Optik 122 (2011) 1481–1485

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

An ultra compact photonic crystal wavelength division demultiplexer using resonance cavities in a modified Y-branch structure

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ARTICLE INFO

Article history:
Received 5 September 2009
Accepted 7 May 2010

Keywords:
Defect
Y-branch
Cavity
Resonance
Crosstalk

ABSTRACT

An ultra small size 4-channel wavelength division demultiplexer based on 2D photonic crystal modified Y-Branch, suitable for integration, is proposed in this paper. The output wavelengths of designed structure can be tuned for communication applications (around 1550 nm) by choosing suitable defect parameters in the corner of each resonance cavity and output waveguides. The cross section of the structure is 313.28 μm^2 (17.8 $\mu m \times 17.6\ \mu m$) and desirable for integration based on popular planar technology. The bandwidth of each channel is near to 1 nm and the channel spacing is approximately 3.5 nm and wavelengths of demultiplexer channels are 1548.8 nm, 1551.9 nm, 1555.4 nm and 1559.3 nm respectively. Also, the crosstalk is between −33.1855 dB and −10.4947 dB. Furthermore, the mean values of the crosstalk and quality factor are −22.54 dB and 1496.7 respectively.

1. Introduction

Small size device design is ultra interesting for integrated circuit designer especially for all optical integrated circuits that is needed in metropolitan optical networks. This significant characteristic is limited by the poor confinement of light in a small space [1–4], thus photonic crystals (PhCs) are believed to defeat this restriction because of their periodically modulated refractive indices. By reviewing recent works in this field, great tendency has been found in PhCs due to their band gap properties [5–7]. This is controllable by some parameters of the structure such as dielectric constant of the used materials or radius of them and lattice constant of the structure [8]. Also, 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 [9].

One of the favorite wavelength selection methods has been proposed based on various defects such as point defects and line defects [10]. The effect of defects has been studied and shown that defects location and situation is very important parameter to control the wavelength of transmitted light beam [11,12]. By distinguishing the defect properties in waveguides, many optical devices such as optical filters [13,14], optical switches [15], multiplexers [16], demultiplexers [17,18] and PhC based beam splitters have been investigated [19]. But all of these devices have special limitations such as unsatisfactory quality factor (Q) of the interesting wavelength [20], efficiency of it [21] and other ones. One of the effective methods to compensate these shortages is using cavity resonance in the structures [22,23].

Resonant cavities in PhC structures improve the interaction of light due to inherent properties [24,25], so using of these phenomena is useful for designing of wavelength division demultiplexers that require powerful confinement of light. In addition, PhCs have enough ability to control light wave propagation through waveguides by using the resonant cavities [26]. Also, waveguides of each structure that is based on PhCs, play an important role in characteristics of them. The density of electromagnetic waves is changeable by controlling the properties of them, such as shape, length, width and angle, therefore, much effort has been devoted to studies of waveguides. Y-shaped waveguide in 2D photonic crystal structures that named as Y-branch is a candidate for light propagation in many studied works [27].

The direction of light propagation in Y-branch in two-dimensional PhCs is tunable. Using Y-branch structure, we can guide the incidence light beam in two separated directions. Thus this effect helps us for approaching optical demultiplexer idea. By modified Y-branch structure, we can create more paths for light propagation. In other words, the paths of demultiplexer can be selected easily by using Y-branch structures. These structures have been used in many optical devices, such as couplers [28], add-drop filters [29] and switches [30].

One of the most important components of the telecommunication systems is demultiplexer that separates desired wavelengths by defined central wavelengths and bandwidth in each output

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0030-4026/$ – see front matter © 2010 Published by Elsevier GmbH.
doi:10.1016/j.ijleo.2010.05.036

channel. In last decade researchers have paid much attention for designing demultiplexers and tried to find a suitable solution for their characteristics. Diffraction management, decreasing the size of structure, cancellation limitations in number of channels, decreasing crosstalk between channels and channel spacing between adjacent channels are the outlooks of designing.

In this work, we propose a novel structure for wavelength division demultiplexer that separates the desired wavelengths for communication applications. With combining modified Y-branch and resonance cavities in the special locations, we obtained a 4-channel wavelength division demultiplexer with approximately 3.5 nm channel spacing and the bandwidth of 1 nm for each channel. Also, the minimum value of crosstalk between channels is −33.1855 dB and the maximum value of it, is −10.4947 dB. In other words, the mean value of crosstalk is −22.54 dB. Finally, the quality factor (Q) for each channel is high in this work. The simulation results show all of these quantities that have been done in next sections and authenticate that the proposed structure has relatively high quality factor and low crosstalk and suitable for photonic crystal integrated circuit design.

2. Theoretical modeling and analysis

For extracting the properties of PhC devices, we need to employ some numerical methods to study and analyze them. The plane wave expansion (PWE) and multiple scattering theories are interesting methods on frequency domain for these structures [31]. The speed of computing in the above-mentioned methods is high, but the problem is just the confinement in calculating the stationary state. Another effective method for analysis of PhC structures is Finite Difference Time Domain (FDTD) that nowadays is a popular numerical solution method [32]. The FDTD is an accurate method for studying electromagnetic problems including the simulation of many PhC based devices. The FDTD is a powerful method for solving the Maxwell's equations in the time domain due to its simplicity. The Full-Wave software is used to simulate and study the electromagnetic waves behavior in the proposed structure.

In this paper, our target was designing a compact structure for wavelength division demultiplexer based on photonic crystals only. In other words, we like to reduce the designed chip size and other parameters such as crosstalk, channel spacing and bandwidth in comparison with previous works only by simple PhCs, without using any especial matter or complex geometry in the structure. Also, we like to increase the quality factor of channels and number of them in our structure. Thus, we model and analyze the proposed device structure to optimize above-mentioned parameters. This structure is composed of three layers, Sio_2–Si–Sio_2, in which 200 nm of Si slab has an 80 nm Sio_2 mask on top and a 1000 nm Sio_2 as the lower cladding on the top of a thick Si substrate. A 2D PhC with a hexagonal lattice is created inside the silicon layer with $R = 115$ nm radius air pores and $a = 420$ nm lattice constant. The dispersion curve is simulated and displayed in Fig. 1. The red lines determine allowed transverse electric (TE) modes. As we know, TE mode is defined as the mode in which light polarization is perpendicular to the air pore.

For the proposed structure, a photonic band gap (PBG) is found only for the TE polarization and displayed in the dark area. In other words, this proposed structure does not have PBG for transverse magnetic (TM) modes. Thus, all of simulations are done in TE mode.

It is shown that PBG is in the range of $0.251 < \omega a/2\pi c < 0.301$ or in other words $1395\ \text{nm} < \lambda < 1673\ \text{nm}$. This range shows that the proposed structure has capability to use in optical communication systems due to its desirable frequency range. For proving the fact that the resonance cavities in our structure are effective in the selected wavelengths of the demiltiplexer, in the initial stage,

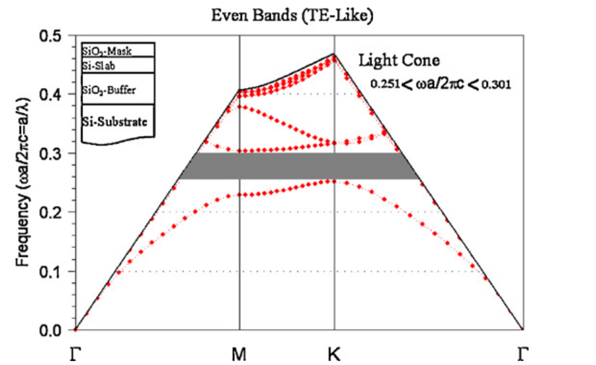

Fig. 1. Dispersion curve for PC with $R = 115$ nm and $a = 420$ nm excited by light with TE mode.

we consider a structure with a single resonance cavity as shown in Fig. 2.

The considered structure is organized from main three parts. First part that is named line defect contains an input waveguide that is created by removing several air pores. In second part, according to Fig. 2, in two upper rows, we create a resonance cavity. As shown in the above figure, this structure has a twin defect in the corners of resonance cavity and a single defect in output waveguide and has no defect in the input one. The cavity creation is done by removing four air pores and producing two defects in two corner sides of resonance cavity. Finally in third part, the structure has an output waveguide that contains a defect in the corner of it and its diameter defined as D_d that $R_d = D_d/2$. Thus, R_d is the radius of output waveguide defect and the quantity of it is 83 nm. The shift of wavelengths can be tuned by removing more or less number of air pores in the cavity. But, for realizing the telecommunication wavelengths, we removed just four air pores in the resonance cavity section. Another parameter that determines resonance wavelength in the resonance cavity is radius of introduced defects inside them. The diameter of defects defined as Dc_i and $Rc_i = Dc_i/2$. Thus Rc_i is the radius of defects in the cavity. Quantities of Rc_i are 98 nm, 93 nm, 88 nm and 83 nm respectively for various amounts of i from 1 to 4. The radius difference between defects is 5 nm, thus this structure is capable for manufacturing by nowadays technology.

After simulation of this structure, some interested phenomena have been shown. One of them is blue shift of the wavelengths

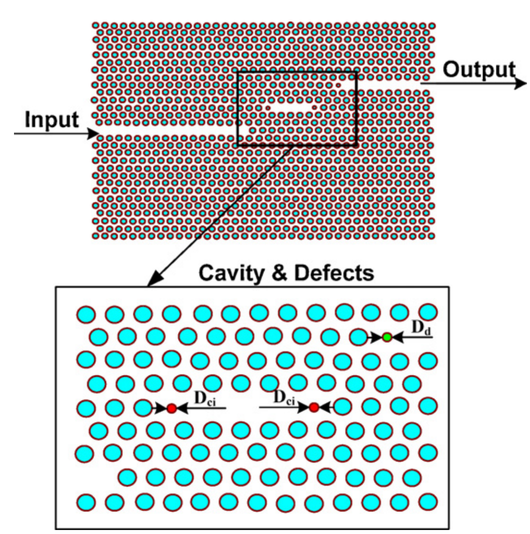

Fig. 2. A structure with a single resonance cavity, one input waveguide and one output waveguide accompanying with shown point defects.

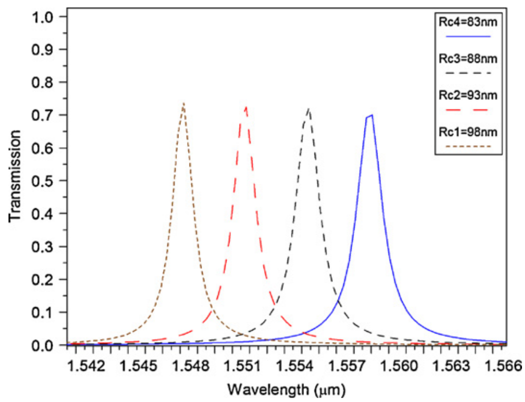

Fig. 3. The ratio of wavelength variations of the output waveguide due to various amounts of Dc_i in the resonance cavity.

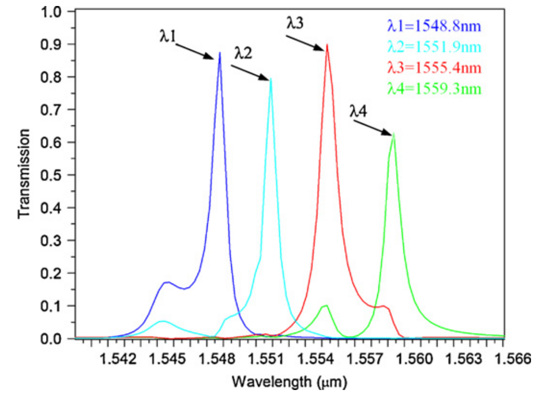

Fig. 5. Representation of the demultiplexer output channels at λ_1, λ_2, λ_3 and λ_4 wavelengths.

by increasing the radius of defects. This is due to decreasing of the cavity effective length. This characteristic is displayed in Fig. 3.

Based on the results illustrated in Fig. 3, with different defect radiuses in cavity (Rc_i) equal to 83 nm, 88 nm, 93 nm and 98 nm, we obtained wavelengths 1559.2 nm, 1555.4 nm, 1551.8 nm and 1548.6 nm, respectively and blue shift of the wavelength has been determined exactly in the figure. Final part that includes an output waveguide is produced by creating a line defect in two upper rows of resonant cavity. In first output waveguide, we introduced a defect (R_d) with radius of 83 nm.

The effects of this defect on the characteristic of the output are attractive, especially on efficiency and bandwidth. It should mention that with increasing the radius of defect the output intensity is reduced. Also, with decreasing the radius the bandwidth of the output channel decreases too. On the other hand, these defects are key parameters in the proposed structure for wavelength selection in demultiplexer.

Finally, the proposed structure for wavelength division demultiplexing is shown in Fig. 4. As shown in this figure, the structure consists of a modified Y-Branch and four cavities in the special locations near the arms of it.

Modification of the Y-Branch is due to the created waveguide in the middle of it as shown that is done in this work. This structure has an input in the left and four outputs in the right hand sides. The corner defects of each waveguide are same for all and radius of it is 83 nm and determined by R_d. As shown in Fig. 4, arrangement of each output channel is determined and named from top to bottom of the structure as output1, output4, output3 and output2 respectively. As we know, near of each output waveguide, there is a resonance cavity with a twin defect in the corner of cavity.

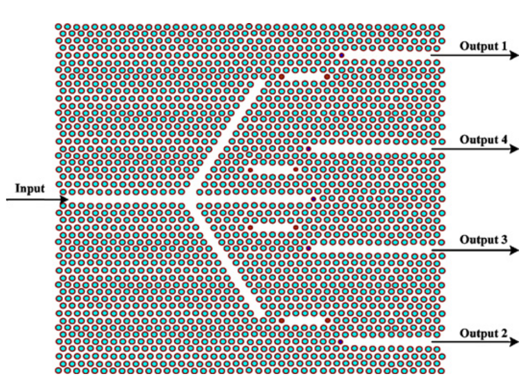

Fig. 4. Four channel demultiplexer based on modified Y-Branch structure.

The resonance cavities of output1, output2, output3 and output4 have twin defects in the corner of them and their radiuses are equal to Rc_1 = 98 nm, Rc_2 = 93 nm, Rc_3 = 88 nm and Rc_4 = 83 nm.

3. Simulation and results

We assigned an effective index of $N_{\text{eff}} = 2.8$ to the dielectric material in the PhC For 2D FDTD simulations. For design and simulation, we used FDTD for Full-Wave numerical simulation. Rigorous modeling of PC structures requires 3D calculations which are extremely time consuming. Effective index approximation of PCs has been used for satisfying this requirement by reducing the full 3D calculations to simpler, through approximate 2D calculations [33,34]. The perfectly matched layer (PML) boundary condition has been used because it gives high performance. We suppose 500 nm width of PML in the surround of the considered structure. The photonic device is composed of 49×43 air pores that lay in the x–z plane. The light propagates in the z direction. The structure is excited with TE polarization. The space steps in the x and z directions are Δx and Δz. The FDTD mesh size used in simulation is $a/20$, and in this work, we take $\Delta x = \Delta z = a/20 = 21$ nm, where a, is the lattice constant. The sampling time is selected to ensure numerical stability of the algorithm. The time step for 2D structure is determined by

$$\Delta t \leq \frac{1}{C\sqrt{(1/\Delta x^2) + (1/\Delta z^2)}}, \quad (1)$$

where C is the speed of light in free space.

Fig. 4 shows the final structure which has been designed for demultiplexing four wavelengths. According to previous part explanations, we used four cavities with different defect radiuses in four suitable places to select four different wavelengths. We placed cavities beside the arms of Y-Branch and near output waveguides to have higher interaction between incident light, cavities and output waveguides. Therefore it leads to higher efficiency.

In simulation process, estimated time was equal to 1382.366 min and the estimated memory was 73.4 MB. After simulation during 30,000 time steps for final structure, we obtained λ_1 = 1548.8 nm in output1, λ_2 = 1551.9 nm in output2, λ_3 = 1555.4 nm in output3 and λ_4 = 1559.3 nm in output4, respectively. These output wavelengths are shown in Fig. 5.

As shown in this figure, the maximum efficiency is 90% for output3 and the minimum is approximately 63% for output4. Amount of efficiency for output1 is 88% and for output2 is 80%. Consequently, the proposed structure has a good efficiency with comparing by the others. Another parameter in wavelength division demultiplexer that effects on the resolution of it, is quality

Table 1
Simulation results of wavelength division demultiplexer.

Demultiplexer outputs	Defect size (Rc_i)	λ_0	$\Delta\lambda$	Q	Efficiency amount
1	98 nm	1548.8 nm	1 nm	1548.8	88%
2	93 nm	1551.9 nm	0.9 nm	1724.3	80%
3	88 nm	1555.4 nm	1.2 nm	1296.2	90%
4	83 nm	1559.3 nm	1.1 nm	1417.5	63%

Table 2
Crosstalk amounts of the proposed structure in dB.

Output	1	2	3	4
1	–	$Xt_{12} = -15.76$ dB	$Xt_{13} = -25.97$ dB	$Xt_{14} = -28.42$ dB
2	$Xt_{21} = -20.37$ dB	–	$Xt_{23} = -19.36$ dB	$Xt_{24} = -22.86$ dB
3	$Xt_{31} = -31.61$ dB	$Xt_{32} = -24.11$ dB	–	$Xt_{34} = -10.49$ dB
4	$Xt_{41} = -33.18$ dB	$Xt_{42} = -26.99$ dB	$Xt_{43} = -11.32$ dB	–

factor (Q) and as we known can be calculated with the following relation

$$Q = \frac{\lambda_0}{\Delta\lambda}, \tag{2}$$

where λ_0 is central wavelength and $\Delta\lambda$ is the full width at half power of output. This structure is a narrowband demultiplexer because of its narrow bandwidths. The amounts of them for outputs 1, 2, 3 and 4 are 1 nm, 0.9 nm, 1.2 nm and 1.1 nm respectively. As shown in this relation if $\Delta\lambda$ decreases, Q increases to high amounts and vice versa. The amounts of Q in this structure is different due to various values of $\Delta\lambda$, for output1, $Q_1 = 1548.8$, for output2, $Q_2 = 1724.3$, for output3, $Q_3 = 1296.2$ and for output4, $Q_4 = 1417.5$. As the results show, this structure has very good quality factor and it is a good performance. Channel spacing (CS) between adjacent channels is shown in Fig. 5 and named as CS_{ij} that i and j indicate outputs and vary from 1 to 4. As shown in this figure, CS_{12} is 3.1 nm, CS_{23} is 3.5 nm and CS_{34} is 3.9 nm. All of these results are shown in Table 1.

Another challenge and critical point in wavelength division demultiplexer designing is crosstalk. When crosstalk decreases, the resolution of demultiplexer increases. In this work, we can decrease the crosstalk of outputs and optimize them to suitable amounts. In Table 2, we show that the proposed structure has very acceptable crosstalk between outputs. This is a main distinction for our proposed structure.

As shown in Table 2 the proposed structure has attractive amounts of crosstalk. In other words, this structure has a high resolution to select desirable wavelengths. In this table, we named crosstalk as Xt_{ij}, which i and j vary from 1 to 4. Xt_{ij} shows the crosstalk between output i and output j and Xt_{ji} means vice versa. For example, Xt_{12} shows the amount of crosstalk between output1 and output2; also Xt_{21} shows the amount of crosstalk between output2 and output1. Consequently, this structure is suitable for high resolution applications in telecommunication systems.

4. Conclusion

In this work, we designed a wavelength division demultiplexer based on PhC structures. The modified Y-Branch is used to separate wavelengths to miscellaneous paths. Also, by using resonance cavities and tuning the amounts of defects in them, selection of desired wavelengths is possible. In this paper, we obtained an ultra compact device that has four output channels. The bandwidth of each channel is near to 1 nm, also the structure has high quality factor, approximately high efficiency and very low crosstalk that suitable for communication applications. One of the main properties of this structure is its ability to integrating due to ultra low cross section. Also, tuning of this structure is suitable by changing the amounts of the defects in resonance cavities for select the desired wavelengths.

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