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Novel Four-Channel All Optical Demultiplexer Based on Square PhCRR for Using WDM Applications

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Abstract: Ring resonators have always been referred to as a highly flexible structure for designing optical devices. In this study, we have designed and simulation a four channel optical demultiplexer using square photonic crystal ring resonator. The square lattice constant for this purpose structure is used. The purposed structure has an average crosstalk, transmission coefficient, quality factor and channel spacing of -14.5 dB, 90%, 858 and 1.6 nm, respectively. To obtain the photonic band gap of the structure, the plane wave expansion (PWE) method has been used and the finite-difference time-domain (FDTD) method has been also used to analyze the optical behavior of the structure. The good results obtained from designing and simulating optical demultiplexer structure such as narrower channel spacing indicate the high flexibility of this structure and ring resonator for being used in designing optical devices as well as their suitability for being used in wavelength division multiplexing (WDM) systems.

Keywords: Photonic Crystal, Ring Resonator, Demultiplexer, Wavelength Division Multiplexing (WDM), Plane Wave Expansion (PWE), Finite-Difference Time-Domain (FDTD).

1. INTRODUCTION

Today, in telecommunication field, photonic crystal (PhC) based optical devices are used for tremendous applications, as the overall size is diminished into nanometer range. Typically, PhC has nano periodic structure that controls the motion of photons while propagating inside the structure [1]. The most important feature that reveals the practical significance of PhCs is the photonic band gap (PBG) [2, 3]. The guided light can be controlled fully by this feature. To control the light in PhCs, the intra-structure defects can be used. By creating appropriate defects, different optical devices based on the PhCs can be

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developed.

Each of these structures has been designed by using point and line defects, cavity, or ring resonators. The use of ring resonators has been highly considered due to their high flexibility in size, design and structural parameters. This flexibility is due to the existence of inner rods, scattering rods, and coupling rods within the structure of ring resonators [4]. The type of ring resonators used in designing optical devices based on PhCs, especially optical demultiplexer, is considered as an important factor for the design, which can be very effective in the final operating results of the structure. Today, various optical devices have been designed and manufactured using the above mentioned features of photonic crystal ring resonators (PhCRR). Optical splitters [5], optical fibers [6], optical add/drop filters [7-11], optical multiplexer/demultiplexer [12-14], optical logic gates [15, 16], and optical sensors [17], are some of these devices. Among the aforementioned devices, PhCRRs based demultiplexers have received considerable attention due to their interesting characteristics, such as the low loss of the incorporated optical waveguide when coupled with the resonator, low nonlinear effects and high quality factor and transmission coefficients [18-21].

In this paper, by a square PhCRR, a new demultiplexer for using in wavelength division multiplexing (WDM) is designed. The proposed structure have very good results. Low channel spacing along with a narrow bandwidth has made the structures very suitable to be used in WDM systems. To design the proposed structures, the plane wave expansion (PWE) method has been used to extract and analyze the limits of the PBGs of the structure, and to simulate and analyze the proposed structure, the two-dimensional finite difference time domain (2D-FDTD) numerical method has been used.

This paper is formed as follows. In Section 2, the analysis method is described. Section 3 and 4, focuses on the band gap structure and designing of the proposed optical demultiplexer, respectively. In Section 5, the simulation and results are presented and discussed, and finally, the conclusions are presented in Section 6.

2. ANALYSIS METHOED

There are various numerical methods to analyze the photonic band gap, as well as to study the normalized output spectrum in periodic photonic crystal structures. In general, numerical methods are divided into two main categories: 1. Frequency domain such as PWE and 2. Time domain ones such as FDTD.

The PWE method is one of the methods based on frequency analysis. Generally PWE method refers to a computational technique in electromagnetics to solve the Maxwell's equations by formulating an eigenvalue problem out of the equation. This method is popular among the photonic crystal community as a method of solving for the band structure (dispersion relation) of specific photonic crystal geometries. PWE is traceable to the analytical formulations, and is useful in calculating modal solutions of Maxwell's equations over an inhomogeneous or periodic geometry. It is specifically tuned to solve problems in a time-harmonic forms, with non-dispersive media. PWE method are rigorous solutions. PWE is extremely well suited to the modal solution problem. Large size problems can be solved using iterative techniques like conjugate gradient method. For both generalized and normal eigen value problems, just a few band-index plots in the band-structure diagrams are required, usually lying on the brillouin zone edges. This corresponds to eigen modes solutions using iterative techniques, as opposed to diagonalization of the entire matrix.

The PWE is highly efficient for calculating modes in periodic dielectric structures. Being a Fourier space method, it suffers from the Gibbs phenomenon and slow convergence in some configuration when fast Fourier factorization is not used. It is the method of choice for calculating the band structure of photonic crystals. It is not easy to understand at first, but it is easy to implement. The main advantage of this method is that it produces directly the frequency stop bands, and there is no need to convert the time domain and frequency domain to each other. The disadvantage of this method is that, in addition to being an approximation method, it is not suitable for finite and aperiodic structures [22].

The FDTD method is applied extensively using precise meshing as a general and flexible method for analyzing arbitrary structures. The basis of these methods is the discretization of the equations describing electromagnetic fields in a finite area by field approximation in general with the Taylor series. Today, this method is used as a major method in PhC calculations and due to being ideal for parallel processing; the time needed to perform calculations can be greatly reduced [23].

The starting point for any FDTD solver is the time-derivative parts of Maxwell's equations, which in their simplest form can be written:

$$\frac{\partial B}{\partial t} = -\nabla \times E - \boldsymbol{J}_B \tag{1}$$

$$\frac{\partial B}{\partial t} = +\nabla \times H - \boldsymbol{J} \tag{2}$$

where (respectively) **E** and **H** are the macroscopic electric and magnetic fields, **D** and **B** are the electric displacement and magnetic induction fields, **J** is the electric-charge current density, and $\mathbf{J}_B$ is a fictitious magnetic-charge current density (sometimes convenient in calculations, e.g. for magnetic-dipole sources). In time-domain calculations, one typically solves the initial-value problem where the fields and currents are zero for $t < 0$, and then nonzero values evolve in response to some currents $\mathbf{J}(\mathbf{x}, t)$ and/or $\mathbf{J}_B(\mathbf{x}, t)$ [24].

3. BAND GAP STRUCTURE

To design the given demultiplexer, a 2D-PhC structure with a square lattice constant (a) of 630 nm has been used. In the 2D-PhC structure, 59 × 21 dielectric rods with a refractive index of 3.9 wich for our structure is concerned, there are high-refractive index composite materials for enabling THz optical components [21], and a radius (R) of 106 nm have been placed in an air background. Prior to creating any defect in the PhC structure, the PBG has been extracted to examine the permissible and functional ranges used in telecommunication areas. The PWE method has been used to calculate PBG of the structure. As shown in Fig. 1, the structure has had 2 PBG frequency ranges in TM modes. According to this figure, the frequency range have been equal to $0.265 \leq a/\lambda \leq 0.429$ and $0.692 \leq a/\lambda \leq 0.729$, which have been equal to the wavelength range of 1468 nm $\leq \lambda \leq$ 2377 nm and 864 nm $\leq \lambda \leq$ 910 nm, respectively. Among the PBG frequency ranges, TM modes has been considered suitable to be used for designing telecommunication devices because it covers a wide range of telecommunication wavelengths.

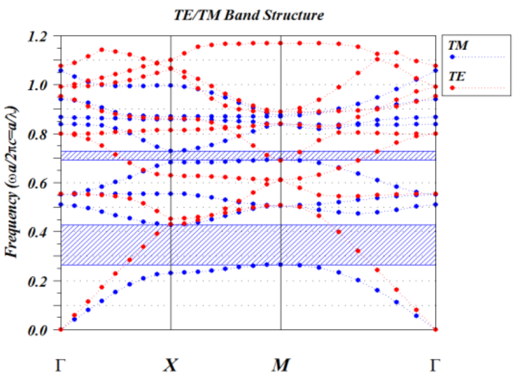

Fig. 1. Band structure of the proposed structure.

4. DEMULTIPLEXER DESIGN

The proposed demultiplexer is designed through eliminating some of the dielectric rods and using four square ring resonators for the purpose of filtering the proposed wavelengths. The general schematic of the ring resonators used in the structure is shown in Fig. 2. To improve the wavelength selectivity, we have introduced four scattering rods for each ring resonator [25]. The structure has one input port and 4 output ports for obtaining the wavelength of the corresponding telecommunication channels. Moreover, to have a better control over the wavelength selectivity of the rings, we have introduced other defects in the square rings, having rods with diameter larger than that of the outer rods [25]. The proposed four channel demultiplexer is shown in Fig. 3. The radii of the inner rods equal to Ri1 = 182 nm, Ri2 = 185 nm, Ri3 = 188 nm and Ri4 = 191 nm, for the first, second, third, and fourth channels, respectively.

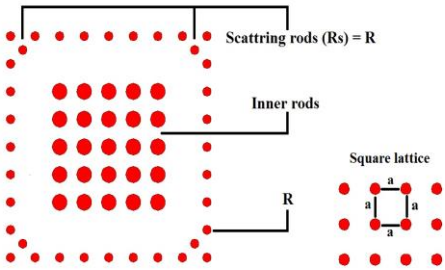

Fig. 2. Proposed of new ring resonator.

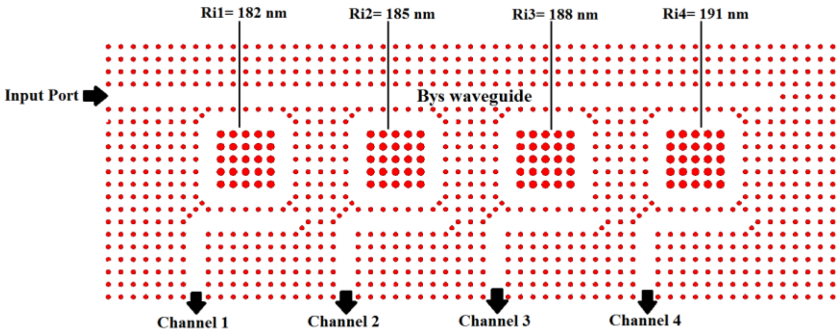

Fig. 3. Proposed of four channel optical demultiplexer.

5. SIMULATION RESULT

For accurate modeling of the optical demultiplexer, we need 3D simulation, but this requires a great amount of computational time. Subsequently, we have used the effective index approximation method of PhCs and with this approximation, we have used 2D rather that 3D simulations [20]. Also the 2D-FDTD method requires careful meshing and time calculations. The meshing size of the structure is Δx=Δz=a/16 which equals Δx=Δz=39 nm, based on the lattice constant a=630 nm. According to formula (1).

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

The time step for calculations equals 0.024, where c denotes the speed of light in the free space.

As shown in Fig. 4, the proposed structure is able to isolate the wavelengths of 1555.8, 1558.2, 1560 and 1561.6 nm by the first, second, third and fourth channel, respectively. The exact values of the transmission coefficient, the quality factor and the spectral width of each channel are listed in Table 1. According to this table, the average values for the transmission coefficient is 90% and the average values for the quality factor is 858. To better understand how the above mentioned wavelengths are isolated by the proposed demultiplexer, Fig. 5 is presented, according to which, light waves with wavelength of 1555.8 nm exit from channel 1 and with wavelength of 1560 nm exit from channel 3. The crosstalk values are presented in Table 2. It can be seen that the average values of crosstalk is -14.5 dB. (For more information, the definition of their parameters are given in Table 3)

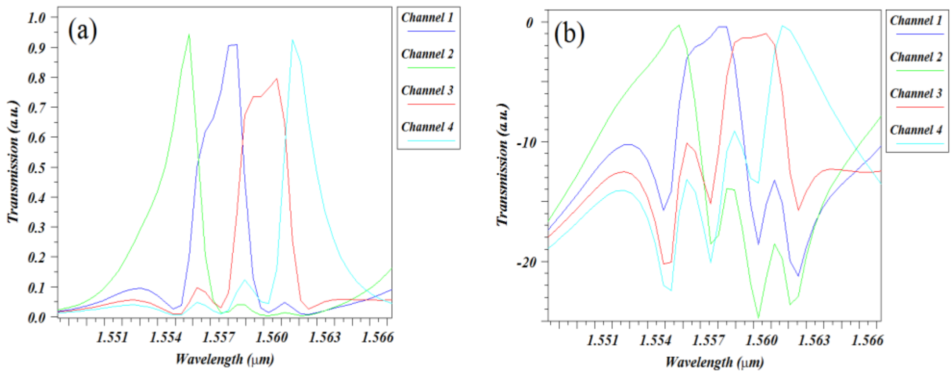

Fig. 4. Output spectra of the proposed demultiplexer, (a) Linear and (b) dB scales.

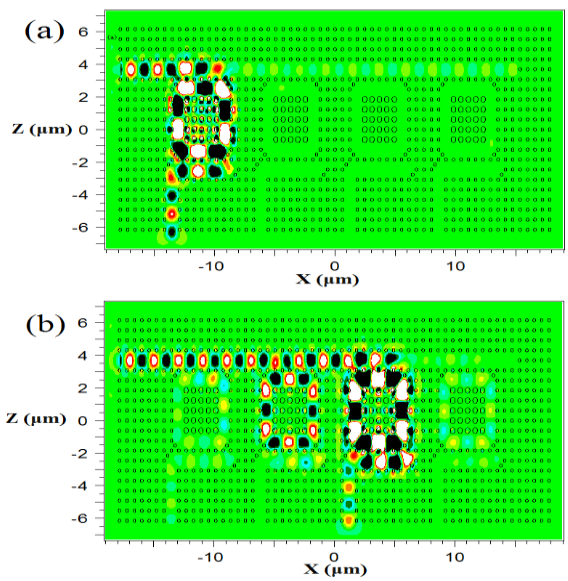

Fig. 5. Distribution of the optical power at (a) λ = 1555.8 nm and (b) λ = 1560 nm.

Table 1. Simulation results of the proposed demultiplexer.

Channel	Wavelength (nm)	spectral width (nm)	Transmission (%)	Quality factor
Channel 1	1555.8	2.1	94.5	741
Channel 2	1558.2	1.8	91	766
Channel 3	1560	2.5	80	624
Channel 3	1561.6	1.2	92.5	1301

Table 2. Crosstalk values of the proposed demultiplexer (dB).

Channel	Channel 1	Channel 2	Channel 3	Channel 4
Channel 1	*	-7.2	-13.3	-16.2
Channel 2	-17	*	-9.5	-15.2
Channel 3	-23.1	-16.7	*	-13.1
Channel 3	-19.6	-15	-5.5	*

Table 3. The definition of parameters.

Parameter	Definition
Transmission coefficient	The transmission coefficient is a measure of how much of an electromagnetic wave (light) passes through a surface or an optical element.
Bandwidth or spectral width	Bandwidth is the difference between the upper and lower frequencies in a continuous band of frequencies.
Quality factor or Q.F	The quality factor describes how underdamped an oscillator or resonator is and characterizes a resonator's bandwidth relative to its center frequency.
Crosstalk	Crosstalk is a phenomenon by which a signal transmitted on one circuit or channel of a transmission system creates an undesired effect in another circuit or channel.
Chanel spacing	The channel spacing is the distance between the two communication channels.

To compare the proposed structure with other reported structures, Table 4 is presented. In this table, transmission coefficient, quality factor, channel spacing and the crosstalk are compared.

Table 4. Comparison between different parameters of the proposed optical demuliplexer with other ones.

Reference	Number of channel	Channel spacing	Transmission (%)	Quality factor	Crosstalk (dB)
Our structure	4	1.6	90	858	-14.5
[12]	3	8	90	608	-29
[13]	3	6.8	95	567	***
[14]	4	3	53	1224	-15
[20]	4	3.13	96	1224	-24
[21]	4	2	95	1942	-18

According to the above table, our four channel demultiplexer has a narrower channel spacing when compared to the reported structures, so it is much more suitable for WDM systems. Our structure has also appropriate transmission coefficient, quality factor and crosstalk values, while previously reported demultiplexers have some restrictions to all or some of the above mentioned parameters.

6. CONCLUSION

In this study, a four channel optical demultiplexer is proposed based on PhCRR. This structure has an average quality factor and transmission coefficient above 858 and 90%, respectively. Also, the average crosstalk is -14.5 dB. In addition to having suitable transmission coefficient and quality factor, this structure has a channel spacing of 1.6 nm, which is much narrower than those of the previously reported structures. Hence, it is highly suitable to be used in WDM application. The proposed structure has also a simple design.

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