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Novel Design of Optical Channel Drop Filter Based on Photonic Crystal Ring Resonators

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Abstract

In this paper, a new design of optical channel drop filter(CDF) based on two- dimensional photonic crystal ring resonators with triangular lattice is proposed. The rods of this structure is silicon with the refractive index nsi=3.46 and the surrounding environment is air with the refractive index of nair=1.The widest photonic band gap obtains for the filling ratio of r/a = 0.2. The filter's transmission spectrum is calculated using the two-dimensional (2D) finite-difference time-domain (FDTD) numerical method. The simulation shows, close to, 100% dropping efficiency and suitable quality factor at 1519.4 nm wavelength achieved for this filter. Also in this paper, we investigate parameters which have an effect on resonant wavelength and transmission spectra in this CDF, such as dielectric constant of inner rods and whole rods of the structure .The overall size of the structure is small (13.97μm × 13.97μm) which is suitable for photonic integrated circuits (PIC) and optical communication network applications.

Keywords: photonic crystal, ring resonators, photonic integrated circuits, optical communication.

Introduction:

Due to ever increasing developments in optical communication networks, designing all optical devices suitable for integrating in all optical circuits has become very popular among researchers [1]. One crucial challenge in designing ultra-compact optical devices is the poor confinement of light in small spaces. This challenge has been solved through employing photonic crystals (PhCs) [1]. In recent years, using of Photonic crystals (PhCs) have attracted more and more attention by the scientific and research communities [2]. Photonic crystals are very suitable candidates for realization of future passive and active optical devices because of their ability to control light-wave propagation, high speed of operation, better confinement, long life period and suitability for integration [3, 4]. PCs are periodic optical nanostructures composed of 2 different materials with low and high dielectric constant [2, 4] As a result of this

periodicity, it possesses photonic band gap (PBG), where the transmission of light in certain frequency range is absolutely zero [5]. Depending on geometry of the structure, PhCs can be divided into three broad categories, namely one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) structures. 2D PhCs due to their complete PBG and ease of design and fabrication attract more attention than1D and 3D structures [6].

With the advent of photonic crystals, Wide development in manufacture of optical components in the nanometer scale was created. In recent years, many of optical devices made were based on PCs. i.e. Multiplexers [7], demultiplexers [8], polarization beam splitters [9], triplexers [10], switches [11], directional couplers [12], bandpass filters [13-15], channel drop filters/add-drop filters [16–21], etc.

Special limitations of these devices are quality factor (*Q*) [22] and output efficiency of the needed wavelength. To compensate these shortages and enhancing them, PhC resonant cavities are used which can improve the interaction of light [23]. Optical filtering elements are among the most important components of the telecommunication systems. On the other hand, channel drop filters (CDFs) are essential components of photonic integrated circuits (PICs) and wavelength division multiplex (WDM) optics communication systems.

An optical filter is a device, which has the property of adding or dropping a given wavelength channels from the multi-wavelength network [24]. In recent years, various constructions 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 [25-28]. Ring resonators are a useful element especially in drop filters [29]. Channel drop filters based on PhC ring resonators are composed of two waveguides namely bus and drop waveguides and a resonant ring located between them. The first report of a photonic-crystal ring resonator (PCRR) proposed by Kumar et al [30] Djavid et al [21] proposed a T-shaped channel drop filter based on PhCRRs. Mahmoud et al. [3,27,28] proposed another channel drop filter based on X-shaped ring resonator structure.

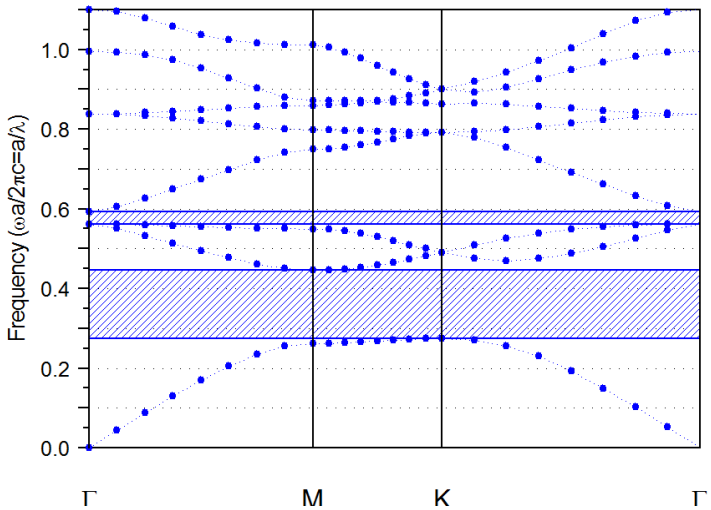
In this paper, a new design of PCRR based on CDF is proposed and numerically demonstrated in triangular lattice photonic crystal (PC) silicon rods using the two-dimensional (2D) finite-difference time-domain (FDTD) technique. The new ring resonator introduced in this study can be used as the basic element for other devices as well. Also, in this paper, We investigate parameters which have an effect on resonant wavelength and transmission spectrum in this CDF, such as dielectric constant of inner rods and whole rods of the structure. The proposed structure provides a possibility of optical channel drop filter and can be used in the future photonic integrated circuits.

The rest of the paper is organized as follows. In next Section, we discuss the structure design procedure of the channel drop filter and describe the ring resonator structure. After, we analyze channel drop filters. The design goal is to obtain a wavelength selective device able to drop central wavelength. End Section concludes the paper.

Structure Design

Our design is based on a 2D triangular lattice of silicon rods with refractive index 3.46 in an air background with refractive 1. In this investigation, the ratio of the rod radius r to the lattice constant a, is 0.2. Also the number of rods in the plate *x-z* is equal to 23×23.In this structure, wider photonic band gap extends from $0.27 < a/\lambda < 0.44$ for TM polarization (in which the magnetic field is in propagation plane and the electric field is perpendicular), where λ is the wavelength in free space. Figure. 1 shows, the band structure diagram of PC. Today, using ring resonators to design optical tools receive more attention compared to point and linear defects among the researchers because ring resonators offer scalability in size, flexibility in mode design due to their multi-mode nature and adaptability in structure design because of numerous design parameters [1]. These parameters can be the radius of the scaterers, coupling rods and the dielectric constant of the structure. Recently, several types of CDF based on 2D PCRR have

been proposed using quasi-square PCRR, square PCRR, dual square PCRR [23], dual curved PCRR [24], hexagonal PCRR [29], 45◦ PCRR [31], circular PCRR [25]. The ring resonators presented in this study is a new design from photonic crystal ring resonators compared to the previous ring resonators presented in different articles. Figure. 2 shows the designed ring resonators structure in this article. Eight additional extra scattering rods with yellow color are introduced to improve the spectral selectivity and obtain a very high dropped efficiency [29]. These scatterers have exactly the same refractive indexes as all other dielectric rods in PC structure and their diameters is chosen to be $r_S=0.965*r$ for better performance. Optical filters are one of the most important building blocks of optical communication networks which play a crucial role in wavelength division multiplexing (WDM) technologies. Optical filters can be used for separating nearly spaced optical channels from each other in WDM applications. In general, a ring resonator is positioned between two optical waveguides provides an ideal basic structure for CDF such that power in one waveguide is transferred into the other through the resonance of the ring, which is used to add or remove a channel from the multiplexed input/output signals. Figure. 3 shows the schematic layout of CDF, which consists of bus and dropping waveguides and ring resonator (coupling element) also the incident port and exit ports are labelled as A, B, C, respectively.



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

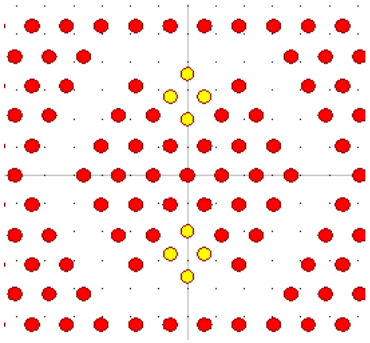


Figure (2) Schematic structure of PCRR

Simulation Results

The spectrum of the power transmission is obtained with finite difference time domain (FDTD) method. FDTD is a time domain simulation method for solving Maxwell's equations in arbitrary materials and geometrics. The basic principle is to substitute the curl equations and partial time differential with finite central differences in spatial domain and time domain respectively [31]. Berenger's perfectly matched layers (PML) are located around the whole structure as absorbing boundary condition [1].A Gaussian input signal is launched into the port A. The normalized transmission spectra are obtained at ports 'B', 'C' and 'D' by conducting Fast Fourier Transform (FFT) of the fields that are calculated by 2D FDTD method. The result of the FDTD simulation for this CDF that shows the normalized optical power transmissions of the structure is shown in Figure. 4. As shown in Figure 4, the wavelength $\lambda = 1519.4$ *nm* of the input port is removed from the upper waveguide and transmitted to the port 'C'. The transmitted power efficiency in this wavelength is about 100%.The value of *Q* for the proposed structure is obtained 189.87. *Q* factor can be calculated with $Q = \lambda / \Delta\lambda$, where λ and $\Delta\lambda$ are central wavelength and full width at half power of output, respectively.

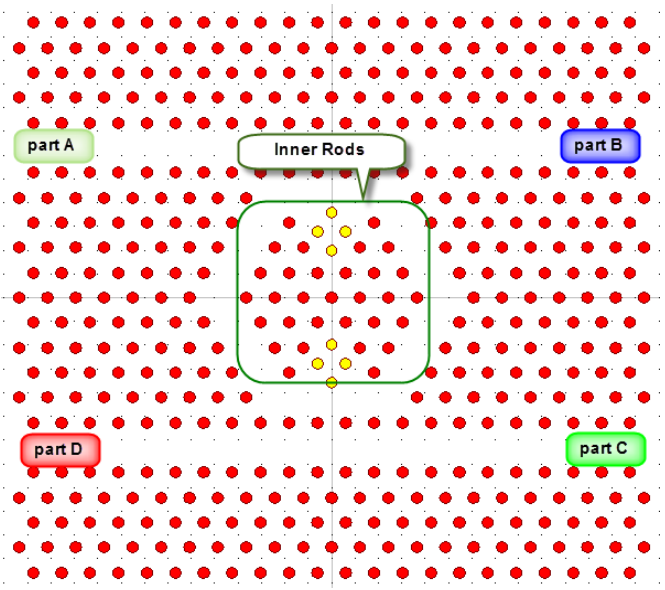
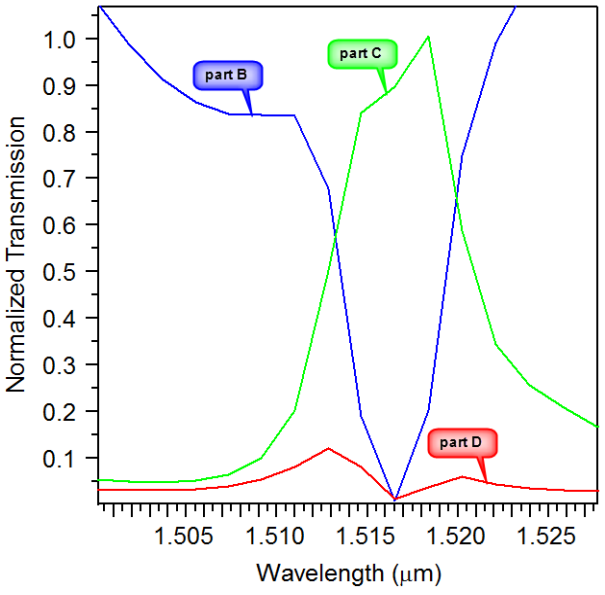


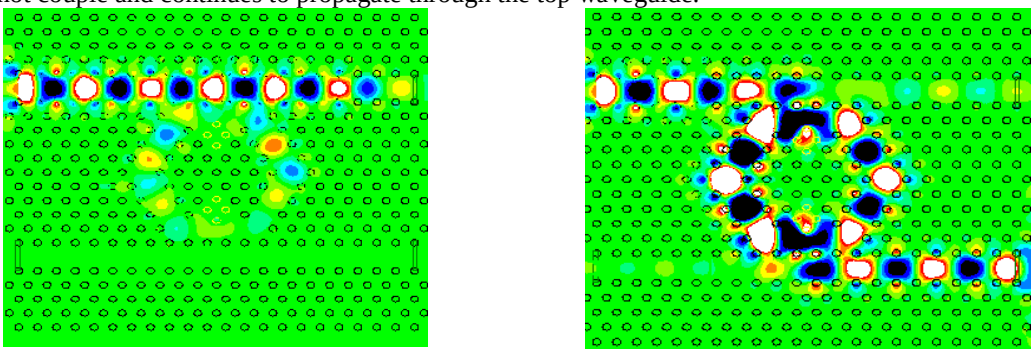
Figure (3) Schematic diagram of the CDF.



Figure(4) Transmission spectra of the CDF at ports B, C and D respectively.

Figure. 5 (a) and (b) shows the electric field distributions of the structure proposed in Figure. 3 for two different wavelengths, λ_1 = 1519.4 *nm*, the resonant and λ_2 = 1501.4 *nm*, the off-resonance wavelength. At

resonant wavelength, the field of the waveguide fully couples to the ring, whereas at off-resonance it does not couple and continues to propagate through the top waveguide.



(a) (b)

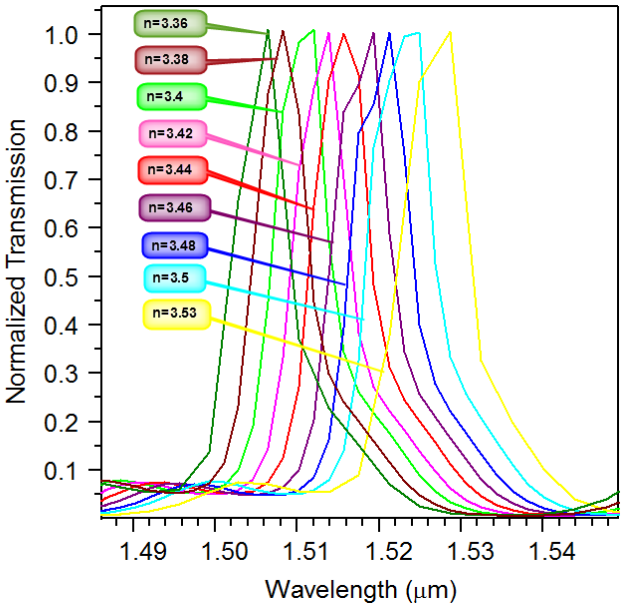
Figure (5) Electric field pattern of the ring resonator at (a) 1501.4 *nm* (non-resonant wavelength) and (b) 1519.4 *nm* (resonant wavelength).

In next sections, we are going to investigate the effect of varying dielectric constant of rods and inner rods on the output spectrum of the filter.

Varying the refractive index of rods

One of the most important features of any filter is its tenability. Here we investigate parameters which affect on resonant wavelength in photonic crystal CDFs. First parameter we are going to investigate is the refractive index of dielectric rods. In order to separate the effect of refractive index from other parameters, we assume all other parameters such as radius of rods and lattice constant of inner rods to be constant. Then obtain the output spectra of the filter for different values of refractive index. The output spectra of the filter for four different values of refractive index are shown in Figure. 6. The output spectra of the filter for nine different values of refractive index are shown in Figure. 6. nine different curves are displayed in Figure. 6 for n_1=3.36, n_2=3.38, n_3=3.4, n_4=3.42, n_5=3.44, n_6=3.46 , n_7=3.48, n_8=3.50 and n_9=3.53.

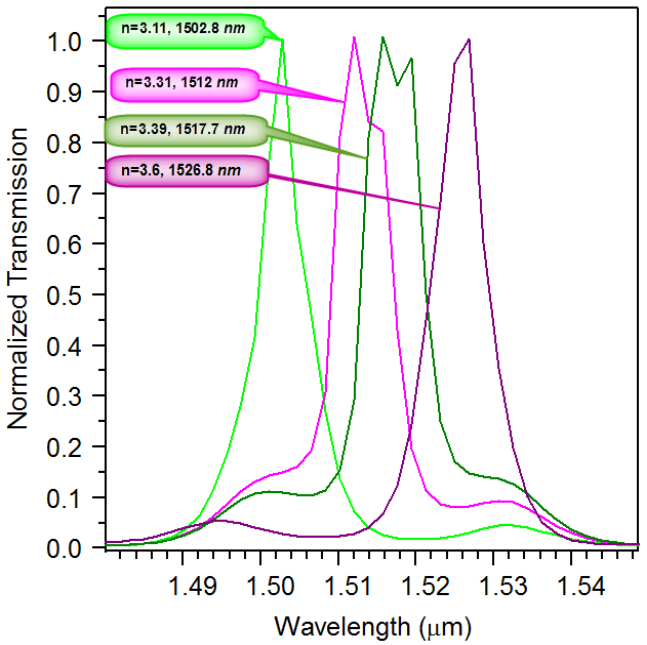
As seen in Figure. 6, the proposed structure, when simulated with the different dielectric constant equal to for n_1=3.36, n_2=3.38, n_3=3.4, n_4=3.42, n_5=3.44, n_6=3.46 , n_7=3.48, n_8=3.50 and n_9=3.53, can select wavelengths λ_1=1506.4 nm, λ_2=1508.3 nm, λ_3=1511.3 nm, λ_4=1513.9 nm, λ_5=1515.7 nm , λ_6=1519.4 nm , λ_7=1521.3 nm , λ_8=1524 nm and λ_9=1528.7, respectively. As shown in Figur. 6, by raising the dielectric constant, the resonant wavelength of the device is increased accordingly. In other words, a red shift occurs in resonant wavelength.



Figur (6) Normalized power transmission spectra of the proposed CDF for different values of refractive index.

Varying of inner rods refractive index

With localized change in inner rods' refractive index, the resonant wavelength can be tuned. This leads to a tunable CDF. Figure. 7 shows the normalized power transmissions of the structure with four different refractive index of inner rods, n_1=3.11, n_2=3.31, n_3=3.39, n_4=3.6.



Figure(7) Normalized power transmission spectra of the proposed CDF for different values of refractive index of inner rods

Conclusions

In this paper, a new design of channel drop filter in triangular lattice PC silicon rods using PCRRs was proposed. Our proposed filter has a resonant wavelength at 1519.4 *nm* with transmission efficiency equal to 100% and suitable quality factor. We studied the impact of varying the parameters which have an effect on resonant wavelength in this CDF. The suggested CDF is compact and the overall size of the chip is about $13.97\mu m \times 13.97\mu m$. Hence, this kind of devices would be more useful to realize circuits of integrated optics for CWDM systems, optical communication network applications and other nanophotonic structures.

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