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Design and Optimization of Photonic Crystal Triplexer for Optical Networks

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Abstract

In this paper, we have proposed an all-optical wavelength triplexer using photonic crystal resonant cavities. The photonic crystal rods is composed of three layers, *InP-InGaAsP-InP*, the substrate consists of *InP* with a refractive index of n_{InP}=3.169 and the guiding layer is InGaAsP, with an index of $n_{InGaAsP}$=3.364. The guiding layer is 0.510μm thick, and it has an *InP* top cladding of 1.500μm. The photonic crystal is created with a hexagonal lattice with r/a=0.18 which r is a radius of rods and a is lattice constant. In this structure, three cavities are used, which can separate three communication wavelengths, 1.31, 1.49 and 1.55μm. The average output efficiency of the proposed triplexer by using finite-difference time-domain (FDTD) method is above 97%. The footprint of the proposed structure is about 144μm^2, thus this structure is suitable for integration. Also, the crosstalk, which is critical factor in triplexer devices, is between $-26.81dB \sim -13.80dB$.

Keywords: *Cavity, Photonic Crystal, Triplexer.*

1. Introduction

Photonic crystals (PhCs), also known as photonic bandgap (PBG) materials, can control the spontaneous emission and the propagation of electromagnetic (EM) waves [1-3]. Due to existence of PBG, PhCs have applications in different areas of optical engineering such as optical filters [4], switches [5], power splitters [6], and demultiplexers [7] which may ultimately pave the way for photonic integrated circuits (PICs). By engineering the photonic band gap, the confinement of light in given wavelengths can be tuned. It means that, we can control the transmittance and reflectance wavelengths interval by adjusting the bandgap of each PhC structure. In other words, PhC structures suggest high spectral selectivity that is necessary for demultiplexer designing [3]. The filtering technology enables us in particular to construct multiplexing and demultiplexing devices. 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 [8].

A triplexer is a demultiplexer for three specific wavelengths, which essentially in optical communication this device is used for demultiplexing 1.31, 1.49, and 1.55μm wavelengths. Triplexers have attracted great attention due to their important applications in the field of optical communication applications and play a very important role in fiber-to-the-home (FTTH) systems. However, the triplexer filter followed the development of conventional waveguide to result in a larger scale, By means of photonic crystals (PhCs), devices can be made smaller in sizes than ever [9].

The Photonic crystal triplexers have been proposed in several papers: Adnan and et al proposed triplexer with square defect silicon scatterers [10]. This device footprint is 196μm^2 with a transmission efficiency of larger than 47%. This efficiency is quite low. Triplexer using PhC ring resonator integrated with directional coupler has been proposed by Wu and et al [9]. Photonic crystal region in this device is 228μm^2 with an average output efficiency of larger than 90%. Shih and et al proposed a Triplexer filter by using 2D PhCs [11]. Photonic crystal footprint in this device is 320μm^2 and transmission efficiency is larger than 94%. In this device, in the resonant cavities, the material of defect rods was assumed to be Si_3N_4. Photonic crystal waveguide based triplexer by two stages of directional couplers has been proposed by Shi and et al [12]. Their structure has two stage directional couplers. They taper the coupling region symmetrically to improve the extinction ratios to more than 16.0dB. Total size of their structure is about 1000μm^2. This footprint is quite large in view of the other achieved structures.

The coupling of a waveguide with resonant cavities can alter considerably the transmission spectrum and useful for demultiplexing applications [8]. Photonic crystal cavities formed by introducing point defects into the PBG structure have encouraged great interests. This is due to the fact that a photonic crystal cavity can localize electromagnetic energy in very small mode volumes [13]. Localization of light in such small volumes opens the

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possibility of realization of extremely compact integrated circuits. Resonant cavities in PhC structures improve the interaction of light due to inherent properties [14, 15].

We propose a pillar photonic crystal triplexer based on *InP*-based materials. PhC components in *InP*-based materials are of practical importance for integration with conventional optoelectronic components on *InP* substrate. With assembling defect cavities and linear defects (i.e. waveguides) the fabrication of filters is possible. The triplexer proposed here is constructed by three similar resonant cavities obtained by varying the point defect radius of these resonant cavities.

The minimum value of crosstalk between channels is −26.81*dB* and the maximum value of it, is −13.80*dB*. In other words, the mean value of crosstalk is −19.42*dB*. The features of this design, in addition to high transmission efficiency and quite low crosstalk, is simplicity of fabrication process and its small dimensions that make it suitable for integration on the single chip.

2. Design and Analysis

Fig.1 shows the triplexer structure based on three output port system, where the waveguides support one mode in the frequency range of interest. The resonator possesses mirror reflection symmetry with respect to the reference plane, which is at the center of the resonator. The amplitude of the incoming wave into the system is denoted by S_{+1} and the amplitudes for the outgoing waves are S_{-i} (i=1, 2, 3, 4).

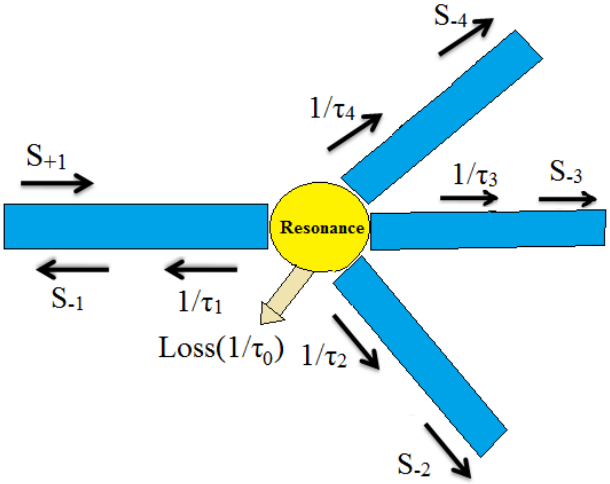


Fig. 1 Sketch of the coupled mode model of our triplexer

According to the coupled mode theory, we can easily obtain the following formulas [16]:

$$R=\left|\frac{S_{-1}}{S_{+1}}\right|^2=\left|\frac{-j(\omega-\omega_0)+\frac{1}{\tau_1}-\frac{1}{\tau_2}-\frac{1}{\tau_3}-\frac{1}{\tau_4}-\frac{1}{\tau_0}}{j(\omega-\omega_0)+\frac{1}{\tau_1}+\frac{1}{\tau_2}+\frac{1}{\tau_3}+\frac{1}{\tau_4}+\frac{1}{\tau_0}}\right|^2 \tag{1}$$

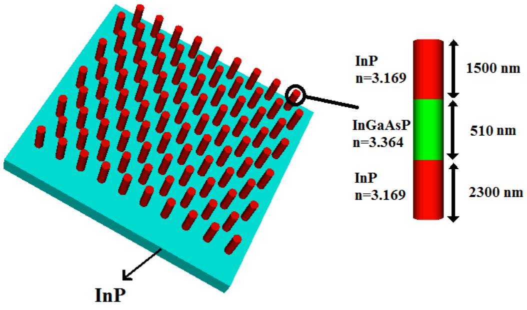
$$T_2=\left|\frac{S_{-2}}{S_{+1}}\right|^2=\left|\frac{\frac{2}{\sqrt{\tau_1/\tau_2}}}{j(\omega-\omega_0)+\frac{1}{\tau_1}+\frac{1}{\tau_2}+\frac{1}{\tau_3}+\frac{1}{\tau_4}+\frac{1}{\tau_0}}\right|^2 \tag{2}$$

$$T_3=\left|\frac{S_{-3}}{S_{+1}}\right|^2=\left|\frac{\frac{2}{\sqrt{\tau_1/\tau_3}}}{j(\omega-\omega_0)+\frac{1}{\tau_1}+\frac{1}{\tau_2}+\frac{1}{\tau_3}+\frac{1}{\tau_4}+\frac{1}{\tau_0}}\right|^2 \tag{3}$$

$$T_4=\left|\frac{S_{-4}}{S_{+1}}\right|^2=\left|\frac{\frac{2}{\sqrt{\tau_1/\tau_4}}}{j(\omega-\omega_0)+\frac{1}{\tau_1}+\frac{1}{\tau_2}+\frac{1}{\tau_3}+\frac{1}{\tau_4}+\frac{1}{\tau_0}}\right|^2 \tag{4}$$

Where R is reflection from input waveguide, $T_{2,3,4}$ are transmissions from three output ports, $\tau_{1,2,3,4}$ are external cavity lifetime, ω_0 is resonant frequency and $1/\tau_0$ is the decay rate due to loss.

In this paper, our goal is designing a compact structure for wavelength triplexer based on *InP*-based pillar photonic crystals. As shown in Fig. 2(a), this structure is composed of three layers, *InP-InGaAsP-InP*, the substrate consists of *InP* with a refractive index of n_{InP}=3.169 and the guiding layer is *InGaAsP*, with an index of $n_{InGaAsP}$=3.364. The thickness of guiding layer and *InP* top cladding are 0.510μm and 1.500μm, respectively. This PhC is created with a hexagonal lattice with r/a=0.18 and has a photonic bandgap (PBG) for a TM mode, as we know, TM mode is defined as the Electric fields are parallel to the dielectric rods axis.



(a)

Fig. 2 (a) The *3D* structure involves three layers (*InP–InGaAsP–InP*) with 1500–510–2300*nm* thicknesses, respectively

Fig. 3 shows a photonic crystal coupled cavity waveguide that consist of point defect. The photonic crystal walls of the waveguide consist of a hexagonal lattice of *InP*/*InGaAsP* rods in *InP* substrate. The considered structure is organized from main two parts. First part that is named line defect contains an input and

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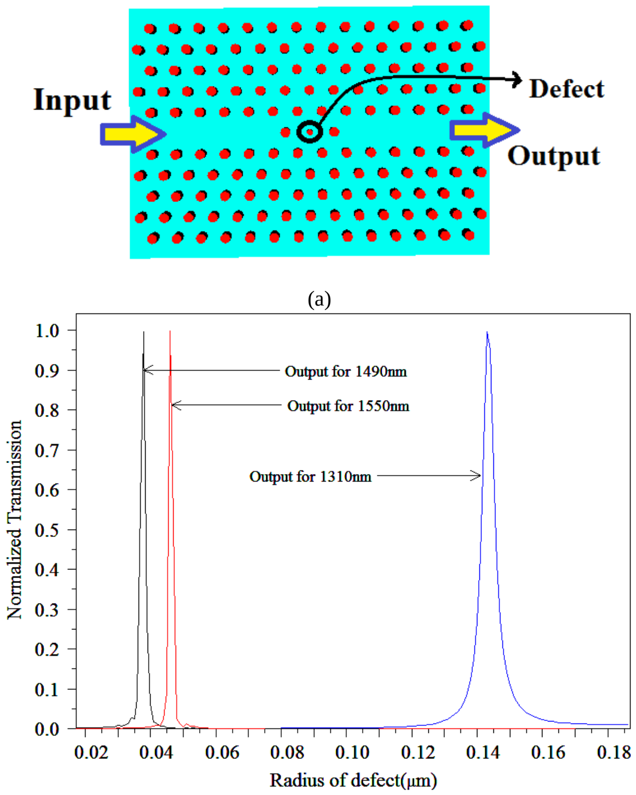
output waveguides that is created by removing several dielectric rods. In second part, according to Fig. 3, in the middle, we create a resonance cavity. As shown in this figure, the cavity creation is done by changing the radius of the middle rod and its diameter defined as d_d that $r_d=d_d/2$. Thus dd is the radius of defect in the cavity.

This defect is key parameter in the proposed structure for selecting wavelength in triplexer device. Here we investigate that a range of rd exists for which the maximum output transmission for each three desired input wavelength i.e. 1.31, 1.49 and 1.55μm appears. Note that the maximum efficiency of this resonant cavity for three input wavelengths 1.31, 1.49 and 1.55μm, as shown in Fig. 3(b), is obtained when defect radius is r_d=0.143, 0.038 and 0.046μm respectively.



(a)

(b)

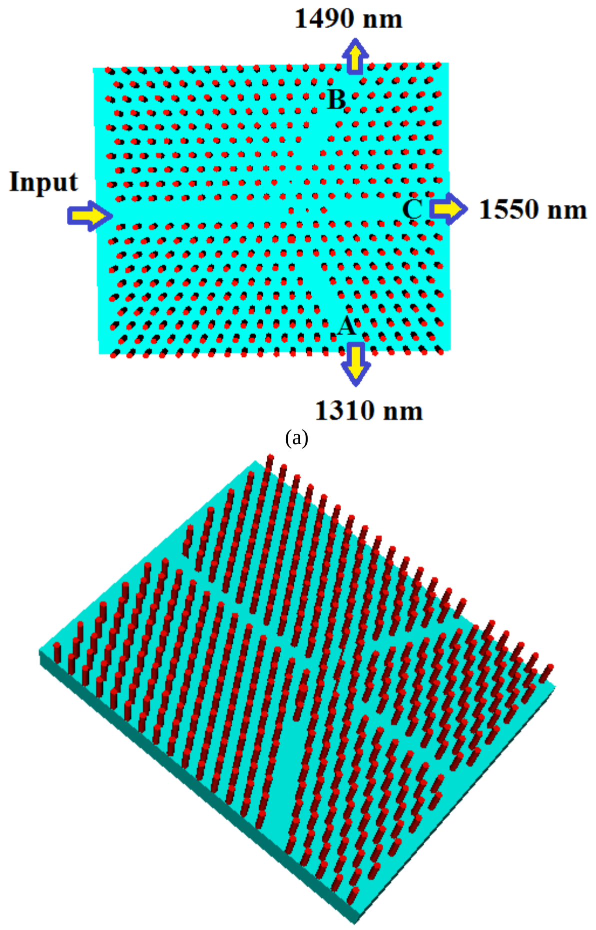
Fig. 3 (a) Schematic diagram of proposed resonant cavity; (b) The ratio of r_{defect} variations for three different input wavelengths of the waveguide in the resonant cavity.

Finally, the proposed structure for wavelength demultiplexing is shown in Fig. 4(a). As shown in this figure, the structure consists of three cavities in the particular locations in the end of the input waveguide. When multiwavelength light is incident on this device and propagates through the input waveguide, the light dependent on its wavelength, in each point defect cavity becomes trapped; the light trapped in each cavity can then be extracted to a separate output waveguide.

3. Simulation and Results

Finite-difference time-domain (FDTD) method [17] is most general method for study of photonic crystals. The FDTD is one of the most advanced methods today for computation of the field distribution inside the PhC based devices which are really optical structures with non-uniform dielectric constant distribution.

Here, the Full-Wave software is used to simulate and study the electromagnetic waves behavior in the proposed structure. To calculate the spectrum of the output power transmission the FDTD mesh size and time step used in this study is: $dx=dy=a/21$, $dt=dx/(2\times c)$, where c is speed of light in free space. The power transmission spectra are computed during 300 time step, 600*min* running time.



(a)

(b)

Fig. 4 Complete sketch of the triplexer based on cavity PhC structure. The radius of defects (r_{di}, i = 1,2,3) for filtering λ=1.31, 1.49 and 1.55μm are 0.143, 0.038 and 0.046μm, respectively (b) Schematic view of proposed non-optimized triplexer having *InP*/*InGaAsP* rods

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Fig. 5 shows the spectral characteristic of proposed triplexer for TM polarization of incident light. From this figure, it is clear that the proposed structure split the three telecommunication wavelengths but the maximum peaks obtained from channel C for 1.55μm is about 84%, and from channel A and B for 1.31 and 1.49μm obtained 72%, 96% respectively.

The transmission efficiency of channel A and C at 1.31 and 1.55μm is quite low. In order to improve transmission efficiency, as shown in Fig. 6 radius of defect in port C has to be modified by decreasing to 0.045μm. This optimization, increase the transmission efficiency of channel A, B and C for 1.31, 1.49 and 1.55μm to %99, %96 and %96 respectively. Finally, the transmitted spectrum of optimized structure is shown in Fig. 7.

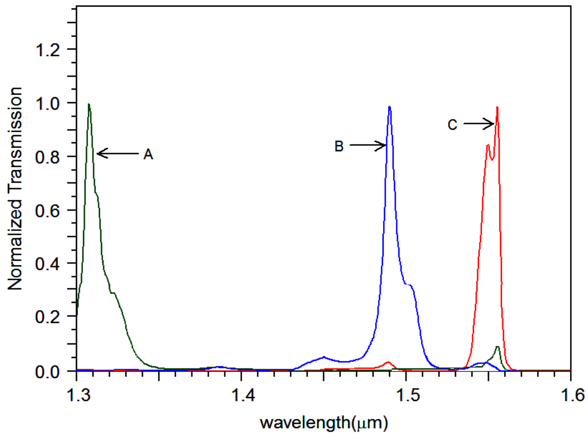

Figure 5. Normalized outputs Transmission for proposed triplexer in Fig. 4(a)

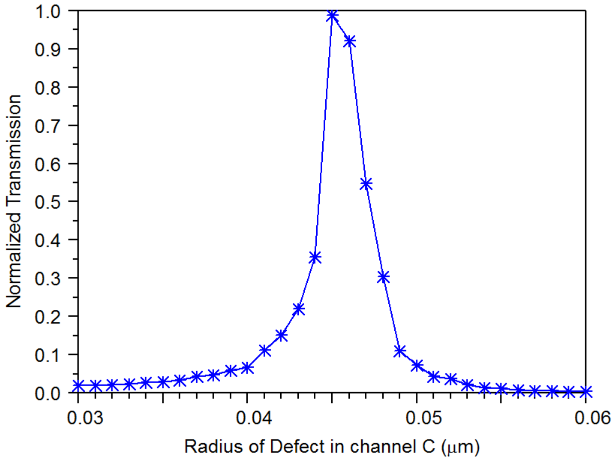

Figure 6. The normalized power transmitted to port C at resonance while r_d in port A is 0.143μm and in port B is 0.038μm.

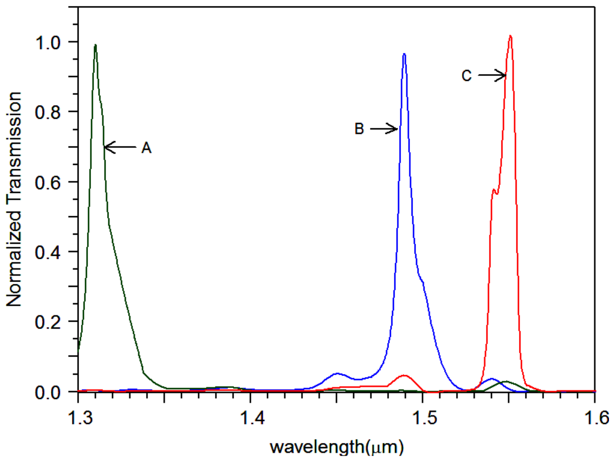

Figure 7. Normalized output transmission for modified triplexer for the three channels. (r_{di}, i = 1, 2, 3) for λ=1.31, 1.49 and 1.55μm are 143, 38 and 45*nm*, respectively.

Critical point in designing a triplexer device is crosstalk between three output channels. In this work, by optimization the radius of defect in port C the crosstalk of outputs decreases to appropriate amounts. Efficiency of this triplexer is confirmed by calculating its extinction ratio. For example ER_{AB} and ER_{BA} defined as [18]:

$ER_{AB}=10\log_{10}$ (Transmittance for 1.31μm obtained from Output A / Transmittance for 1.31μm obtained from Output B),

$ER_{BA}=10\log_{10}$ (Transmittance for 1.49μm obtained from Output B / Transmittance for 1.49μm obtained from Output A)

It is found to be ER_{AB}=23.14*dB*, ER_{AC}=23.93*dB* for 1.31μm, ER_{BA}=26.81*dB*, ER_{BC}=13.80*dB* for 1.49μm and ER_{CA}=21.37*dB*, ER_{CB}=13.80*dB* for 1.55μm. This extinction ratios shows that the proposed structure has satisfactory crosstalk among three outputs.

Crosstalk information from each port for the different wavelengths is written as following table:

Table 1: Output transmission of channels by optimization

Wavelength	***Port A (%)***	***Port B (%)***	***Port C (%)***
1310*nm*	99	0	0
1490*nm*	0	96	4
1550*nm*	4	0	96

4. Conclusions

In this paper, we have investigated a triplexer based on photonic crystal *InP/InGaAsP* pillars to split three communication wavelengths, 1.31, 1.49 and 1.55μm. Spectral characteristics of the probe structure reveal the excellent wavelength separation and transmission. Average transmission efficiency of the output channels is over 97%, the mean value of crosstalk is -19.42dB and the total size of the proposed optical triplexer is about 144μm^2 that is sufficiently for the application in photonic integrated circuits. The key features of the proposed device are densely and easily fabrication and integration. Therefore, the proposed optical triplexer is very convenient and useful for optical FTTH and WDM communication system.

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