Design of Six Channel Demultiplexer by Heterostructure Photonic Crystal Resonant Cavity

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ABSTRACT: We have proposed a six channel demultiplexer based on a Heterostructure photonic crystal (PhC) resonant cavity. In order to achieve the structure of demultiplexer, six improved cavities with different refractive indexes of 3.50, 3.48, 3.46, 3.44, 3.42 and 3.40 have been used. Each cavity has an individual refractive index; it means that each cavity has a varying resonant frequency. Simulation results using finite-difference time-domain (FDTD) method reveals that in our proposed structure an average transmitted power higher than 95.5%, channel spacing is about $12.5 \times 10^{-4}$ c/a, mean value of quality factor (Q) is 2319 and bandwidth for each individual channel is about $18 \times 10^{-5}$ c/a. The mean value of the crosstalk between outputs channels is about -29dB. By changing the refractive index, various frequencies can be chosen; therefore this structure is able to dropping desired frequencies.

Key word: FDTD method; Tunable; Frequency

INTRODUCTION

Nowadays, for the development of new devices for integrated optics, photonic crystal (PhC) structures are becoming a significant platform (Mansouri-Birjandi et al., 2008). Photonic crystals (PhCs), also known as photonic band gap (PBG) materials, can control the spontaneous emission and the propagation of electromagnetic (EM) waves (Joannopoulos et al., 1995; Rostami et al., 2011). In these structures optical refractive index shows a periodic modulation with a lattice constant. The most important feature of PhC structures is PBG in addition to the allowed modes which are concentrated around the defects therein. By engineering the PBG, the confinement of light in given frequencies can be tuned. PhC based structures enable the researchers to make smaller devices which can be integrated in single chips. Up to now, many optical devices have been designed based on PhCs such as optical filters (Kim et al., 2004; Saghirzadeh Darki and Granpayeh, 2010; Mahmoud et al., 2012; Guan et al., 2012), switches (Wang et al., 2010), splitters (Ghaffari et al., 2008; Wan et al., 2011; Shuo et al., 2012), and demultiplexers (Selim et al., 2011; Rakhshani and Mansouri-Birjandi, 2012; Momeni et al., 2006), which may ultimately pave the way for photonic integrated circuits (PICs). These devices are being used mainly in optical communication systems, like a wavelength Division multiplexing (WDM) system. As an essential element of such systems, demultiplexer is being used for selecting a channel with a specific frequency.
Multiplexing is the operation which enables us to inject in one waveguide frequencies incoming from two or more different waveguides. Demultiplexing is the inverse operation enabling us to extract from one waveguide one frequency and to send it to another waveguide (Pennec et al., 2010). The main characteristics of demultiplexers for the optical communication systems are features like polarization independent, low crosstalk, high spectral resolution and compactness (Akosman et al., 2011). So far, several topologies have been proposed for demultiplexer designing, such as using line defect PhC waveguides (Akosman et al., 2011; Zhang et al. 2012), coupled cavity PhC waveguides (Rostami et al., 2010), directional coupling (Selim et al., 2011; Moreolo et al., 2006) and ring resonators (Djavid et al., 2008). The resonant cavities which are coupled to the waveguides can be used as frequency selecting devices. Resonant cavities in a specific frequency, which is the cavity resonant frequency, localize electromagnetic energy from an input waveguide into the cavity and then transmit it to the output waveguide.

In this paper, a heterostructure demultiplexer structure has been designed by using resonant cavity for dropping desired frequencies. We used PhC resonant cavity to achieve a new type of demultiplexer with acceptable power transmission and high quality factor. Six cavities have been used in our proposed device to transmit the frequencies of 0.31796, 0.31922, 0.32037, 0.32151, 0.32277 and 0.32414 c/a. In this structure, the channel spacing is about $12.5 \times 10^{-4}$ c/a and average transmitted power is above 95.5%. On the other hand, the average crosstalk for the output channels is about -29dB; which is suitable for WDM communication systems. These characteristics are highly appropriate for devising a full cavity based demultiplexer. The performance of proposed structure is investigated using the FDTD method with the perfectly matched layer (PML) absorbing boundaries conditions at all boundaries. The distinctive features of this structure are high Q factor, low channel spacing, high power transmission and its tunability for desired frequencies. The proposed resonant cavity provides a possibility of optical demultiplexer and can be used as the building block for other devices as well.

**Design Of Photonic Crystal Demultiplexer**

A typical resonant cavity obtained from a square lattice of dielectric rods in air background is displayed in Figure 1(a). The dielectric rods have a dielectric constant of 11.56, and radius of $r=0.2a$ is located in air, where $a$ is a lattice constant. The point defect with radius of $r_d=0.08a$ is located in the center of resonant cavity in the output port. The PhC waveguide is formed by implementation of linear defect. By locating a waveguide beside the resonant cavity, the resonant cavity at its resonant frequency drops light from the top waveguide and sends it to the bottom waveguide. In other words, the resonant cavity can be coupled to the waveguide to localize the electromagnetic energy in the resonant cavity.

The dispersion diagram for this structure, shows band gap for the normalized frequency of $0.2872< c/a <0.422$ for TM polarization (in which the magnetic field is in propagation plane and the electric field is perpendicular), where $c$ is the speed of light. The spectrum of the power transmission is calculated with finite difference time domain (FDTD) method. FDTD is a time domain simulation method for solving Maxwell’s equations in arbitrary materials and geometrics (Taflove and Hagness, 2005). The perfectly matched layer as absorbing boundary condition (PML) (Berenger, 1994) has been used due to its distinguished high performances. The outcome of the FDTD simulation for this structure, that shows the normalized optical power transmissions, is shown in Figure 1(b). As shown in Figure 1(b), the frequency of $f=0.3457$ c/a of the input port is removed from the upper waveguide and transmitted to the output through the cavity. The transmitted power efficiency in this frequency is about 46%.

To increase the optical power transmission, we can modify the radius of adjacent rods of the resonant cavity defect. In Figure 2, variation of the power transmission for different radii of two adjacent rods is shown. As shown in
Figure 2, to obtain 100% transmission efficiency, the radius of adjacent rods of the cavity, placed at the left and right of the cavity center, must be changed to 0.3a, where a is a lattice constant. As seen, for radius of 0.3a for adjacent rods, the normalized transmission of the new resonant frequency, i.e. $f = \frac{0.32414 \text{ c}}{a}$, is 100%. The value of $Q$ for the optimized structure is obtained 1930. $Q$ factor can be calculated with $Q = \frac{f}{\Delta f}$, where $f$ and $\Delta f$ are central frequency and full width at half power of output, respectively. We note that the amount of 1930 is an acceptable quality factor for resonant cavity based demultiplexer.

![Diagram of demultiplexer with one output by resonant cavity and normalized power transmission spectrum of this structure](image)

One of the most important features of any demultiplexer is its tunability. Optical power transmission spectrum of the structure proposed in Figure 1(a) with eight refractive indexes of 3.36, 3.38, 3.40, 3.42, 3.44, 3.46, 3.48 and 3.50 is shown in Figure 3. As shown in this figure, by raising the refractive index, the resonant frequency of the device is decreased accordingly. Similarly, by decreasing the refractive index of the PhC pillars, the resonance frequency shifts
to higher frequencies, which means that this structure is adjustable for desired frequencies. It is shown that by increasing the refractive index by the value of 0.14, output efficiency is not changed.

In this study, we present a design of heterostructure PhC demultiplexer using resonant cavities with six outputs. As shown in Figure 4, this demultiplexer contains six cavities with different refractive indexes. The refractive indexes of \( n_i \) (i=1, 2… and 6) are 3.50, 3.48, 3.46, 3.44, 3.42 and 3.40, respectively. These different refractive indexes can produce with electro-optic (E-O) or thermo-optic (T-O) materials. Refractive indexes of E-O materials are changed in response to the external electric field. In T-O materials we can control the refractive index through the heat generated by optically produced carriers.

![Figure 2. The output of the resonant cavity for different radii of adjacent rods.](image)

![Figure 3. Transmission efficiency characteristics of structure illustrated in Figure 1(a) with eight refractive indexes for whole rods.](image)
This structure is named a heterostructure PhC, because it is created from six refractive index substructures. In order to prevent propagation losses at the boundary of the different refractive index substructures, the band gap of these substructures must be overlapped in some range of frequency. We explore six structures band gaps using a two dimensional plane wave expansion method for TM polarization, and the results are written in Table 1.

On account of the PhC substructure with different refractive indexes have different band gaps, it is possible that discontinuity in their energy bands will occur when substructures is brought together. To guiding a light in heterostructure PhCs with no propagation losses, band gap matching should be considered. Certainly, six different regions have individual band gaps.

![Figure 4. Schematic of proposed heterostructure PhC demultiplexer](image)

Table 1. Band gap for different refractive indexes of whole rods.

<table>
<thead>
<tr>
<th>Refractive index of rods</th>
<th>Band gap range (c/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.40</td>
<td>0.2872 - 0.422</td>
</tr>
<tr>
<td>3.42</td>
<td>0.2857 - 0.4191</td>
</tr>
<tr>
<td>3.44</td>
<td>0.2841 - 0.418</td>
</tr>
<tr>
<td>3.46</td>
<td>0.2825 - 0.4169</td>
</tr>
<tr>
<td>3.48</td>
<td>0.281 - 0.4158</td>
</tr>
<tr>
<td>3.50</td>
<td>0.2795 - 0.4147</td>
</tr>
</tbody>
</table>

The six band gaps must be overlapped in some ranges of frequencies. Since different PhCs have different band gap ranges, an equivalent band gap of the heterostructure demultiplexer is the overlapping band gaps of substructures (Djavid et al., 2008). According to Table 1, the equivalent band gap is: 0.2872<c/a<0.4147. The input waves with frequencies of 0.2872<c/a<0.4147 can be transmitted through the waveguide and going through all six regions without any losses.
In this paper, we propose a novel scheme for a demultiplexer with six outputs based on PhC's heterostructure. By using a single resonant cavity, we obtained the output power efficiency close to 100%. It was shown that the resonance frequency of demultiplexer has been tuned by varying refractive index. In the final structure, six improved resonant cavity had been used, wherein six outputs with channel spacing of $12.5 \times 10^{-4} \text{c/a}$, average bandwidth of $981$ dB and show good ability for the demultiplexer device in practical applications. The mean value of dropping efficiency and Q factor as shown in Table 2 are larger than 95.5% and 2319 respectively.

The demultiplexers reported in (Djavid et al., 2008; Bouamami and Naoum, 2012) are based on two dimensional photonic crystals in which the average transmission efficiency in each case are above 85% and 40%, respectively. In addition, quality factor in this papers are more than 55 and 50 respectively. Consequently, one can realize that the output channels in our proposed structure have higher power transmissions as well as high quality factor in which redound to smaller frequency spacing. These fundamental characteristics have a great impact on frequency selectivity which is an essential problem in today's optical transmission technology.

CONCLUSIONS

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18×10^{-5} \text{c/a} and average dropped power efficiency over 95.5% had been achieved. The mean value of crosstalk between the outputs channels and quality factor are about -29dB and 2319 respectively. We have shown that there is flexibility in design of the demultiplexer with photonic crystal resonant cavities. Such structure may offer promising applications for photonic integrated circuits based on PhCs and other nanophotonic structures.

Table 2. Simulation Results of our proposed structure

<table>
<thead>
<tr>
<th>Output number</th>
<th>Output frequency (c/a)</th>
<th>Quality factor</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.31796</td>
<td>1745</td>
<td>81</td>
</tr>
<tr>
<td>2</td>
<td>0.31922</td>
<td>2610</td>
<td>93</td>
</tr>
<tr>
<td>3</td>
<td>0.32037</td>
<td>2600</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>0.32151</td>
<td>1942</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>0.32277</td>
<td>2814</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>0.32414</td>
<td>2203</td>
<td>100</td>
</tr>
</tbody>
</table>
Figure 6. Field distributions of our proposed demultiplexer structure for frequency of $f=\begin{align*}
(a) & 0.31796, \\
(b) & 0.31922, \\
(c) & 0.32037, \\
(d) & 0.32151, \\
(e) & 0.32277 \text{ and } (f) 0.32414 \text{ c/a}
\end{align*}$

REFERENCES


Shuo L, Shu-Guang L, Ying D. 2012. Analysis of the characteristics of the polarization splitter based on tellurite glass dual-core photonic crystal fiber. Optics & Laser Technology. 44: 1813-1817.


