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A new design of tunable four-port wavelength demultiplexer by photonic crystal ring resonators

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ABSTRACT

A four-channel wavelength demultiplexer based on photonic crystal ring resonators (PCRR), which can be used for photonic integrated circuits, is designed. Dropping efficiency and Q factor of single improved ring are 100% and 842, respectively. In order to achieve the structure of demultiplexer, three improved rings have been used, that every ring has an individual inner rod radius; it means that each ring has a varying resonant wavelength. The results of simulation using finite-difference time-domain (FDTD) method in our proposed structure reveals an average transmitted power higher than 90% for each output port, Channel spacing is about 8 nm and bandwidth for each individual channel is about 2.8 nm. The mean value of the crosstalk between output channels and the area of the proposed structure are about −29 dB and 317 μm^2, respectively. By changing the radius of inner rods, various wavelengths can be chosen, therefore this device is tunable.

1. Introduction

On account of features like electromagnetic wave emission controllability, compactness, high rate of performance speed and long life period and property for integrating on optical circuit, the photonic crystals (PhCs) has been used for designing optical devices since 1978. In 1978 Yablonovitch [1] and John [2] first proposed the idea that periodic dielectric structures are able to provide photonic band gap (PBG) for distinct regions in the frequency spectrum, just like that of electronic band gap (EBG) in solid-state crystals behavior. PhC is a structure in which the optical refractive index shows a periodic modulation with a lattice constant in wavelength performance. The most important feature of photonic crystals is PBG. PBG intercepts the propagation of waves in distinct direction with specific frequency in the structure, i.e. there is no allowed mode [1–3]. By making controlled defects, the PhCs have been used for several purposes. Defects conclude designable attributes and features with a specific usage. The allowed modes that appeared in PBG make possible the propagation of wavelength in the structure [4].

Up to now, many optical devices have been designed based on photonic crystals such as optical switches [5,6], filters [7,8], beam splitters [9] and wavelength demultiplexers [10]. These devices are being used mainly in optical communication systems, like a wavelength Division multiplexing (WDM) system. As an essential element of such systems, wavelength demultiplexer is being used for selecting a channel with a specific wavelength.

Among the main characteristics of demultiplexers for the optical communication systems are features like polarization independent, low crosstalk, high spectral resolution and compactness [11]. So far, several topologies have been proposed for wavelength demultiplexers, such as using line defect PhC waveguides [11,12], coupled cavity PhC waveguides [13,14], directional coupling [15,16] and ring resonators [17,18]. The ring resonators which are coupled to the waveguides can be used as frequency selecting devices. Ring resonators in a specific frequency, which is the ring resonant wavelength, localize electromagnetic energy from an input waveguide into the ring and then transmit it to drop waveguide. The ring resonators play an important role in wavelength demultiplexer systems and have the advantage of the high quality factor and inherent single-mode nature [17]. Several ring resonators pertaining to different types of rods in the ring have been designed until now [18,19].

Djavid et al. [18] proposed a four-channel photonic crystal full ring demultiplexer using two-dimensional (2-D) PhCs. Their structure is composed of three regions with three different values of dielectric constant. In other words their structure is hetero. Normalized transmission of output channels in this device is over 85%, (quite low), with a spectral spacing of 28 nm, (very high), but the crosstalk level is not suitable. Therefore, their structure is not appropriate for optical integrated circuits design.

In this paper, a wavelength demultiplexer structure has been designed by completely round circles for selecting different

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wavelengths. Three rings have been used in our proposed device to transmit the wavelengths of 1507.8, 1516.2 and 1524.2 nm. In this structure, the channel spacing is about 8 nm, average power transmit efficiency is above 90% while full width at half maximum (FWHM) for each individual channel is about 2.8 nm. These characteristics are highly appropriate for devising a full-ring based wavelength demultiplexer. The overall size of the proposed device is about 317 μm^2 which is appropriate for photonic integrated circuits. On the other hand, the average crosstalk for the output channels is about −29 dB, which is suitable for WDM communication systems. The distinctive feature of this structure is that the resonant wavelength for each ring is tunable. By changing the inner rods radius, the resonant wavelength can be tuned. The new ring resonator introduced in this study can be used as the basic element for other devices as well. The optical power transmission characteristics and optical field distribution pattern have been simulated by finite-difference time-domain (FDTD) method. FDTD method is the most famous method for photonic crystal analysis [20]. FDTD is a time domain simulation method for solving Maxwell's equations in arbitrary materials and geometrics. The basic principle is to substitute the curl equations and partial time differential with finite central differences in spatial domain and time domain respectively. Berenger's perfectly matched layers (PML) are located around the whole structure as absorbing boundary condition [21].

The paper is further organized as follow: in Section 2, we will discuss a new design of PhC ring resonator. In Section 3, our wavelength demultiplexer is designed utilizing the improved ring resonator. Finally in Section 4, the conclusion will be provided.

2. Design of photonic crystal ring resonators

A typical 5 × 5 ring resonator, based on the number of inner rods, in square lattice of photonic crystal is shown in Fig. 1. The system under consideration is two-dimensional (2-D) and consists of an array of *Si* rods with a radius of $r = 0.18a$ located in air, where "a" is a lattice constant. This structure is excited with transverse magnetic (TM) polarization. The TM mode is defined as the Electric fields parallel to the dielectric rods axis. PBG for this structure is placed between normalized frequencies of $0.300 < a/\lambda < 0.435$. The four additional rods completely similar to the other rods are placed at each corner of ring resonator which are named here as "scatterer". Back reflection on the sharp corners of the ring resulted in appearing unwanted propagation modes while these rods intended to decrease the effects of the counter propagating modes [22]. According to Fig. 1(a), if the ring is coupled with two waveguides, then it would be able to trap electromagnetic energy from the input waveguide and afterward transmit it into the bottom waveguide.

For improving transmitted power to port B, radius of adjacent and coupling rods are set to $r_{coupling} = 0.97r$, and $r_{adjacent} = 0.87r$ respectively, where r is the radius of other rods. To further increase the transmission power to port B, we can shape the ring as pseudo-circular. As shown in Fig. 1(a), the inner rods of the ring placed at the corners are shifted toward the center of the ring up to quarter of lattice constant, allowing the ring to be shaped like a circle.

The Gaussian input signal is launched into the input port, and the normalized transmission spectrum at port 'A' and 'B' of this structure obtained by applying Fast Fourier Transform (FFT) on the fields which are calculated using 2-D FDTD method. This spectrum is shown in Fig. 1(b). As shown in the figure, the wavelength $\lambda = 1516.2$ nm of the input port is removed from the upper waveguide and transmitted to the port 'B'. The transmitted power efficiency in this wavelength is about 100%, and the FWHM for this spectrum is about 2.8 nm.

Because of its significant features, this filter can also be used as a basic element of other similar structures. This structure resonate

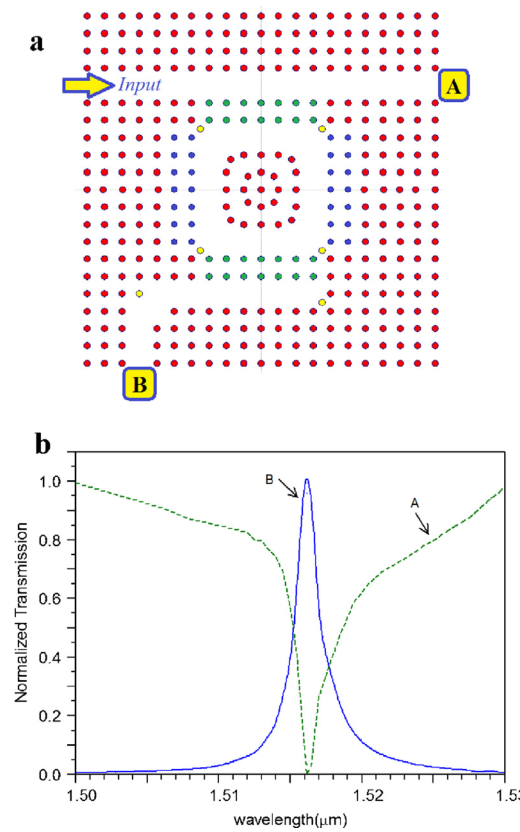

Fig. 1. (a) Photonic crystal ring resonator with optimized coupling and adjacent rods' radii and; (b) its normalized power transmission spectrum.

the wavelength $\lambda = 1516.2$ nm inside the ring and remove electromagnetic energy from input waveguide and transmits it to port B.

3. Designing a wavelength demultiplexer by an improved ring resonator

Here, we will discuss designing of a four-channel wavelength demultiplexer using an improved ring resonator. The main feature of the proposed ring resonator is that by changing the inner rod's radius, r_{in}, the resonant wavelength can be tuned. The inner rods are effective parameters which has great effects on the amount of the coupling between the propagating modes of the waveguides and the resonant modes of the ring [23]. For the structure given in Fig. 1(a), the power transmission characteristics for three different radii of inner rods have been shown in Fig. 2. As it can be seen, by increasing the inner rod's radius the resonant wavelength shifts toward longer wavelengths while by decreasing the radius it shifts toward shorter wavelength. By increasing the inner rod's radius, the transmitted power of resonant wavelength gently lowers, as by increasing from $r_{in} = r$ to $r_{in} = 1.1 \times r$, the transmitted power experiences a 5% decrease, approximately. By decreasing the radius of the rods, the transmitted power remains almost unchanged.

The final structure of wavelength division demultiplexer is shown in Fig. 3(a). In this structure three improved rings have been used for the radius of inner rods wherein $r_{in} = 1.1r$ for the left ring, $r_{in} = r$ for the middle ring and $r_{in} = 0.9r$ for the right ring, where r is denoted as the radius of other rods. The transmission spectrum of this structure which is shown in Fig. 3(b) indicates that, the structure transmits the three wavelengths $\lambda_1 = 1507.8$, $\lambda_2 = 1516.2$ and $\lambda_3 = 1524.2$ nm to the ports B, C and D, by resonating the right, middle and left rings, respectively. On other hand, the remaining