

All optical gate based on photonic crystal ring resonator

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Abstract: The aim of this paper was to propose and design a photonic crystal drop filter based on ring resonators and study its properties numerically. This structure is constituted in a two-dimensional square lattice. The resonant wavelengths of the PCRR proposed are $\lambda = 1.553 \mu\text{m}$, the extraction efficiency exceeds 99% with a quality factor of 5177. To study the all-optical OR and XOR logic gate function, we calculated the electric field distribution of the 2D photonic crystal for the $1.553 \mu\text{m}$ signal light.

Key words: photonic crystals ; filter ; ring resonators ; logic gates ; OR ; XOR .

1. Introduction

PCs are periodic optical nanostructures composed of two different materials with low and high dielectric constant [1-2]. As a result of this periodicity, it owns photonic band gap (PBG), where the transmission of light in certain frequency range is absolutely zero [3]. Depending on the geometry of the structure, PCs can be divided into three broad categories, namely one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) structures. 2D PCs due to their complete PBG and ease of design and fabrication attract more attention than 1D structures [4].

In this study, we propose a new design of PCRR based on square photonic crystal ring resonator with flower shaped. The COMSOL Multiphysics based on the finite element method FEM is used for simulate the distribution and transmission of electromagnetic wave. In our design, 100% dropping efficiency with quality factor of 5177 is achievable at wavelength $\lambda=1.553 \mu\text{m}$, which is a satisfactory result in comparison with other T-shaped channel drop filters based on photonic crystal ring resonators.

Optical logic gates are essential components required for optical signal processing and optical communication networks Saidani [5] proposed a multifunctional logic gate in a 2D PCs waveguide structure using multimode interference concept. By switching optical signal to different input waveguides, different functions such as XOR, OR, NOR and NOT gates have been obtained. An all optical NOR gate have been proposed by Isfahani [11]. We used the PCRR presented to realize the gate logic for OR and XOR function, there are presented by studying the electric distribution of the 2D photonic crystal for the $1.553 \mu\text{m}$ signal light.

2. Structural characteristics

2.1. Band gap structure

To determine the physical parameters of the filter, it is necessary to calculate the band gap diagram of the design. This last is traced using the plane wave expansion method PWE under COMSOL Multiphysics software [7]. The dielectric rod radius $r=0.188 \times a$, and background constant are taken $a=0.64 \mu\text{m}$. As shown in Fig.1, the PCs

structure supports a photonic band gap in the region $0 < \omega a / 2 \pi c < 0.455$, $0.525 < \omega a / 2 \pi c < 0.545$ and $0.675 < \omega a / 2 \pi c < 0.750$ for TE mode.

The resonant frequency is chosen such that there will not be a propagative mode in a photonic structure without defect as shown in Fig. 1. At the wavelength $1.553 \mu\text{m}$ ($\omega a / 2 \pi c = 0.412$), we observe the absence of modes in these regions. The electric field is reflected back because of the existence of the PBG as show in Fig. 1.

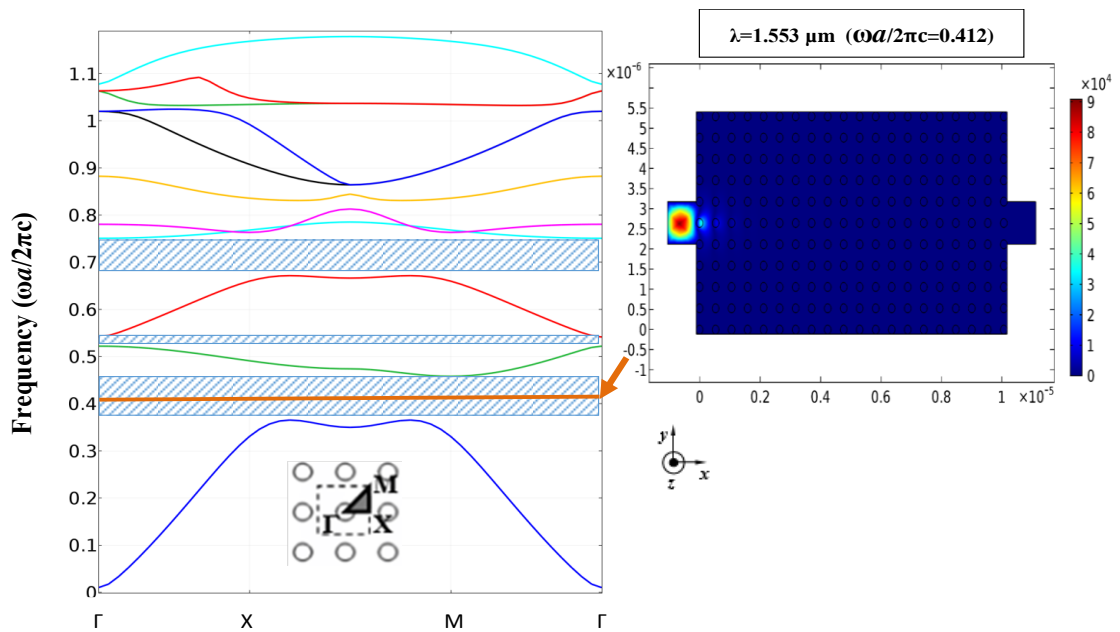


Figure 1. Schematic of photonic band gap.

2.2. Field formulation

Use the Helmholtz field equation and starting from the frequency-domain governing equation:

$$\nabla \times (\mu^{-1} \nabla \times \mathbf{E}) - \omega^2 \epsilon_c \mathbf{E} = \mathbf{0} \quad (1)$$

The total electric field, \mathbf{E} , can be decomposed into two components:

$$\mathbf{E} = \mathbf{E}_{\text{total}} = \mathbf{E}_{\text{background}} + \mathbf{E}_{\text{relative}} \quad (2)$$

In mode analysis and the boundary mode analysis COMSOL Multiphysics solve equation (1), the electric field in spectral domain is given by:

$$\mathbf{E}(\mathbf{r}, t) = \text{Re}(\tilde{\mathbf{E}}(\mathbf{r}_T) e^{j\omega t - j\beta z}) = \text{Re}(\tilde{\mathbf{E}}(\mathbf{r}) e^{j\omega t - j\beta z}) \quad (3)$$

The spatial parameter, $\alpha = \delta z + j\beta$

- β : Propagation constant
- δz : Attenuation constant

Use the scattering boundary condition to make a boundary transparent for a scattered wave. The boundary condition is also transparent for an incoming plane wave.

$$\mathbf{E} = \mathbf{E}_{sc} e^{-jk(\mathbf{n} \cdot \mathbf{r})} + \mathbf{E}_0 e^{-jk(\mathbf{k} \cdot \mathbf{r})} \quad \text{Plane} \quad (4)$$

2.3. Design of the channel drop filter

In this study, the structure of the two-dimensional photonic crystal considered is formed by a square lattice of dielectric cylindrical rods of GaAs embedded in an air background. The numerical simulations are based on finite element method exploiting the commercial software COMSOL. Rods have a refractive index value of $n=3.28$, and a radius of $r=0.188 \times a$, $a=640$ nm being the lattice of the photonic crystal structure which is defined as the distance between centers of two adjacent rods, and a resolution of 20 rods horizontally and 20 rods vertically. Fig.2 shows the schematic structure of a Channel-Drop Filter CDF based on a PCRR. In this structure the ring resonator is created by removing a 7×7 square of dielectric rods and then replacing it with four flowers with height holes each separated by a hole the radii $r_1=0.2356 \times a$. In this study the used mesh is non-uniform and the type of sequence used is physics-controlled mesh with scattering boundary condition.

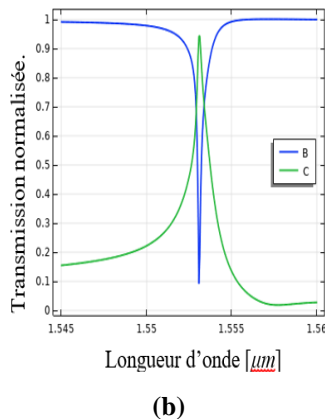
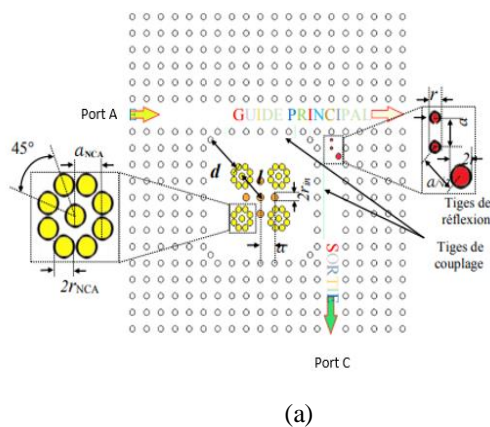


Fig. 2. (a) Single ring PCRR. (b) Normalized transmission spectra at two output ports B and C for PCRR. The designing parameters of the proposed

NRC-QSRR : $a= 640$ nm, $r=120.32$ nm, $r_{in} = 151.3$ nm, $a_{NRC}=551.36$ nm, $r_{NRC} =130.34$ nm, $d= 1608.36$ nm, $l= 1169.61$ nm.

The optical waves enter the structure through port 1 and exit through port 2, but during resonance, the optical wavelengths will be transferred to the drop guide via the resonant ring and exit through port 3. At the resonance wavelength $\lambda = 1.553 \mu\text{m}$, the extraction efficiency exceeds 99% with a quality factor of 1411.

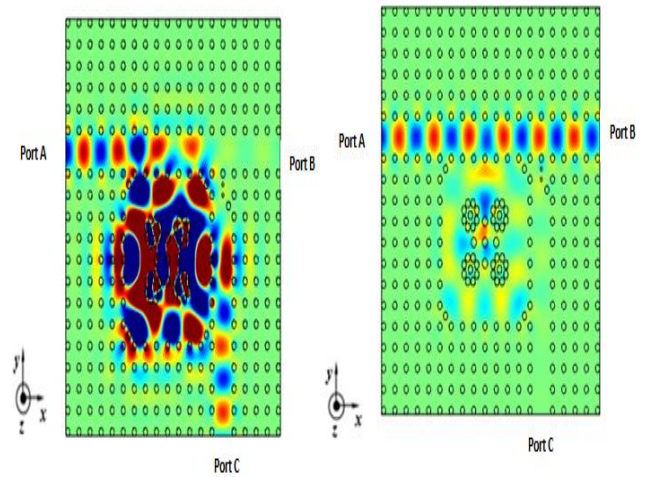


Fig.3. Electric field pattern of the ring resonator at a) $\lambda = 1.553 \mu\text{m}$ (the resonant wavelength). b) $\lambda = 1.556 \mu\text{m}$ (the off-resonance)

The electromagnetic wave transverse component E_z is presented around the wavelengths $\lambda=1.553 \mu\text{m}$ and $\lambda=1.556 \mu\text{m}$ where the positive pulses are in red and the negative pulses are in blue.

3.2. OR gate

The proposed OR gate structure is formed from two waveguides and two ring resonators with a resolution of 38 rods horizontally and 23 rods vertically. Two symmetrical optical waveguides AY and BY were formed along the $\Gamma-M$ direction by removing two rows of GaAs rods, and put two ring resonators between them. The refractive index, radius and lattice constant of the structure are the same as the PRCC structure. The final schematic of our proposed OR gate structure is shown Fig.4.

The all-optical OR logic gate operation is presented by studying the electric field distribution of the 2D photonic crystal for the $1.553 \mu\text{m}$ signal light, and the calculated results are shown in Fig.4. If a signal is injected into input port A, then the

signal light can transmit through the optical waveguide AY and be output from port Y, as shown in Fig.4 (b). If a single beam is injected into input port B, then the signal light can transmit through the optical waveguide BY and be output from port Y, as shown in Fig.4 (c). If two beams are injected into input ports A and B simultaneously, then the signal light can transmit through optical waveguides AY and BY, as shown in Fig4. (d). Thus, an all-optical OR logic gate can be achieved very easily.

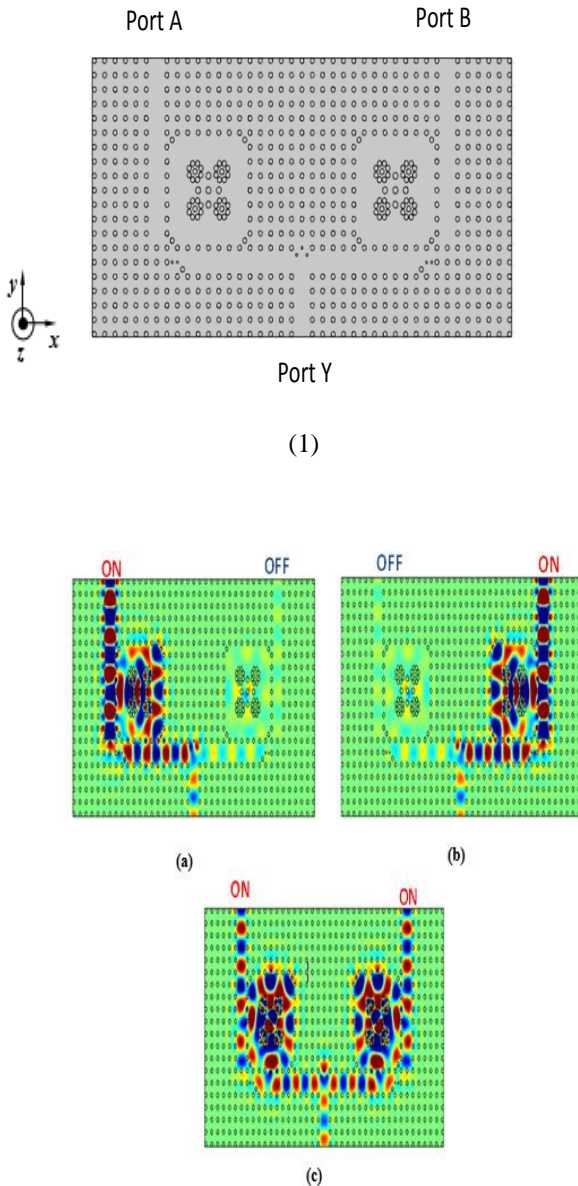


Fig.4 (A) OR gate structure. (a) $1 \text{ OR } 0 = 1$. (b) $0 \text{ OR } 1 = 1$. (c) $1 \text{ OR } 1 = 1$. The OR gate structure parameters are set such as: $n=3.28$, $r=0.188 \times a$ and $a=640 \text{ nm}$.

3.3. XOR gate

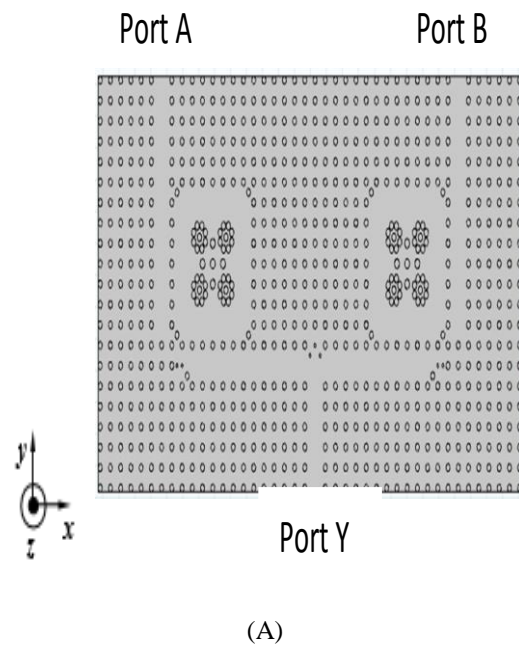
To study the all-optical XOR logic gate function, the same structure of OR gate 2D photonic structure is used adding one column of rods after the first ring resonator and is presented in Fig.5. The optical XOR logic gate operation is presented by studying the electric field distribution of the 2D PCRR device for a particular wavelength $\lambda=1.553 \mu\text{m}$.

First, we insert a signal light into only port A of the input waveguide. A large part of this signal travels to the port Y through the ring resonator waveguide. This is identified as the logic phenomenon “1 XOR 0 gives 1” and it is shown in Fig.5 (b).

The similar situation occurs, when the signal is incident to the B port only, and we get output as 1. This corresponds of the logic operation “0 XOR 1 gives 1” as shown in Fig.5 (c).

When the signals given to the input ports A and B simultaneously, there occurs a phase difference between these two signals due to path difference, and we get a destructive interference. As a result of this, there is approximately zero output at the port Y. This corresponds to the logic operation “1 XOR 1 gives 0” as shown in Fig. 5 (d).

When the both input signals are same (“0”, “0” or “1”, “1”) the output of XOR gate is zero “0” and both are different (“0”, “1” or “1”, “0”) the output is one “1”.)



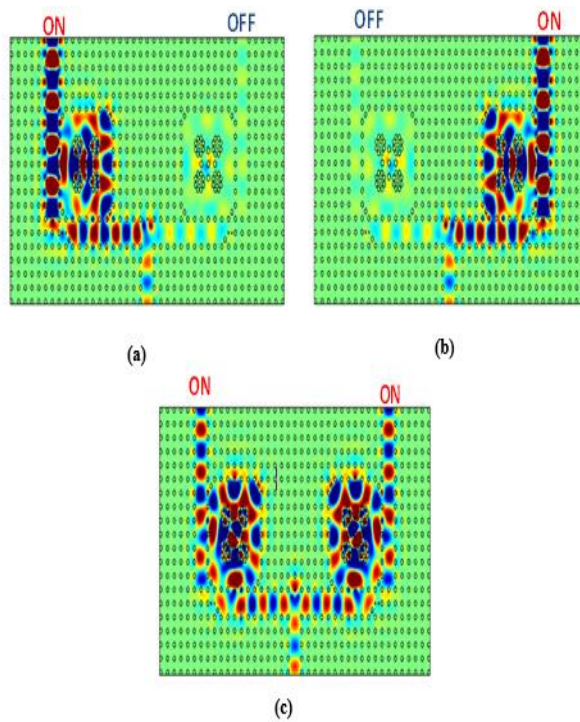


Fig. 6 (A) XOR gate structure. (a) $1 \text{ XOR } 0 = 1$. (b) $0 \text{ XOR } 1 = 1$. (c) $1 \text{ XOR } 1 = 0$. The XOR gate structure parameters are set such as: $n=3.28$, $r=0.188 \times a$ and $a=640 \text{ nm}$.

4. Conclusion

In this article, photonic crystal ring resonator based Channel-Drop Filter is designed and investigated. First we designed a flower shaped PCRR based on only one photonic crystal ring resonator. By combining two ring resonators, we proposed OR and XOR gates operating with TE mode optical signals.. Photonic crystal manufacturing is one of the main inconvenient that can be confronted where is expensive in production. Sub 100 nm dimensions need generally employing of high resolution electron beam lithography (EBL).

References

- [1] S.H. Kim, H.Y. Ryu, H.G. Park, G.H. Kim, Y.S. Choi, Y.H. Lee, 'Two-dimensional photonic crystal hexagonal waveguide ring laser', *Appl. Phys. Lett.* 81 PP.2499–2501, 2002.
- [2] V. Dinesh Kumar, T. Srinivas, A. Selvarajan, 'Investigation of ring resonators in photonic crystal circuits', *Photon. Nanostruct.* 2 pp.199–206, 2004.
- [3] Z. Qiang, W. Zhou, R.A. Soref, Optical add-drop filters based on photonic crystal ring resonators, *Opt. Express* 15 pp.1823–1831, 2007.
- [4] S. Robinson, R. Nakkeeran, 'Investigation on two dimensional photonic crystal resonant cavity based band pass filter', *Optik*, Volume 123, pp.451–457, 2012.
- [5] H. Alipour Banaeia, S. Seraj mohammadib, F. Mehdizadehc, 'All-optical NOR and NAND gate based on nonlinear photonic crystal ring resonators', *Optik* Volume 125 pp.5701–5704, 2014.
- [6] Mahmoud M Y, Bassou G, Taalbi A, Chekroun Z M. Optical channel drop filter based on photonic crystal ring resonators. *Optics communications* 2012; 285:368-372.
- [7] M. A. M. Birjandi, and M. R. Rakhshani, "A new design of tunable four-port wavelength demultiplexer by photonic crystal ring resonators" *Optik* (2013), <http://dx.doi.org/10.1016/j.ijleo.2013.04.128>.
- [8] L. Mokhtari, H. A. Badaoui, M. Abri, M. Abdelbasset, F. Lallam, and B. Rahmi, "Proposal of a New Efficient or/Xor Logic Gates and All-Optical Nonlinear Switch in 2D Photonic Crystal Lattices," *Progress In Electromagnetics Research C*, Vol. 106, 187-197, 2020. doi:10.2528/PIERC20051501 <http://www.jpier.org/pierc/pier.php?paper=20051501> (scopus)
- [8] Saidani N, Belhadj W, Abdel Malek F. 'Novel all-optical logic gates based photonic crystal waveguide using self imaging phenomena'. *Optical Quantum Electron* 47:1829–46, 2015.
- [9] Isfahani BM, AhamdiTameh T, Granpayeh N, Javan AM. 'All optical NOR gate based on nonlinear photonic crystal microring resonators'. *Optical Society of America*, volume 26, pp.1097–102, May 2009.
- [10] Mounzar A, Badaoui H, Abri M, '16-Channels Wavelength Efficient Demultiplexing around

1.31/1.55 μm in 2D Photonic Crystal Slab',
Optik (2019),
<https://doi.org/10.1016/j.ijleo.2019.04.032>