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...
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 0.1$a$, 0.1025$a$, 0.105$a$, 0.1075$a$ and 0.11$a$, 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.
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 $r_c < r$, 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 superr–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 $L_c$ decreases and becomes small. $L_c$ should be integral times of $\lambda$ and can be defined as [6]:

$$L_c = \frac{2\pi}{|k_{\text{even}} - k_{\text{odd}}|} \quad (1)$$

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 ($L_c$) on the transmission spectra for two wavelengths $\lambda = 1494\text{nm}$ and $\lambda = 1554\text{nm}$. The dependency between $L_c$ 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; $r_c = 0.111a$.

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.

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

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

![Image of graph showing transmission spectra](image-url)
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 × 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.

It has been found that different radiiuses \( R \) 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 \( \lambda = 1550 \) 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.7: Schematic diagram of the proposed demultiplexer.

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 709.92μm², 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.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Transmission Efficiency (%)</th>
<th>Quality Factor (Q)</th>
<th>Crosstalk (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1545.7</td>
<td>99.98</td>
<td>8630</td>
<td>-55</td>
</tr>
<tr>
<td>1548.5</td>
<td>99.97</td>
<td>8950</td>
<td>-48</td>
</tr>
<tr>
<td>1550.7</td>
<td>99.639</td>
<td>9572</td>
<td>-41</td>
</tr>
<tr>
<td>1552.1</td>
<td>99.73</td>
<td>8869</td>
<td>-42</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Reference</th>
<th>Transmission Efficiency (%)</th>
<th>Quality Factor (Q)</th>
<th>Crosstalk (dB) Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>[23]</td>
<td>98</td>
<td>1823</td>
<td>-26.9</td>
<td>-3.4</td>
</tr>
<tr>
<td>[26]</td>
<td>99.25</td>
<td>7358.5</td>
<td>-46.68</td>
<td>-9.79</td>
</tr>
<tr>
<td>[27]</td>
<td>94.5</td>
<td>1577.7</td>
<td>-48.3</td>
<td>-8</td>
</tr>
<tr>
<td>In this work</td>
<td>99.829</td>
<td>9005.25</td>
<td>-55</td>
<td>-41</td>
</tr>
</tbody>
</table>

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.

References:


