength drop ( $\lambda_1$ ) at Port C. (b) Electric field distribution of  $\lambda_1$

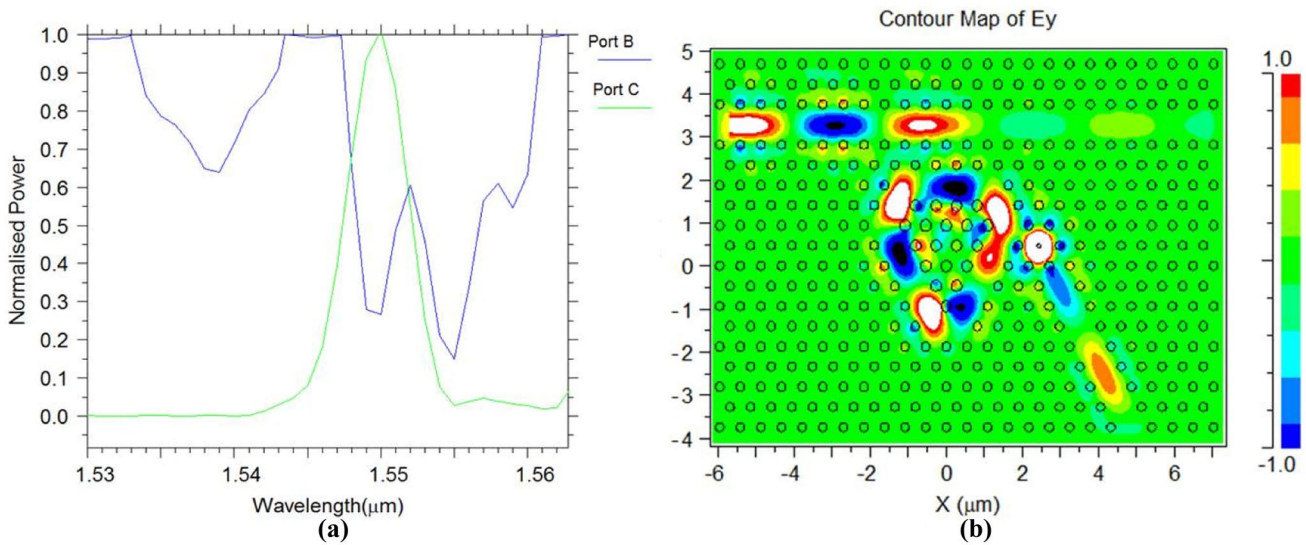
that the 100% maximum dropping efficiency is obtained for all the proposed structures. The quality factor of the proposed filter structure is calculated by using  $\lambda/\Delta\lambda$ , where  $\lambda$  is the resonant wavelength and  $\Delta\lambda$  is the spectral width of the filter.

Table 2 gives the comparison of the structural and performance parameters of the proposed OCDF structure with the existing structures. It is observed that the proposed design results in a better quality factor value when compared with that of the existing structures for

the communication wavelength of 1550 nm. Also, the device dimension is reduced further when compared with that of the existing structures. Hence, it is concluded that the proposed OCDF is more suitable for photonic integrated applications.

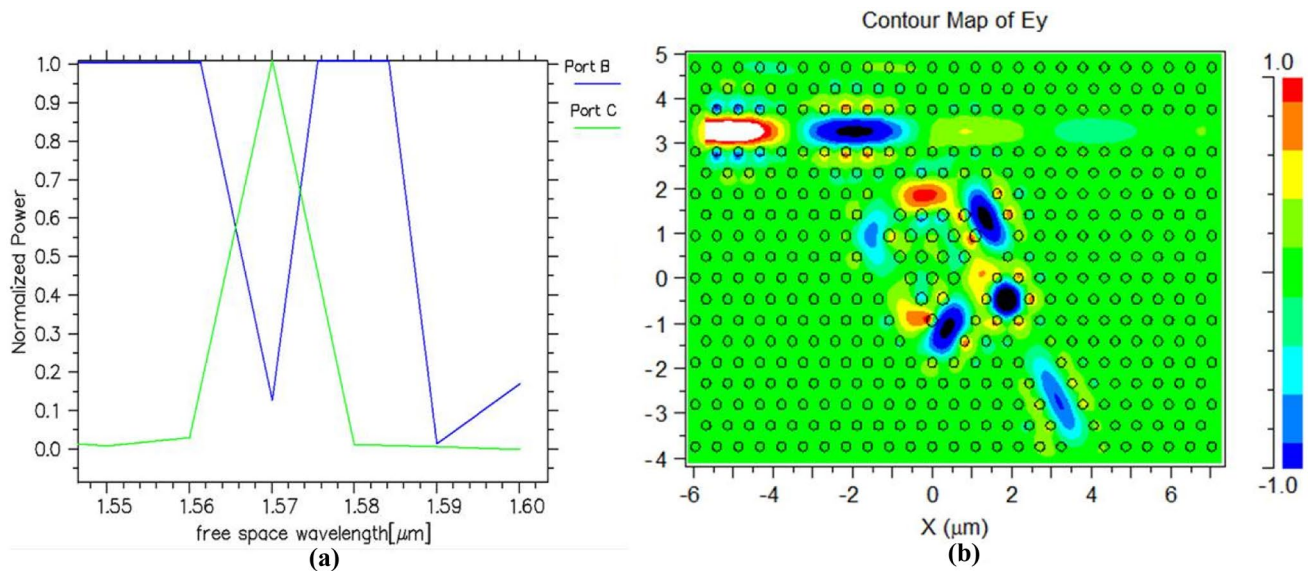
### Conclusion

The optical channel drop filter based on PCRR combined with the MCR mechanism is proposed in this paper. The



**Fig. 5** OCDF structure-II: (a) Resonant wavelength drop ( $\lambda_2$ ) at Port C. (b) Electric field distribution of  $\lambda_2$

structure is built in a triangular lattice arrangement to



**Fig. 6** OCDF structure-III: (a) Resonant wavelength drop ( $\lambda_3$ ) at Port C. (b) Electric field distribution of  $\lambda_3$

**Table 1** Structural and performance parameters of proposed OCDFs

| OCDF types    | PCRR type | Lattice type | Dropping wavelength | Dropping efficiency (%) | Quality factor | Dimension ( $\mu\text{m}^2$ ) |
|---------------|-----------|--------------|---------------------|-------------------------|----------------|-------------------------------|
| Structure-I   | Diamond   | Triangular   | 1540 nm             | 100                     | 530.00         | 111.8                         |
| Structure-II  | Diamond   | Triangular   | 1550 nm             | 100                     | 534.48         | 111.8                         |
| Structure-III | Diamond   | Triangular   | 1570 nm             | 100                     | 506.45         | 111.8                         |

**Table 2** Structural and performance parameters comparison of proposed OCDF with the existing structures

| Authors                        | PCRR type<br>Lattice type      | Dropping efficiency (%) | Quality factor | Dimension ( $\mu\text{m}^2$ ) |
|--------------------------------|--------------------------------|-------------------------|----------------|-------------------------------|
| Zohreh Rashki et al. [7]       | Diamond<br>Triangular          | 100                     | 502.6          | 185                           |
| Mayur Kumar Chhipa et al. [14] | Z shaped<br>Triangular         | 99                      | 192            | 123                           |
| Juan Zhang et al. [15]         | Nested dual loop<br>Triangular | 98                      | -              | -                             |
| R. Rajasekar, S. Robinson [17] | Trapezoid<br>Triangular        | 100                     | 514.3          | 117.6                         |
| Proposed OCDF Structure-II     | Diamond<br>Triangular          | 100                     | 534.48         | 111.8                         |

provide better coupling efficiency with simple design aspects. The diamond-shaped ring resonator with MCR exists between the input and output waveguides for mode coupling, and it is created only by removal of column of rods (i.e.) without any position adjustment/alteration of the rods in the basic PC structure. Further, the OCDF design is investigated by varying the position of the MCR to explore

the different dropping wavelengths at the output port. It is observed from the simulation results, that the proposed structure performs better in terms of the quality factor of 534.48 and the dropping efficiency of 100% for the communication wavelength of 1550 nm. The footprint of the device is also compact in size of about  $111.8 \mu\text{m}^2$ . The dropping

wavelengths obtained by the proposed structure are suitable for C band applications.

**Author Contribution** All the authors contributed in the preparation of manuscript. The article has been read and approved for submission by all the authors.

## Declarations

**Conflict of Interest** The authors declare that they have no conflict of interest.

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