Journal of Applied Sciences

ISSN 1812-5654

science alert

ANSInet
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Journal of Applied Sciences 8 (11): 2178-2182, 2008
ISSN 1812-5654
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A New Broadband Photonic Crystal Add Drop Filter

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Abstract: In this study, we present a photonic crystal Add-Drop Filter (ADF) design based on 3×3 ring resonators. The normalized transmission spectra for single-ring and dual-ring configurations have been investigated by using the two-dimensional Finite-Difference Time-Domain (FDTD) technique in a square lattice dielectric-rod photonic-crystal structure. In this study, firstly we investigate a single ring bend structure and we show that this structure can act as a broadband bend in third communication window. Then we suggest a new structure with two rings to develop a new ADF. This filter consists of an input and two outputs. Our FDTD simulation yields more than 90% efficiency over each output. We investigate parameters which affecting resonant frequency in photonic crystal add-drop filters. These parameters include dielectric constant of rods and the ring size as well as the radius of the coupling and scatterer rods.

Key words: Integrated optics, photonic crystal, add drop filter, FDTD, ring resonator

INTRODUCTION

Photonic Crystal (PC) structures offer a powerful scheme for the realization of ultra compact and multi-functional devices for high-density integrated optics. It is well known that simple line defects in such PC structures form very effective optical waveguides (Yablonovitch, 1994; Joannopoulos *et al.*, 1995). The optical Add-Drop Filter (ADF) is one of the fundamental building blocks for Optical Add-Drop Multiplexers (OADMs), reconfigurable OADMs, optical modulators and optical switches needed for silicon photonics, Photonic Integrated Circuits (PICs) and Wavelength Division Multiplexed (WDM) optical communication systems (Soref, 1993; Little *et al.*, 1997; Fan *et al.*, 1998). Many approaches have been suggested for developing add-drop filters, using photonic crystal ring resonator is one of them. If a ring resonator is located between two waveguides the structure will act as an ADF (Qiang and Zhou, 2007). Here, we suggest a new structure based on two ring resonator bends. Such 90° bends can be achieved by using ring resonators (Djavid *et al.*, 2007). We achieved an ADF by placing two of these bends together. The main feature of this structure is its broadband nature. The structure's dropping band can be extremely wide in the communication window.

Optical resonators: Many kinds of optical resonators can be constructed in photonic crystals. Changing the size or dielectric constant of each rod causes the consequent defect to behave as a resonator. In fact by creating a defect in the structures, the periodicity and completeness of the bandgap are broken and light can be localized in the defect region with the frequency corresponding to the defect frequency inside the gap (Villeneuve *et al.*, 1996). Other types of optical resonators are ring resonators. If we remove some rods in order to have a ring shape, we have a ring resonator. For these structures, the choice of the ring size is determined by the desired resonant wavelength and the tradeoff between the cavity Q and the modal volume V (Qiang and Zhou, 2007). Compared to point-defect or line-defect PC cavities, Photonic Crystal Ring Resonators (PCRRs) offer scalability in size and flexibility in mode design due to their multi-mode nature (Manolatou *et al.*, 1999). The ring resonator used in this research is shown in Fig. 1. Four scatterer rods are placed at the corners of the ring for higher quality factor (Dinesh Kumar *et al.*, 2004). The design parameters for a ring resonator can be the radius of the scatterers, the radius of coupling rods as well as the dielectric constant of the structure.

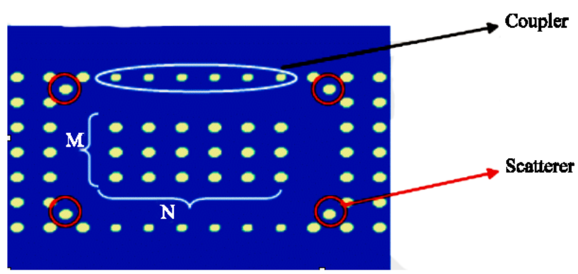

Fig. 1: An M×N Photonic Crystal Ring Resonator (PCRR) which its scatters are specified in circles and the coupling rods in the oval

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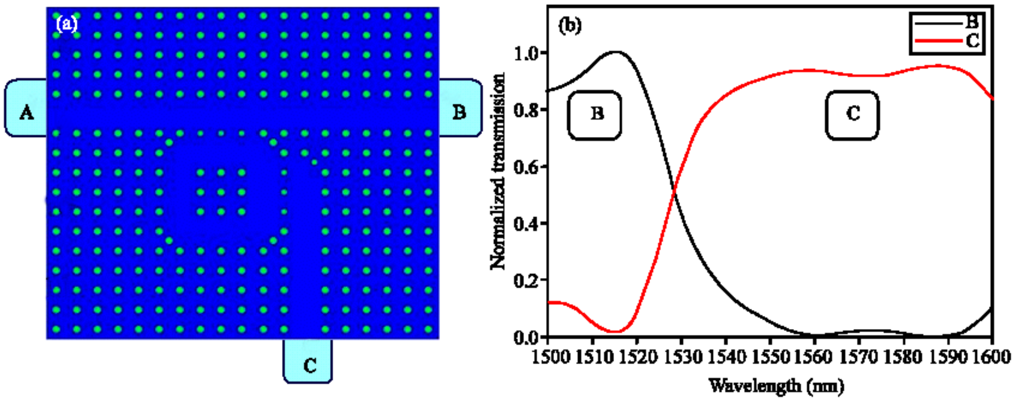

Fig. 2: (a) New L-shaped bent waveguide with ring resonator (PCRR) and (b) the power spectra of the new bend

New L-shaped bent waveguide: First, design of an L-shaped bent waveguide with excellent power transmission is investigated. This bend structure is shown in Fig. 2a. The structure is a square lattice of dielectric rods in air host with lattice constant α, radius 0.185α and a dielectric constant (ε) of 12, which corresponds to Si. By choosing the lattice constant a = 540 nm and therefore the rods radius r = 99.9 nm, we will have a broadband bandgap with a guided single-mode spans from 1270 to 1740 nm in our waveguide.

By putting the ring resonator next to the waveguide, the electromagnetic energy propagating in the waveguide will be coupled to the ring resonator. This phenomenon occurs because of coupling between the waveguide and ring resonator at resonant frequency (Dinesh Kumar *et al*., 2004; Notomi *et al*., 2004; Barwicz *et al*., 2004).

Utilizing an optimization process, the structure is designed such that power can be delivered to both B and C port, about the wavelengths of the 1550 nm communication window. Here the optimization parameters are the radius of the coupler and scatterer rods. After optimization the radius of the couplers and scatterers are chosen to be R_c = 0.8 and R_s = 1, respectively (Ghafari *et al*., 2007).

Finite Difference Time Domain (FDTD) method is used to simulate the structure and Perfect Matched Layers (PML) are placed as absorbing boundary conditions. A Gaussian pulse which is adequately broadband is launched into port A and power is calculated at each port. Then the power spectra of each as shown in Fig. 2a, port is normalized to the power spectra of the input port.

Figure 2b shows the normalized transmissions of the structure over the third communication window. Normalized transmission power in range 1537-1600 nm is above 80% and in range 1549-1595 nm is above 90%, therefore the acceptable frequency range is achieved (Djavid *et al*., 2007). According to Fig. 2b, both B and C ports have high transmission in some part of the communication window, so it is possible to use this structure in developing an add-drop filter.

Double ring photonic crystal add-drop filter: Considering all above mentioned information, it is possible to extend our structure to an add-drop filter, so a similar ring and another waveguide should be added to the structure (Fig. 3a). In this case the wave propagating toward port D will be coupled to the third waveguide because the second ring is just the same as the first and resonates at the same frequency. This configuration results in an add-drop filter and its transmission is shown in Fig. 3b.

As it is apparent in the Fig. 3b, wave propagates toward port B in the lower band of the communication window and drops and propagates toward port C in the upper band. Both of the through and drop channels are wideband. The drop efficiency is more than 99% at λ = 1561 nm (The transmission is over 90% over a wide rang of frequencies). The electric field pattern for both through and drop channels are illustrated in Fig. 4a, b.

Adjusting the through and drop frequencies: One of the most important features of an add-drop filter is to be adjustable. Changing the spectral characteristic of the structure can be obtained according to various parameters. Here the effect of changing dielectric constant is reviewed. According to the simulations, by increasing the dielectric constant of rods, the dropping frequency band will be decrease. The transmission spectra of the structure for four different dielectric constants are shown in Fig. 5. Therefore choosing a proper material can be the first step in designing a desired filter. Figure 6 shows the dependence of through and drop frequency on the

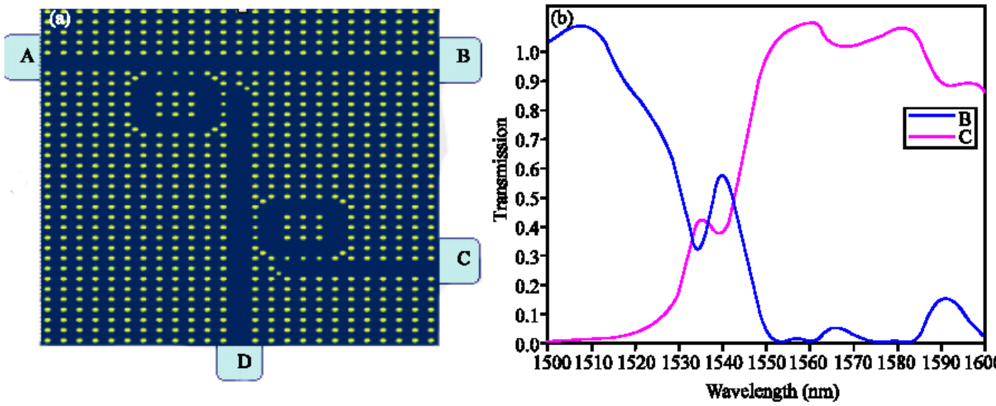

Fig. 3: (a) New ADF structure consists of three waveguide and two ring resonators (PCRR) and (b) the power spectra of the new scheme, 99% drop efficiency achieved at $\lambda = 1561$ nm

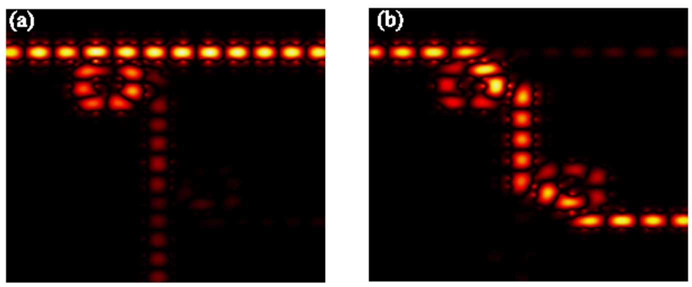

Fig. 4: The electric field patterns for the (a) through (off resonance: $\lambda_0 = 1507$ nm), (b) first drop channel (on-resonance: $\lambda_1 = 1561$ nm)

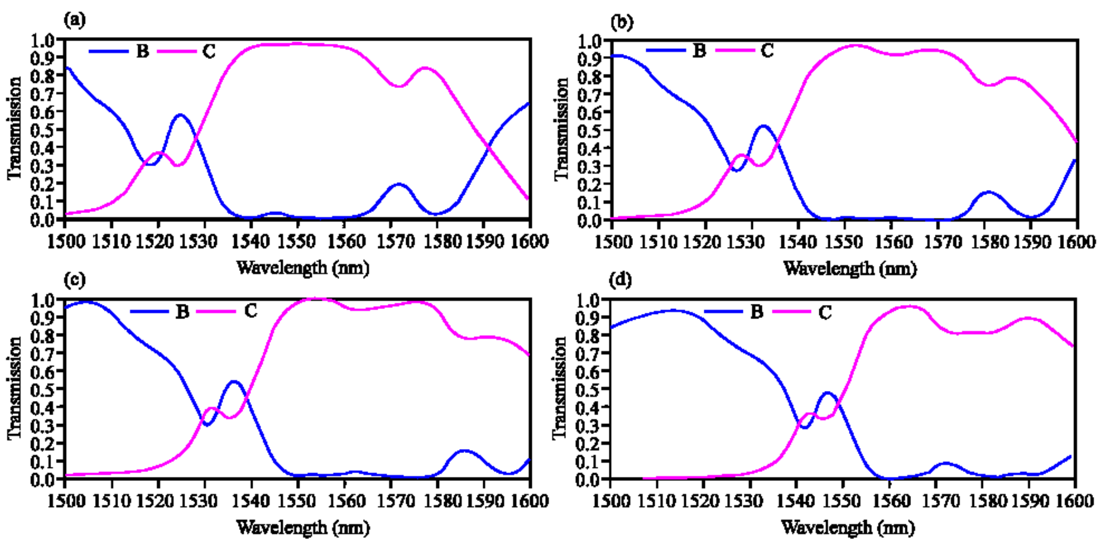

Fig. 5: Power spectra for (a) $\varepsilon_r = 11.2$(b) $\varepsilon_r = 11.6$ (c) $\varepsilon_r = 11.8$ (d) $\varepsilon_r = 12.4$. It is clear that by increasing the dielectric constant of the rods, drop and through spectra are shifted to the higher wavelengths

dielectric constant of the rods which can be a design guide. Let's think these dielectric rods are made of an electro-optical material so we can change the dielectric constant of the structure. With change in dielectric constant of whole rods, the filter can be tuned.

Another way to set the filter's parameters is to change the ring size. If the ring's size (N and M in Fig. 1) is changed the resonant frequency of the ring will be changed, so the whole filter characteristic will be changed. Figure 7 shows the transmission spectra for a

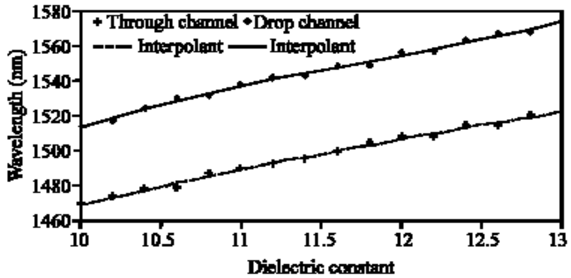

Fig. 6: Through and drop wavelength versus dielectric constant

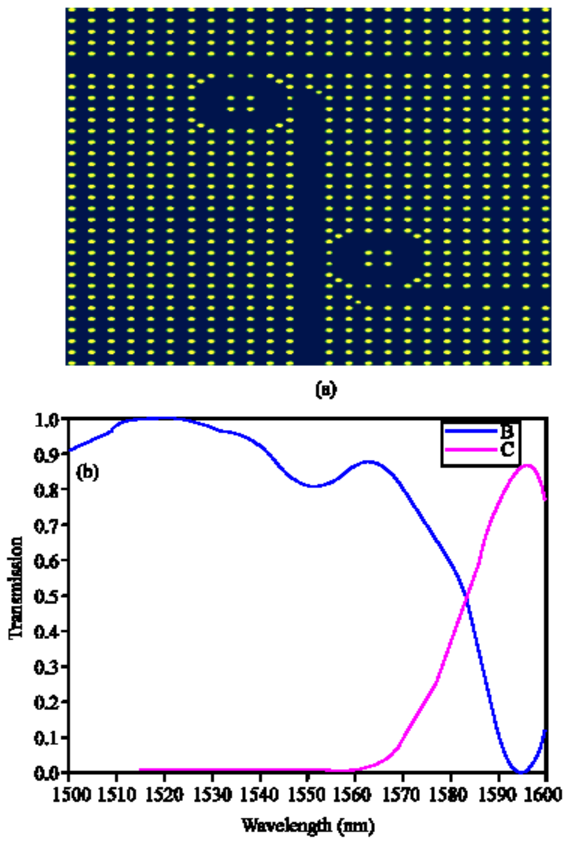

Fig. 7: (a) A photonic crystal ADF with 2×2 ring resonators and (b) the power spectra of the new scheme, 80% drop efficiency achieved at $\lambda = 1595$ nm

2×2 ring and $\varepsilon_r = 12$. Comparing with transmission spectra in Fig. 4 for a 3×3 ring it is obvious that the transmission spectra are completely different. In a 2×2 ring, the drop band is narrower and is shifted to larger wavelengths.

Changing the radius of coupling and scatterer rods as well as changing the dielectric constant affects the filtering characteristic. These parameters were investigated for a single ring in previous studies (Ghafari *et al.*, 2007).

CONCLUSION

In this study, we proposed a new class of ultra-compact optical add-drop filters based on photonic crystal ring resonators. We showed that more than 98% drop efficiency can be obtained. Filtering characteristic of such structures can be adjusted in many ways. Here we reviewed the effect of dielectric constant and the ring size. We proved that increasing the dielectric constant results in increasing the drop and through wavelengths. Such structures offer new and promising building blocks for ultra-compact scalable photonic integrated circuits based on photonic crystals and other nanophotonic structures.

ACKNOWLEDGMENTS

This research was supported by Iran Telecommunication Research Center.

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