Optik 123 (2012) 167–170

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Multi-channel drop filters using photonic crystal ring resonators

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ARTICLE INFO

Article history:
Received 23 June 2010
Accepted 21 November 2010

Keywords:
Optical devices
Photonic integrated circuits
Ring resonators
Photonic crystals
Heterostructure
FDTD

ABSTRACT

In this paper, we propose a photonic crystal multi-channel drop filter based on ring resonators and investigate its properties numerically by using the finite-difference time-domain (FDTD) method. This structure is constructed in a two-dimensional square lattice. Our multi-channel drop filter is composed of three waveguides and three ring resonators. These ring resonators are located in two different regions (heterostructure) which each region has specific dielectric constant. At resonance of each ring resonator, the power with certain wavelength transferred to one of the three drop waveguides is found to be more than 81%.

1. Introduction

Artificial structures with periodic dielectric modulation, such as photonic crystals (PCs), can exhibit frequency ranges in which the propagation of electromagnetic waves is prohibited. This prohibition of wave propagation is tagged photonic band-gaps (PBGs) [1,2]. These structures have many potential applications because of their ability to control light-wave propagation and to be integrated into optical circuits. Moreover, PCs exhibit many interesting properties related to the defect modes in PBGs [3]. The introduction of a local defect inside a perfect 2D periodic dielectric structure may give rise to a resonant state inside the crystal in the vicinity of the defect. Optical waveguides in two-dimensional (2D) PCs produced by insertion of linear defects into PC structures had been proposed [4]. Planar PC circuits consist of devices, such as splitters [5], Wavelength Division Demultiplexers, filters [6], and channel drop filters [7], by controlling the interaction between static devices, such as waveguides, resonators. A multi-channel drop filter consists of two parts, a waveguiding element, realized by linear defects in a photonic crystal, and frequency-selective elements, realized by photonic crystal resonators. The performance of such filters is based on the coupling between cavity modes of ring resonators and guiding modes of waveguides.

In this paper, a PC multi-channel drop filter using ring resonators instead of point defects is proposed, and its properties are numerically investigated by using the FDTD method. This PC multi-channel drop filter can be obtained utilizing two different refractive indexes into the 2D photonic crystal with square lattices. The resonant wavelength can be changed in the ring resonator by adjusting these refractive indexes. It makes controlling the light wave with a certain wavelength in PC waveguide possible. We incorporate these two different regions and ring resonators in a multi-channel drop filter. The multi-channel drop filter considered here is chosen to be a three-channel system with three ring resonators. This filter picks out three different wavelengths of a signal sent along a waveguide tagged bus and transfer them to another waveguides tagged drop while leaving other wavelengths undisturbed. The remainder of the paper is organized as follows: Section 2 presents a brief review of numerical method which is used in our simulations. In Section 3 we describe the ring resonator structure. In Section 4, we analyze multi-channel drop filters. The design goal is to obtain a wavelength selective device able to drop central wavelength. Section 5 concludes the paper.

2. Numerical analysis

Plane Wave Expansion (PWE) method is most popular method which is used for theoretical analysis of photonic crystal structures. This method can express periodic structures as a superposition of a set of plane waves. And it can obtain an accurate solution for the dispersion properties of a PC structure, but due to considering propagation modes, transmission spectra and field distribution cannot be extracted. Dispersion diagrams of our structures are calculated using this method.

On the other hand, FDTD method [8] is an accurate method for studying electromagnetic problems including the simulation of

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doi:10.1016/j.ijleo.2011.04.001

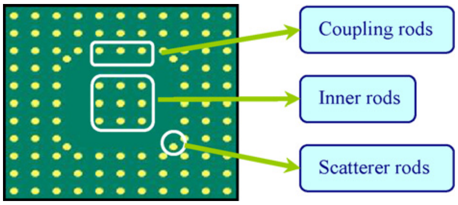

Fig. 1. A photonic crystal ring resonator obtained by removing a ring shape of columns from a rectangular lattice of dielectric rods.

many PC-based devices. The FDTD method for solving Maxwell's equations has been the workhorse of computational electromagnetic in the time domain, due to its simplicity. The FDTD mesh size and time step used in this paper are: $\Delta x = \Delta y = a/21$ and $\Delta t = \Delta x/2c$, where c is speed of light in free space and a is lattice constant. Berenger's perfectly matched layers (PMLs) are surrounded the whole structure as absorbing boundary condition [9]. The number of PMLs is set to be 12. This structure is excited with TM polarization.

An adequately broadband Gaussian pulse is launched into input port, and then we placed a detector inside each waveguide channel of the filter, measuring the time-varying electric and magnetic field. The power transmission spectra are computed by taking the Fast Fourier Transform (FFT) of the fields that are calculated by FDTD and integrating the poynting vector over the cells of the output ports. In this paper we use FDTD method to calculate the spectrum of the power transmission, in our *MATLAB* code during 30,000 time step (about 240 min running time for final structure). The computer used in this simulation is P4 3.00 GHz and has 4 GB of RAM.

3. Photonic crystal ring resonators

A typical ring resonator [10,11] is depicted in Fig. 1. This ring resonator is obtained by removing a ring shape of columns from a square lattice of dielectric rods. Photonic crystal ring resonators are new kinds of cavity defects which their size is determined by the desired resonant wavelength, and the tradeoff between the cavity Q and the modal volume. Compared to point-defect cavities, ring resonators offer scalability in size, flexibility in mode design due to their multi-mode nature and adaptability in structure design because of numerous design parameters [12]. These parameters can be the radius of the scaterers, coupling rods and the dielectric constant of the structure. The ring resonator side-coupled to a line defect waveguide traps photons at resonant frequency from the waveguide through evanescent coupling, and emits close to whole of them in the drop waveguide. Using this method, complete wavelength selective operation and perfect power transfer from the bus waveguide to the drop waveguide are obtained in our filter.

The system under consideration is two-dimensinal and consists of an array of rods with a square lattice structure. Rods of *Si*, with a radius of $r = 0.185a$ are perforated in air, where a is lattice constant. As shown in Fig. 1, by adding the four extra scatterer rods at each corner of the ring resonator at half lattice constant, which are the same as other rods, the performance of the ring resonator is improved. Back-reflections at the sharp corners of the ring lead to appear undesirable propagating mode. Adding the four extra rods, act like a right-angled reflector, minimizes the effect of these modes.

First, in order to couple to the signal being sent in the waveguide formed by removing one row of rods, a basic requirement is that the resonator modes' wavelengths lie in the band-gap of the photonic crystal structure and match that of a guided mode of the waveguide. As shown in Fig. 2(a), by putting waveguides next to the ring resonator, an add-drop filter is formed. In this structure, top waveguide can couple to the ring resonator at its resonant frequency to trap the electromagnetic energy which is propagating in the waveguide and localized it in the ring resonator. In another word, the light is dropped from the top waveguide by ring resonator and it is sent to the bottom waveguide [13,14]. This structure consists of an input waveguide labelled A, and three output channels labelled as B, C and D. In this structure, by choosing the refractive index of 3.46, the lattice constant (a) of 540 nm and the rods' radii (r) of 99.9 nm, band-gap opens for the normalized frequency $a/\lambda = 0.31–0.46$ for TM polarization (electric field parallel to the rod axis), where λ is the wavelength in free space.

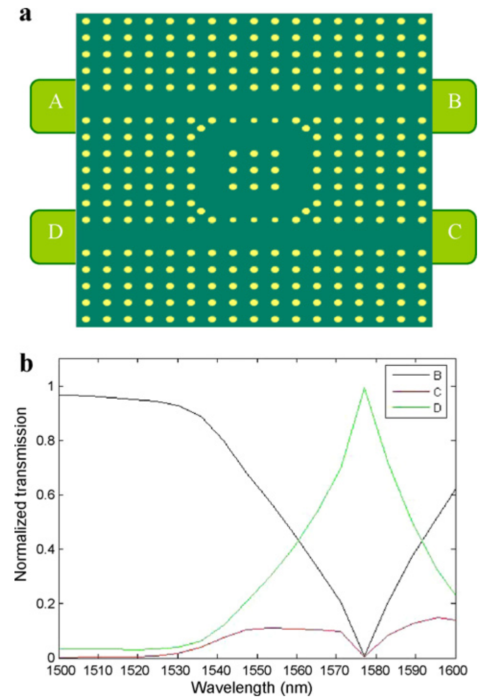

Fig. 2. (a) An add-drop filter with ring resonator and (b) optical power transmission characteristic of this filter.

The transmitted spectra in the top and bottom waveguide are shown in Fig. 2(b). These were calculated by sending in a Gaussian pulse centered at the resonant frequency of the ring resonator modes and normalizing using the transmission of input waveguide. As seen, the transmission in the drop waveguide is about 98% at resonance and the transmitted flux in the bus waveguide is about 96%. Snapshots of time domain simulation are depicted in Fig. 3. It shows the electric field intensity of mentioned structure at (a) $\lambda_1 = 1500$ nm of port B and (b) $\lambda_2 = 1577$ nm of port D in the communication window.

4. Heterostructure multi-channel drop filters using photonic crystal ring resonators

In this section, we present a design for heterostructure photonic crystal multi-channel drop filter that leads us to utilize three output ports. This structure is a hybrid structure which contains two sub-structures. So final structure has the optical characteristics of both sub-structures and overcomes single refractive index constraints. In order to avoid internal mismatches at the interface between the different refractive index structures, these structures must be matched in band-gap sizes. In other words, if a photonic crystal is formed from multiple refractive index structures, the newly formed structure is called a heterostructure photonic crystal. In our paper, we use heterostructure photonic crystal which contains two regions with various refractive indexes as shown in