Wavelength Division Demultiplexer for Optical Communication Applications Based on Photonic Crystals

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Abstract

We propose a novel structure to separate the desired wavelengths for optical communication applications by introducing resonance cavity in the 2D photonic crystal structure. We know that with considering cavity type and alignment of the suitable defects, resonance wavelength can be tuned. Therefore, we design and simulate the desired cavities based on photonic crystal to separate two wavelengths with 5.8 nm channel spacing, 12.7dB crosstalk, acceptable quality factor and efficiency. Also this structure can be fabricated and integrated easily based on planar technology. All Simulation results are based on Finite Difference Time Domain (FDTD) method. Due to its very small cross section, the proposed structure is suitable candidate for very large scale integrated circuits in full optical systems.

Key words: Demultiplexer, Communication, Wavelength, Photonic Crystal, FDTD

1. Introduction

Photonic crystals (PCs) are artificial dielectric or metallic structures in which the refractive index modulation gives rise to stop bands for optical waves within a certain frequency [1]. PCs are now privileged due to their intrinsic ability in light controlling for the design of new devices [2]. Many optical devices based on PC structures, have been submitted, such as optical filters [3], power splitters [4], optical switches [5, 6], optical circulators [7] and light couplers [8]. Also PC structures can be applied as optical filters into Wavelength Division Multiplexers (WDM).

In WDM and Dense Wavelength Division Multiplexers (DWDM) communication systems, photonic crystal based narrow band optical filters for channel extraction are used. Waveguide based filters which utilize coupling between two closely spaced waveguides [9], Heterostructure that use photonic crystal ring resonator [10], structure that use several defects to trap arbitrary different wavelengths in a line defect waveguide [11], tunable channel filter that is modulated by electro optic in birefringence material [12], and negative refractive index super-prism based filters [13, 14] are some of the examples which have recently been used to achieve PC based wavelength demultiplexing. In these researches all tries have been led to obtain demultiplexers that able to select different wavelengths with ultra narrow band width, high resolution and optimum efficiency. On the other hand, high quality factor (Q), low channel spacing and high efficiency are the specific and desired characteristics.

In this paper, we propose a novel structure based on resonance cavity designed by 2D photonic crystal to demultiplex wavelengths for telecommunication network purposes. Photonic crystal cavities have special properties. One of the important characteristics of them is their ability to confine light and trap particular wavelengths strongly. This main property cause researchers apply them in their proposed structures for demultiplexers. There are some applications in engineering tasks, such as ultra-small filters [15], low-threshold lasers [16], photonic integrated circuits [17], nonlinear optic switches [18] in which photonic crystal cavities can be used. The major critical point for use of these cavities is that, we can't simultaneously realize both high quality factor (Q) and small modal volume (V).

In other words, the ratio Q/V shows the strength of the various cavity interactions, and an ultra-small cavity enables large-scale integration. Also, we know that the fabrication of high-Q cavity is so difficult for optical wavelength ranges.

In this work, by replacing cavities in suitable situations and correctly adjusting size and situation of the defects, we obtained demultiplexer with two channels with 5.8 nm channel spacing and 12.7dB crosstalk. The quantity of Q is 777 for first wavelength and 1114 for the other one. The simulation result show several privileges such as low channel spacing, low cross talk, tolerable quality factor and integrated fabrication capability.

2. Theoretical Modeling and Analysis

There are many numerical methods to study and analyze the properties of 2D PCs devices. The plane wave expansion (PWE) [19] and multiple scattering [20] are desired methods on frequency domain. The important privileges of above methods were the high computing speed, but problem was the confinement in calculating the stationary state only. The other one of popular numerical solution methods for analysis of PCs is finite-difference time-domain (FDTD) [21]. The FDTD is an accurate method for studying electromagnetic problems including the simulation of many PCs-based devices. The FDTD method is a powerful method for solving the Maxwell's equations in the time domain, because of its simplicity. The Full-Wave software is used to simulate and study the electromagnetic wave behavior in the proposed structure.

We modeled and analyzed the proposed device structure to optimize for low channel spacing wavelength. This structure is composed of three layers, Sio_2-Si-Sio_2, in which 200 nm of Si slab has a 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 PC 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. The 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 for the TE polarization only and displayed in the dark area. It is shown that PBG is between $0.251 < \frac{wa}{2\pi c} < 0.301$ or $1395nm < \lambda < 1673nm$.

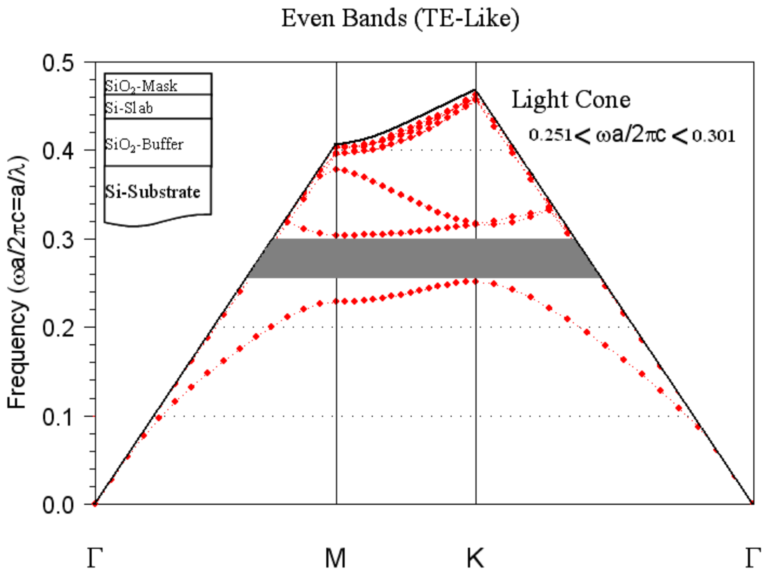

Fig 1: Dispersion curve for PC with R=115 nm and a= 420 nm excited by light with TE mode.

First of all, we consider a structure with a single resonance cavity that is shown in Fig 2.

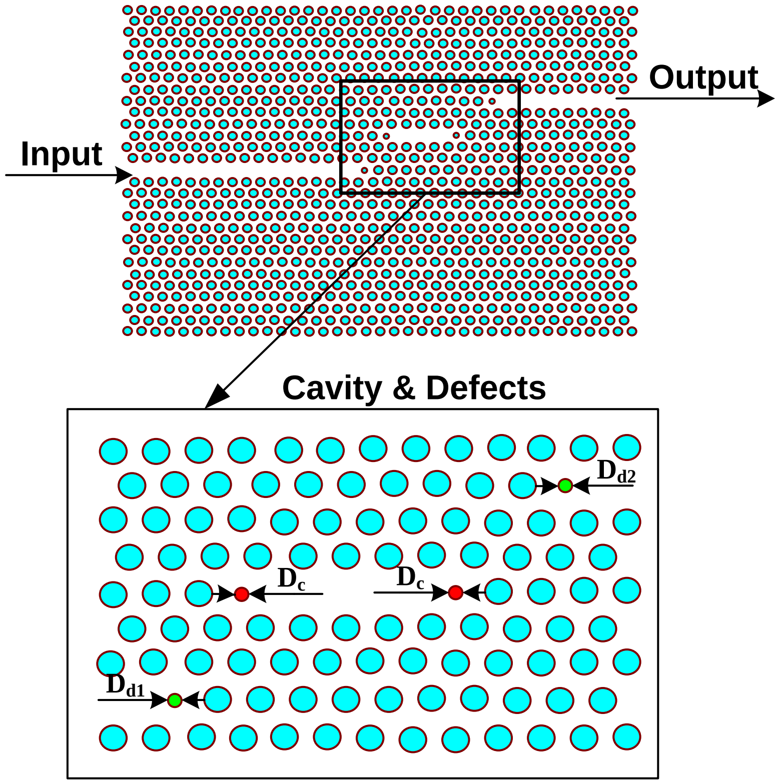

Fig 2: Structure with a single resonance cavity (D_{d1}=D_{d2}).

Considered structure is composed of three parts. First part includes an input waveguide that yields by removing several air pores. In the end of input waveguide, we introduce a defect with small radius of air pore compared with other lattice elements ($R_{d1}=D_{d1}/2$). In second part, according to Fig 2, in two upper rows, we create a resonance cavity. This work is done by removing five air pores and producing two defects in two corner sides of resonance cavity ($R_C=D_C/2$). The shift of wavelengths can be achieved by removing more or less number of air pores. But for realizing the telecommunication wavelengths, we removed just five air pores in this structure. The second parameter that determines resonance wavelength in resonance cavity, is radius of introduced defects. Increasing defect radius results to blue shift resonance wavelength because of decrease in cavity length. This characteristic is displayed in Fig 3. According to Fig. 3 with different defect radiuses in cavity equal to 76 nm, 83 nm, 90 nm, we obtained wavelengths 1564.5 nm, 1559.3 nm and 1553.5 nm, respectively. Final part that includes an output waveguide is produced by removing several air pores in two upper rows of resonant cavity. In incidence of output waveguide, we introduced a defect with small air pore radius ($R_{d2}=D_{d2}/2$).

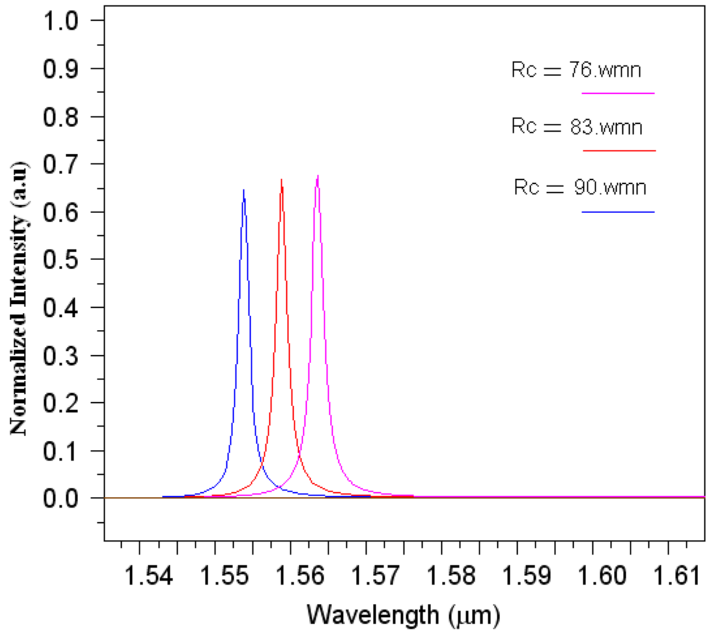

Fig 3: Different wavelengths selection with change the radius of defects in cavity (1564.5 nm, 1559.3 nm and 1553.5 nm for defect radiuses 76 nm, 83 nm and 90 nm respectively)

Two defects in the end of input waveguide and the start of output waveguide play two vital roles in efficiency and band wide of output. If they aren't same or their radiuses are relatively larger in comparison with radius of structure(R), output power will be weak. Also with decreasing their radius, cause to decrease in band width of output. On the other hand it is key parameter to control optical characteristics of output.

3. Simulation and Results

In design and simulation, we used FDTD for Full-Wave numerical simulation. For 2D FDTD simulations, we assigned an effective index of $N_{eff} = 2.8$ to the dielectric material in the PC. 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 [22]. The perfectly matched layer (PML) boundary condition [21] has been used because it gives high performance. We suppose 500nm width of PML in the surround of the considered structure. The photonic device is composed of 29×37 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=0.021 nm, where a, is the lattice constant. The sampling time is selected to ensure numerical stability of the algorithm [21]. The time step for 2D structure is determined by:

$$\Delta t \le \frac{1}{c.\sqrt{\frac{1}{\Delta x^2}+\frac{1}{\Delta z^2}}} \qquad (1)$$

where C is the speed of light in free space. Fig 4 shows the final structure which has been designed for demultiplexing two wavelengths. According to previous part explanations, we used two cavities with difference defect radius in two suitable places to select two different wavelengths.

We placed cavities in front of input waveguide to have higher interaction between incident light and cavities. Therefore it leads to higher efficiency.

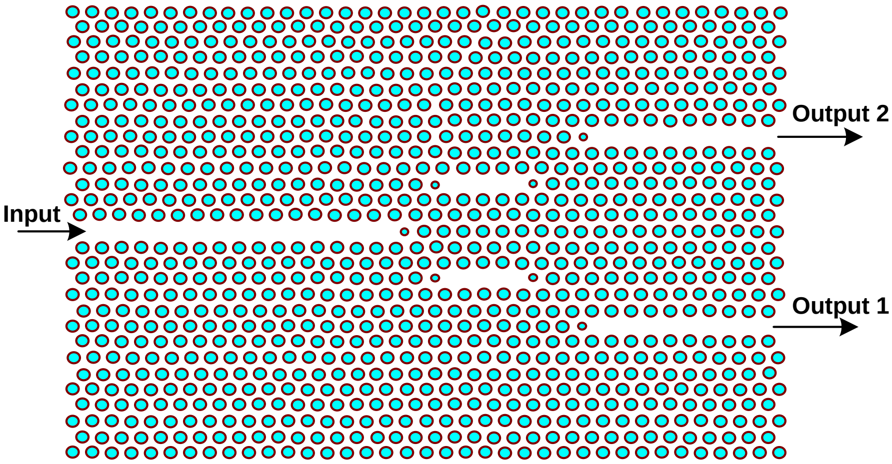

Fig 4: Final proposed structure for two wavelengths division demultiplexing

We choose radiuses of defects in input and output waveguides equal to R_{d1}=R_{d2}=83 nm and in top and bottom cavities equal to R_{tc}=83 nm and R_{bc}=90 nm, respectively.

Then, we simulated during 30,000 time steps equal to 1374mins run time for final structure.

We obtained $\lambda_1 = 1.5535\mu m$ and $\lambda_2 = 1.5593\mu m$ with 54.5% and 56% efficiency, respectively. Simulation result is shown in Fig 5.

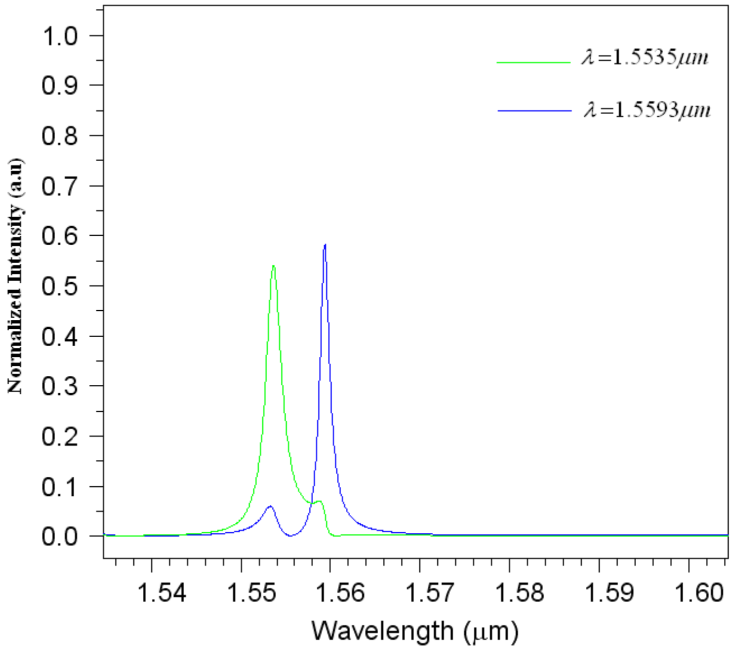

Fig 5: Final structure output with align radiuses of defects equal to R_{d1}=R_{d2}=83 nm, R_{tc}=83 nm and R_{bc}=90 nm.

Quality factor (Q) for demultiplexers can be calculated with:

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

Where λ_0 is the central wavelength and $\Delta\lambda$ is the full width at half power of output. The quality factor in proposed structure for the first and second outputs are equal to 777 and 1114, respectively. In the other side, cross talks of two outputs are 12.7 dB. As shown in Fig 5, channel spacing is equal to 5.8 nm that is changed with varius radiuses of defects in cavities. We simulated in several different states and got their results in the Table 1.

R_{d1} (nm)	R_{d2} (nm)	R_{tc} (nm)	R_{bc} (nm)	Port 1 (nm)	Port 2 (nm)	Cross talk 1 (dB)	Cross talk 2 (dB)	Q_1	Q_2
75	75	80	90	1553.5	1561	14.3	14.8	777	781
75	75	85	90	1553.5	1558	10.7	10.9	777	1298
85	85	80	90	1553.5	1561	14.3	15.3	913	975
85	85	80	85	1557	1561	10.6	10.9	741	1300
83	83	83	90	1553.5	1559.3	12.7	12.7	777	1114

Table 1. Simulation results for different radius of defects in cavities and waveguides

According to Table 1, increasing the difference of radius of defects in two cavities cause to increase in channel spacing and decrease the cross talk.

5. Conclusions

In this paper, we tried to approach a demultiplexer for DWDM communication systems. We used a structure that is capable to be integrated and fabricated. According to the resonance cavity characteristics which can be demultiplexe different wavelengths by regulating the length of cavity and radius of defects in it, this structure can separates two wavelengths with 5.8 nm channel spacing. The other properties of the proposed structure are low crosstalk and tolerable efficiency.

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