A New Design of a Modified Y-Branch Demultiplexer Based on Photonic Crystal Resonant Cavities and Directional Couplers

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Abstract: - In this paper a novel design of an optical modified Y-branch demultiplexer based on photonic crystal (PC) architecture is investigated. The designed structure is used to select four-channel around the central wavelength of 1550 nm. The presented device is formed by the combination of the directional couplers (DCs) and resonant cavities (RCs). The coupling region consists of three entire rows of decreased silicon (Si) rods. As fundamental structure a square lattice of Si rods is used. The performance of our demultiplexer has been analyzed and investigated using difference time domain (FDTD) method. The results show that the average transmission efficiency obtained is 99.829% and the channel spacing is approximately 2.13nm. The minimum and maximum crosstalk between channels is -55dB and -41 dB, respectively. Furthermore, the mean value of the quality factor is 9005.25. The compact size of our designed structure makes our proposed demultiplexer suitable for photonic integrated circuits (PIC).

Key-Words: - Photonic crystal, filter, modified Y-branch demultiplexer, directional couplers , resonant cavities

1 Introduction

Recently, optical communication networks have been developed due to a rapid increasing demand of the internet and multimedia. In the optical networks, optical fibers are used as transmission medium for transferring information and data. We can increase the capacity to transfer multiple wavelengths over a single optical fiber using wavelength-division multiplexing (WDM) and dense wavelength-division multiplexing (DWDM) technologies. In the receiver, we need a device that can separate and send a maximum number of channels for each corresponding user are needed. This device is known as optical demultiplexer. Due to the importance of this component, many efforts have been focused for designing demultiplexers based photonic crystal (PC). Photonic crystals offer a promising prospect for ultra compact photonic devices and integrated circuits. These materials are artificial, whose dielectric permittivity is modulated periodically on one, two or three directions in space [1, 2]. This periodic variation of the dielectric permittivity results in photonic band gap (PBGs): a frequency region where the electromagnetic waves are forbidden for both polarizations and all directions of the propagation [3]. By creating different defects in PCs, allowed modes appear within PBGs. This will give various applications using the PBG concept, such as photonic crystal waveguides [4] switch [5] etc…

Several topologies have been proposed for designing demultiplexers based PCs, such as using couplers [6] waveguide couplers [7] line defect [8] coupled cavity waveguides [9-11] ring resonator [12- 14] heterostructure [15] core-shell rods defects [16], etc...

An additional effort has been made recently to design Y-branch demultiplexer in two dimensional photonic cristals [17-19]. Using Y-branch structure, we can construct two or more paths for optical wave propagation.

In this paper we proposed a new design of a modified Y-branch optical demultiplexer using two-dimensional photonic crystal. The designed structure can separate four wavelengths in the telecommunications field, with approximately 2.13 nm channel spacing. Our calculated results indicate that the average transmission efficiency obtained is 99.829%. The crosstalk level of the designed structure varies from -55dB to -41 dB. The plane wave expansion method [20, 21] and finite difference time domain method [22] are utilized to analyze and simulate the characteristics of the proposed demultiplexer.

The rest of the paper is structured as follows: section 2, described the design of the filter and the basic structure parameters. The directional coupler design and the guided modes calculation are presented in section3. The described design of the modified Y-branch demultiplexer and the simulation results are discussed in section 4, and finally in section 5 we concluded our work and simulations.

2 Filter Design

In this section, our goal is to design an optical filter using two dimensional photonic crystal. For designing our device, we employed square lattice of silicon rods immersed in air background with refractive index of 3.4. The radius of the rods is $r = 0.19a$, where a is the lattice constant of the basic structure. With these parameters, the crystal has a photonic band gap for transverse electric (TE) modes in the range of normalized frequency varying from 0.2953 $(\omega a/2\pi c)$ to 0.4329$(\omega a/2\pi c)$.

The proposed filter consists of three main parts. The function of the first part named input waveguide is to guide the received light toward the resonant cavity. The third part of the filter is the output waveguide whose role is the selection of the wavelength toward the output port. The input and output waveguides are formed by removing several Si rods in the central line of the structure and they are connected to each other via a resonant cavity. The RC consists of one hole situated in the middle of the structure surrounded by eight defect rods. We named the radius of these defect rods R and which are shown in Fig. 1 in green colour.

A Gaussian input light signal with a central wavelength of 1550nm is launched into the input port of the waveguide as the incident source, it will interact with the resonant cavity and get detected with the monitor placed at the output waveguide. In order to improve the transmission efficiency of our filter, the two neighbor rods in each side of the cavity are vertically shifted down with a distance d equal to $0.3418*a$. By choosing different values for R we can obtain different resonant wavelengths. As shown in Fig. 2, our proposed filter is simulated with different R equal to $0.1a$, $0.1025a$, $0.105a$, $0.1075a$ and $0.11a$, that can select wavelengths 1.4897nm, 1501.2 nm, 1514 nm, 1526.2 nm and 1540.3nm, respectively. According to Fig. 2, it has been shown that an increase in R results in red shift in resonance wavelengths because of a decrease in the cavity size.

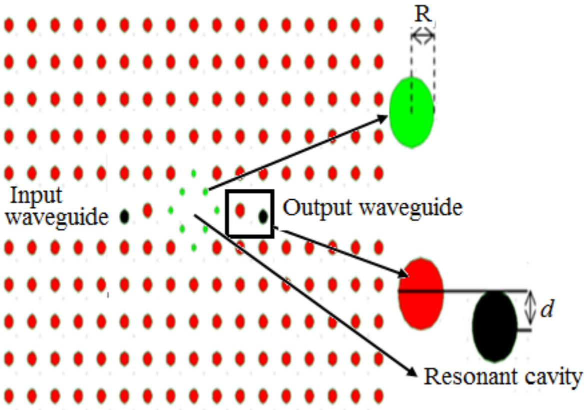

Fig.1: Schematic diagram of the proposed filter

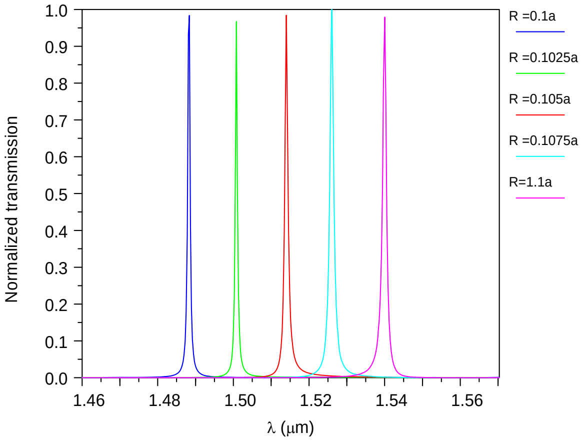

Fig.2: Schematic spectra of the filter for different values of R.

3 Directional Coupler Design

In this section we investigated a PC directional coupler which is formed by two parallel identical waveguides separated by three rows of Si rods whose radius is $rc<r$, as schematically shown in Fig.3. The structure can support two even and odd modes regarding the symmetry plane between the two waveguides. These guided modes are known as fundamental supper–modes and they have different propagation constants, k even and k odd. The electromagnetic wave launched at the input entrance will shift periodically between the two waveguides. When the difference between the k even and k odd increases, the coupling length Lc decreases and becomes small. Lc should be integral times of a and can be defined as [6]:

$$Lc = 2\pi / | k\ even - k\ odd| \qquad (1)$$

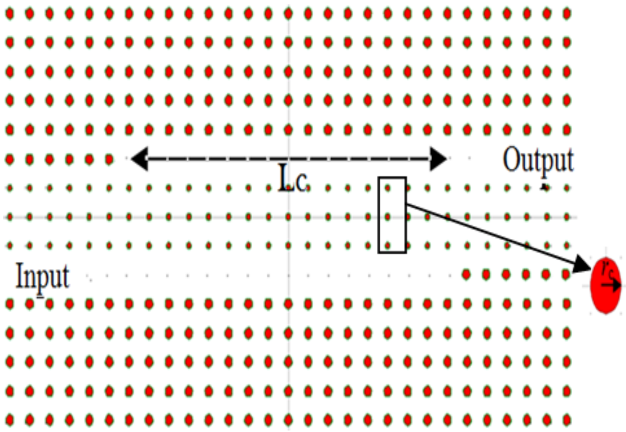

Fig.3: Schematic diagram of photonic crystal directional coupler which is formed by creating two waveguides separated by three rows of Si rods.

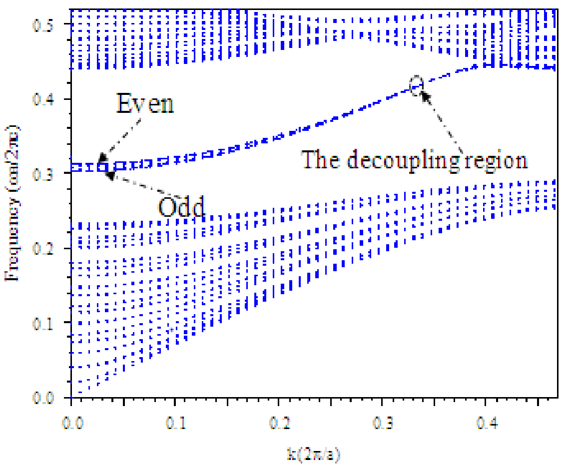

Fig.4: The super-modes k (even) and k (odd) inside the band gap

The dispersion curves of the TE-modes for our directional coupler are shown in Fig. 4. The two curves of the two modes overlap each other at the normalized frequency 0.4, which correspond to the decoupling region.

We have investigated the effect of the coupling length (Lc) on the transmission spectra for two wavelengths λ = 1494nm and λ = 1554nm. The dependency between Lc variation and the normalized transmission is shown in Fig. 5. Based on the results illustrated in Fig. 5 the shorting coupling length which corresponds to the highest normalized transmission of the two signals is $7a$. In this case we have considered the radius of the three rows of rods of the coupling region; $rc = 0.111a$.

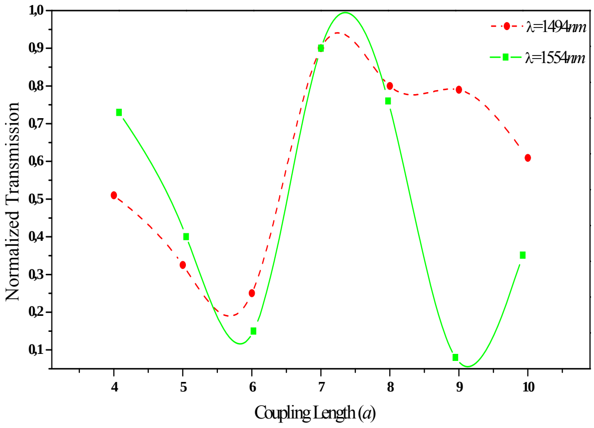

Fig.5: Normalized transmission spectra of the two wavelengths 1494nm (dashed line) and 1554nm (solid line) as a function of Lc.

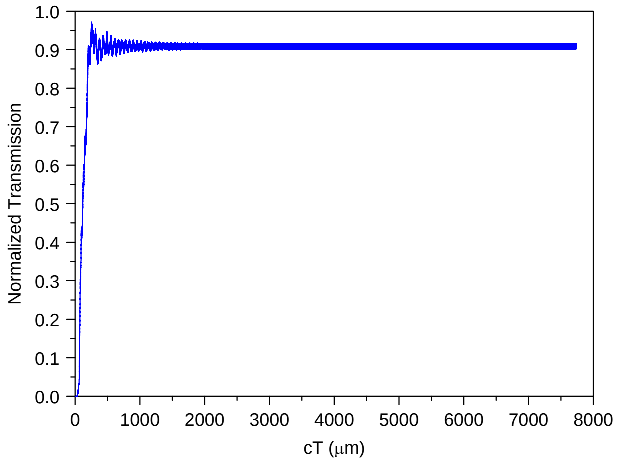

Fig.6: Calculated steady state intensity response of the directional coupler when $Lc=7a$ and $rc=0.111a$.

The steady state intensity response of the directional coupler when rc=0.111a and Lc=7a is shown in Fig. 6. One can see from this figure that the transmission efficiency obtained for the two wavelengths is 90% and the response time T attained is less than 3.26ps.

4 Modified Y-Branch Demultiplexer Design

In this section, we proposed four channel demultiplexer based on modified Y-branch structure in two dimensional photonic crystals. The main task of our designed device is separating four wavelengths in the telecommunication field. For performing the demultiplexer task, we employed four resonant cavities. The basic structure consists of a 40 x 36 square lattice of Si rods immersed in air background. As illustrated in Fig. 7, the proposed design is composed by one horizontal input waveguide, four coupling areas (C1 ,C2 , C3 and C4), four resonant cavities and four horizontal output waveguides. The modification of the Y-branch is due by placing directional couplers between the input and the output waveguides. We have considered the coupling lengths Lc =7a and the radius of the rods of the coupling area rc= 0.111a . After simulation of this designed device, some important phenomena have been observed; One of them is red shift of the resonant wavelengths by increasing R. When the light signal is applied to the input port, it coupled in the coupling area, trapped in the resonant cavity, and then it can be extracted to the output port. Wavelength selection was performed by changing the defect rods (R) of the resonant cavity.

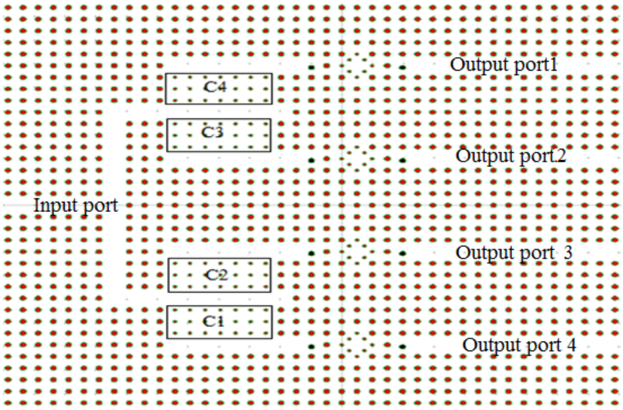

Fig.7: Schematic diagram of the proposed demultiplexer.

It has been found that different radiuses R equal to 0.11a, 0.112a, 0.113a and 0.114a, can select different wavelengths of 1545.7nm, 1548.5nm, 1550.7nm and 1552.1nm, respectively. As shown in Fig. 8 the structure transmits four channels around the central wavelength of λ = 1550 nm, with channel spacing approximately 2.13 nm. In addition, high transmission efficiency and quality factor are obtained. This means that our designed device has an excellent demultiplexing performance.

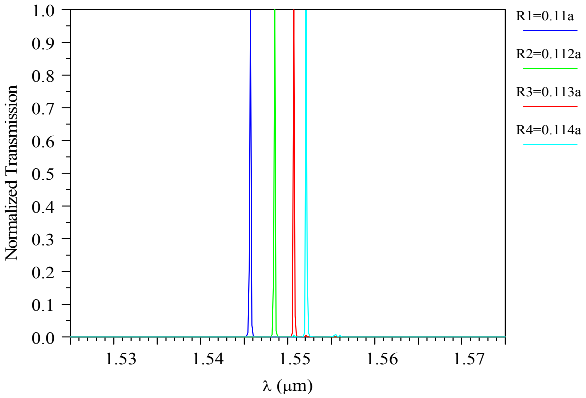

Fig.8:Normalized transmission spectra of the modified Y-branch demultiplexer

Another crucial parameter in evaluating the performance of the optical demultiplexer is the crosstalk, which shows the magnitude of interference of energy between neighboring channels.

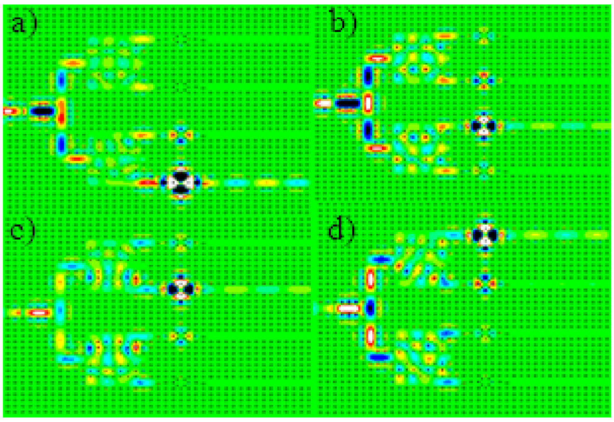

Fig.9: Field distribution of designed demultiplexer at (a) 1545.7nm, (b) 1548.5nm,(c) 1550.7nm,(d) 1552.1nm.

The crosstalk, quality factor, and transmission efficiency at each port are summarized in Table 1. Our FDTD simulations show that the crosstalk between channels, are varied from -55dB to -41dB. We have found also that the average quality factor and the transmission efficiency obtained are 9005.25 and 99.829%, respectively. In addition the channel spacing is around 2.13nm. Compared with other structures presented in the recent literature [23-27], our device has much better performance. The comparison of our results with these works is presented in Table 2. The total size of the designed demultiplexer is 709,92μm^2, its dimension is small for integrating and practical for communication applications.

In order to confirm the performance of the proposed structure, the steady-state electric field distribution for the four-channel is depicted in Fig. 9. From this figure the demultiplexing effect is clearly observed. The four states have been created by changing the radiuses *R* of the resonant cavity.

Table 1. Significant parameters of the four- channel demultiplexer based on modified Y-branch structure.

Wavelength (nm)	Transmission Efficiency %	Quality Factor	Crosstalk (dB)
1545.7	99.98	8630	-55
1548.5	99.97	8950	-48
1550.7	99.639	9572	-41
1552.1	99.73	8869	-42

Table 2. Comparison of the designed demultiplexer structure and other recent works.

Reference	Transmission Efficiency (%)	Quality Factor (Q)	Crosstalk (dB) Min	Crosstalk (dB) Max
[23]	98	1823	- 26.9	-3.4
[24]	93	4320	-46	-11
[25]	92	1039	-24	-13
[26]	99.25	7358.5	-46.68	-9.79
[27]	94.5	1577.7	-48.3	-8
In this work	99.829	9005.25	-55	-41

5 Conclusion

In this paper, we proposed a four –channel demultiplexer based on a modified Y-branch structure in a square lattice photonic crystal geometry for WDM optical communication applications. The demultiplexing properties have been analyzed using the finite difference time domain method. The proposed structure can separate four telecommunication wavelengths by varying the radiuses of the resonant cavity. Our designed device present high demultiplexing performance, where the average quality factor and transmission efficiency obtained are 9005.25 and 99.829%, respectively. The minimum and maximum crosstalk between channels is -55dB to-41dB, respectively. In addition the channel spacing is approximately 2.13nm. This structure has a small footprint, which make it suitable for optical integrated circuits.

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