A 5-Channel DWDM Demultiplexer in C Band on Silicon Photonic Crystal Slab: Design and Numerical Analysis

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Abstract

In this work we propose a novel design of 5-channel DWDM demultiplexer and, numerical analysis of its optimal design parameters and device performance is presented. Photonic crystal hexagonal ring resonators of airholes on a silicon slab are used as channel drop filters. Wavelength controlling is achieved by fine tuning of coupling holes outside each ring resonator. For the proposed design, the resolved wavelengths are in the range of 1535 to 1539nm, where Erbium Doped Fiber Amplifiers are applicable. The average coupling efficiency and cross talk are found to be 72.4% and -18.31dB, respectively. Photonic bandgap computation is performed by using plane wave expansion method and spectral characteristics are obtained by applying 3D finite difference time domain method.

1 Introduction

The requirement for increased information transmission rate forces various optical components in optical communication networks to be integrated. In this regard Photonic Crystal (PhC) based devices have become attractive due to their ability of guiding electromagnetic waves with ultrasmall dimensions. This is due to the presence of photonic bandgap where propagation of electromagnetic modes of certain wavelengths is forbidden. On the other hand, DWDM (Dense Wavelength Division Multiplexing) demultiplexing technology resolves a single optical channel centered at a wavelength into multiple channels at different wavelengths. Conventional DWDM devices are reported, based on grating polarizer [1], asymmetric Y-Junctions [2], dielectric thin films [3]. Due to their bulk dimensions, they are not suitable to be integrated with other optical components. Considering this point, many integrated optical devices are proposed based on Photonic Crystals (PhC). Miniaturized devices are achievable by using photonic crystals due to the existence of photonic bandgap [4]. They offer zero bending losses due to their tight in-plane light confinement. Other than DWDM devices, various applications of PhCs include force sensors [5–6], chemical sensors [7], bio sensors [8], temperature sensors [9], optical memories [10], optical logic gates [11–12].

Over the past one and half decade investigations have been carried out on PhC based devices for WDM applications. PhC based DWDM devices with point defect cavities [13–14], line defect cavities [15], Y-branches [16], T-branches [17], ring resonator [18] and directional couplers [19] are proposed using channel drop filters. Ring resonators are preferable for applications wherever channel dropping filters are used. This is due to their flexibility in design parameters and reduced radiation losses.

Various PhC ring resonator configurations are studied based on dielectric rods in air structures [20–23]. However, considering the reduced complexity in fabrication and packaging process, devices with holes-in-slab are preferable. Due to the availability of cost-effective fabrication capacity and ability to integrate easily with the other integrated optical devices, SOI (Silicon on Insulator) platform is preferable. A hexagonal ring resonator with super defect on SOI platform is reported with optimized airholes to exhibit reduced radiation losses [24]. It is also observed that the size of airholes inside the resonators may be considered as design parameters for wavelength tuning in channel dropping applications. A 4-channel DWDM demultiplexer is theoretically demonstrated with detailed analysis. Airhole sizes inside the individual resonators were chosen as design parameters to select drop wavelengths and the effects of fabrication errors on the device performance is numerically analyzed [25]. Recently Balaji et al computationally demonstrated a novel 6-channel DWDM demultiplexer for ITU-T G.694.1 standard in the wavelength range of 1555 to 1560nm [28]. A photonic crystal of

silicon rods in air is used and the channel wavelengths are chosen by controlling the radii of the rods between input waveguide and corresponding cavities. The spectral characteristics along with the analysis of performance metrics like crosstalk, power distribution and quality factor are presented in detail based on 2D FDTD computations. In the current work, a five channel DWDM demultiplexer is proposed with novel method for channel wavelength tuning, based on a 3D FDTD method numerical analysis. A ring resonator in hexagonal lattice of holes-in-slab PhC on SOI platform is chosen as the channel dropping element. Such ring resonators array is coupled through a line defect bus waveguide formed in PhC. The individual resonators resonate at different wavelengths and the corresponding resonated power is coupled to the corresponding output waveguides. The resonant wavelengths are selected by fine tuning the corresponding input coupling holes. The photonic bandgap and spectral characteristics of the proposed device are computed by using the numerical methods PWM (Planewave expansion Method) and FDTD (Finite Difference Time Domain) method, respectively. The next section explains the design of hexagonal PC ring resonator-based channel drop filter, followed by the proposed design of 5-channel DWDM device.

2 Ring Resonator-based Channel Drop Filter

The unperturbed PhC structure consists of hexagonal lattice of airholes on a 220nm thick silicon device layer. The refractive index of silicon is taken as 3.48 at the wavelength of 1550nm in FDTD and bandgap computations [26]. Filling ratio (r/a) of the considered photonic crystal structure is chosen to be 0.3 to have photonic bandgap in the wavelength range corresponding to the optical communication window centered at 1550nm wavelength. Photonic band structure of the considered structure is computed by using the tool MPB, an open source of planewave expansion method [27]. As it is shown in Fig. 1, the primary bandgap for TE like mode of propagation consists of normalized frequencies (a/λ) in the range of 0.26 to 0.32 equivalent to the wavelength range of 1280 to 1580nm.

Figure 2 shows the schematic of the considered four port hexagonal ring resonator designed on the above-mentioned PhC structure. It is formed by creating point defects along the contour of the hexagonal ring. Line defects waveguides are created above and below of the ring resonator as shown in the schematic. FDTD method is used to simulate the transmission characteristics of the ring resonator at transmissions, along forward drop and backward drop ports.

A Gaussian broadband light source centered at 1550nm wavelength is launched into the input waveguide. Fourier transform is applied to the time domain field responses obtained from 3D FDTD method, to get the spectral characteristics at various ports of the resonator. The spectral characteristics are normalized with respect to the input power using the following relation.

$$T(f) = \frac{1}{2I_p} \int \text{Re}(\mathbf{P}(f)) \cdot d\mathbf{S}$$

Where $T(f)$ is the normalized transmitted power at the particular port, $\mathbf{P}(f)$ is the poyinting vector, $d\mathbf{S}$ is the surface normal at the monitering area and I_p is the input power at the launching end of the input waveguide. The properties of electromagnetic modes propagating inside the photonic crystals are governed by the master equation shown below.

$$\nabla \times \left(\frac{1}{\epsilon(r)} \nabla \times \mathbf{H} \right) = \left(\frac{\omega}{c} \right)^2 \mathbf{H}(r)$$

From the above equation it is obvious that variation in permittivity of the material affects the frequency of the EM modes. The space varying dielectric function is inversely proportional to the angular frequency ω of the EM wave.

The normalized spectral characteristics of the outputs at various ports of the ring resonator are shown in Fig. 3. These results are obtained from FDTD computations where one lattice period in X and Y directions contain 20 and 35 spatial grids, respectively. The asymmetrical channel dropping of the resonator is explained in detail based on field distribution in the resonator [25]. It is observed that the resonant wavelengths will change if the design parameters inside, outside the resonator are changed and hence the considered structure can be treated as a tunable channel drop filter. The next section presents tuning of the resonator by varying the coupling hole indicated in green colour in Fig. 2. Such tunable ring resonators are used to design DWDM demultiplexer.

3 Design Of 5-channel Dwdm Demultiplexer

In the current work, DWDM demultiplexing is achieved by tuning the central coupling hole that is outside the ring resonator mentioned in the previous section. Five hexagonal ring resonators with the same dimension are serially coupled by the input waveguide, the separation between the resonators is kept as six lattice periods. Each resonator is connected to a 120° bent output waveguide which acts as demultiplexing channel. The input bus waveguide is closed with a reflecting hole at the receiving end. 3D FDTD method is applied on the proposed design with a Gaussian source centered at 1550nm wavelength launched at the input port. Figure 4 shows the DWDM device layout and output spectral characteristics, in which five resonators tuned by varying the radius of the central coupling hole. Starting from the left most, the radius of the green hole corresponding to each resonator is varied insteps of 5nm, from 95nm to 115nm, as it is seen in the figure. Thus, the left most resonator and the right most resonator contain the tuning holes of radius 95nm and 115nm, respectively as indicated in Fig. 4. It is clear from the spectrum that coupling to the resonator output channels is not up to the expected level and it is non-uniform among the eight DWDM channels. Blue shift is observed in the resonant wavelength variation from 1538.6nm to 1536nm, as the hole radius increased. The power distribution among the five output channels may be improved by adding more reflecting holes at the receiver end of the input waveguide. The next section deals with optimization of the design to get improved coupling efficiency to the output channels of the DWDM demultiplexer.

4 Optimization Of Dwdm Device

The proposed DWDM device is optimized to get maximum power coupling efficiency at the corresponding output channels. The number of reflecting holes is increased at the receiving end of the input waveguide to improve coupling at the output ports. FDTD computations are performed on the device with increased number of reflecting holes and corresponding intensities at various output ports are recorded. The results of the computations are summarized in Table 1.

Table 1. Summary of FDTD computations to optimize the coupling efficiency.

Number of blocking holes	Maximum intensity	Minimum intensity	Average intensity	Maximum cross talk	Average Q-factor
2	75%	41%	67.1%	-15.60dB	5950
3	80%	68%	72.4%	-15.39dB	5150
4	72%	3%	42.3%	-17.1dB	5643

As shown in the table, the average intensity at the output ports is improved by increasing the number of reflecting holes at the receiving end of the input waveguide. After the addition of second blocking hole, the average intensity at various output ports of device is found to be improved to 67%. In order to further improve the performance, the number of blocking holes is increased to 3. As shown in Table 1, for three blocking holes case Max. and Min. coupling efficiencies are found to be improved. Looking at this trend of improvement in the performance, the number of blocking holes is further increased to 4 and the results are shown in Table 1. It is observed that the coupling efficiency is drastically affected after the addition of the 4th blocking hole. The non-uniformity in power distribution is attributed to increased material loss along the input waveguide due to extra reflecting holes and hence significantly more power is coupled to lower wavelengths. The spectral characteristics of various cases presented in Table 1 are plotted in figures, Fig. 5 to Fig. 7.

Spectral characteristics are presented in Fig. 5 and Fig. 6 for the device with two and four reflecting holes, respectively. DWDM channel 4 is coupled with power of just above 40% when the input waveguide is blocked by two holes as shown in Fig. 5. On the other hand, output power distribution is drastically reduced to 3% at channel 2 when four reflecting holes are used as shown in Fig. 6.

As it is evident from Table 1, the device with three reflecting holes gives the best performance among all considered cases. To explain this, the spectral characteristics are presented in Fig. 7 with the corresponding device layout. As it is seen in the figure, a maximum intensity of almost 80% is coupled to channel 5 and a minimum of 68% is coupled to the channel 3. An average coupling efficiency of 72.4% is achieved with a maximum cross talk of -15.39dB observed between channels 4 and 5. The detailed crosstalk analysis is presented in Table 2. Looking at various aspects like coupling efficiency, crosstalk and the quality factor, device with three reflecting holes is considered as the optimal design. With the current advancements in silicon fabrication technology, we hope that the realization of the proposed optimized device with the appropriate dimensions is possible in near future.

Table 2 Cross talk analysis of the optimized device.

Channels	1	2	3	4	5
1	-	-17.72dB	-	-	-
2	-17.72dB	-	-23.09dB	-26.02dB	-33.4dB
3	-	-23.09dB	-	-15.39dB	-27.95dB
4	-	-26.02dB	-15.39dB	-	-17.07dB
5	-	-33.4dB	-27.95dB	-17.07dB	-

5 Conclusions

A novel 5-Channel DWDM demultiplexer device is proposed based on hexagonal ring resonators in silicon photonic crystal slab. Central coupling hole outside the resonators are used to tune the output resonant wavelengths. Numerical analysis is carried out in detail to study the coupling efficiency, cross talk and other relevant parameters for different cases. Based on the analysis of the results it is concluded that the device with three reflecting holes is found to be a promising design. For this optimal case, the average coupling efficiency is found to be 72.4% of the input power. The average cross talk between the adjacent channels is calculated as -18.31dB, whereas the average Q-factor is 5150. The proposed device has a footprint size of approximately 800 square microns, and it is suitable to be integrated with the other optical components. The proposed design is within the process limits of the silicon fabrication technology.

Declarations

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Conflict of Interest

We confirm that there is no conflict of interest.

Availability of data material

We confirm that the relevant data to the presented results in the current work is available with us.

Ethics approval

The authors approve that the publication ethics recommended by the journal are strictly followed.

Consent to participate

Not applicable

Consent for publication

The authors approve the publication of the results that are submitted in the manuscript.

Authors' Contributions

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in this journal.

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Figures

Figure 1

Photonic bandstructure of the PhC for TE-like modes. The modes inside the light cone region are non-radiative and hence only they are of our interest

Figure 2

Schematic of the simple hexagonal ring resonator

Figure 3

Spectra signals at outputs at various ports of the PC ring resonator

(a)

(b)

Figure 4

(a) DWDM demultiplexer layout and (b) the spectral characteristics

Figure 5

Spectral characteristics of DWDM device with two reflecting holes

Figure 6

Spectral characteristics of DWDM device with four reflecting holes

Figure 7

(a) Device layout and (b) spectral characteristics of optimized DWDM 5-channel demultiplexer