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Proposal of a New Efficient OR/XOR Logic Gates and All-Optical Nonlinear Switch in 2D Photonic Crystal Lattices

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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 $\lambda = 1.553\,\mu\text{m}$, and 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. In order to have a large selectivity of filtering and also of having a fast switching in the field of nonlinearity, we increase the number of ring resonators, and the latter are used for designing all optical logic gates which work using the Kerr effect equal to $10^{-6}\,\text{m}^2/\text{w}$.

1. INTRODUCTION

In recent year, all photonics crystals (PCs) have received much interest because of their wide applications: power splitters, channel drop filters, reflectors, optical switches, and demultiplexers are some examples.

PCs are periodic optical nanostructures composed of two different materials with low and high dielectric constants [1, 2]. As a result of this periodicity, PCs structure 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].

Photonic crystal ring resonator (PCRR) is a fundamental structure constructed of two waveguides namely bus and drop waveguides and a resonant ring situated between them. In this structure, the resonant ring can carry out filtering and wavelength selection task, such that optical waves propagating in the bus waveguide at a certain wavelength called resonant wavelength will drop to the drop waveguide, so PCRR can be used as optical filters [5–10]. It has been shown that the resonant wavelength of PCRR depends on the refractive index, radius, and dimensions of the core section of resonant ring [6]. It means that by selecting different values for the structural parameters of resonant ring core section, we can choose different wavelengths at the output, and by combining multiple resonant rings with different structural parameters in a single structure one can design and realize an all optical gate logic [7].

The first report of a photonic crystal ring resonator (PCRR) was in a hexagonal waveguide ring laser cavity [1], where flexible mode design and efficient coupling were treated. Later, the spectral characteristics of the waveguide-coupled rectangular ring resonators in photonic crystals were studied by Dinesh Kumar et al. [2], where a large single quasi-rectangular ring was introduced as the frequency selective dropping elements. Qiang et al. [3] investigated add-drop filters based on square lattice PCs.

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The quality factor of a single square ring filter is increased from 160 to over 1000 by elevating the coupling sections between waveguide and ring.

In this study, we propose a new design of PCRR based on a square photonic crystal ring resonator with flower shape. The COMSOL Multiphysics based on the finite element method FEM is used for simulating the distribution and transmission of electromagnetic wave. The structure consists of two photonic crystal waveguides with a ring resonator between them. 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 et al. [11] 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 was proposed by Isfahani et al. [12]. We used the PCRR presented to realize the gate logic for OR and XOR functions, and they are presented by studying the electric distribution of the 2D photonic crystal for the 1.553 µm signal light.

Finally, we added some nonlinear rods around the ring core for having a fast switching for high intensity input power equal to $1\,\text{kW}/\mu\text{m}^2$.

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. The last is traced using the plane wave expansion method PWE under COMSOL Multiphysics software [13]. For our proposed filter, the effective refractive index $n = 3.28$ demonstrated and published by Skauli et al. in 2003 [14] is integrated in COMSOL Multiphysics by using the Inorganic materials subfamily under Optical material family. The refractive index values are given by an interpolation function from a table of values as function of the incident electromagnetic beam wavelength at 22°C of temperature. The dielectric rod radius $r = 0.188 \times a$, and background constant is taken $a = 0.64\,\mu\text{m}$.

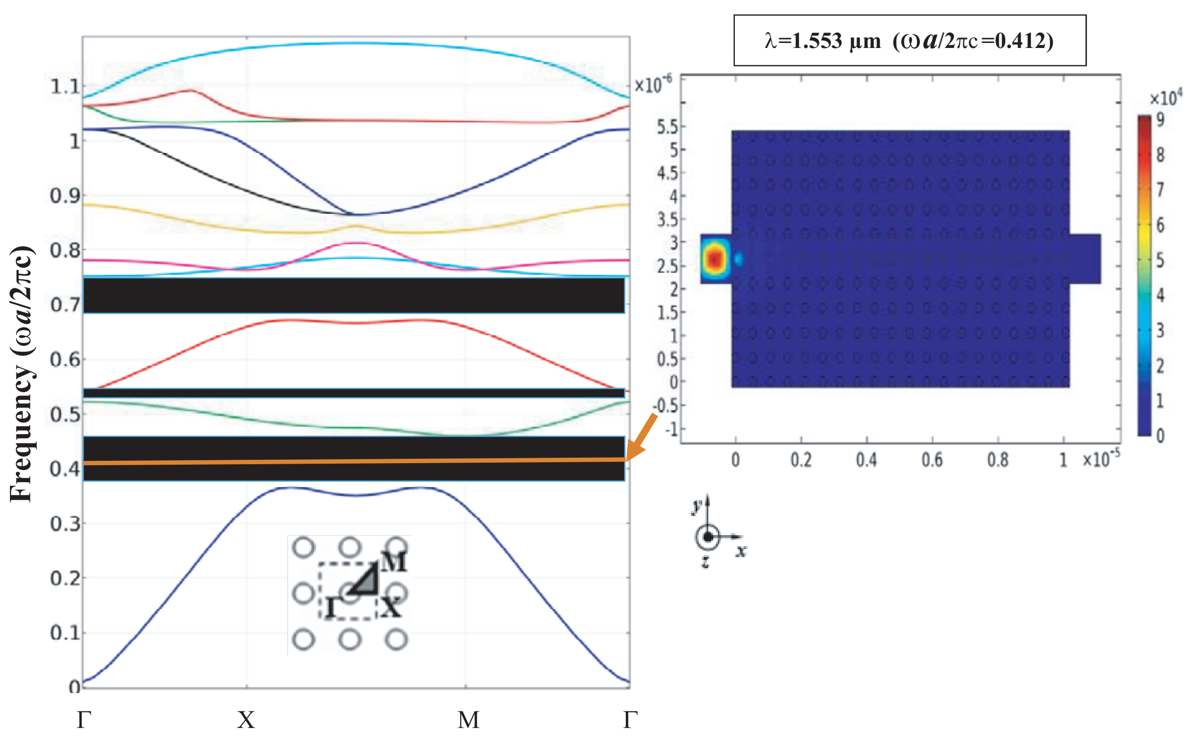


Figure 1. Schematic of photonic band gap.

As shown in Fig. 1, the PCs structure supports a photonic band gap in the region $0 < wa/2\pi c < 0.455$, $0.525 < wa/2\pi c < 0.545$ and $0.675 < wa/2\pi c < 0.750$ 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 µm ($wa/2\pi c = 0.412$), 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.

2.2. Field Formulation

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

$$\nabla \times \left(\mu^{-1}\nabla \times \mathbf{E}\right) - \omega^2\varepsilon_c\mathbf{E} = 0 \tag{1}$$

The total electric field, E, can be decomposed into two components:

$$E = E_{\text{total}} = E_{\text{background}} + E_{\text{relative}} \tag{2}$$

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

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

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

- β: Propagation constant.
- δ: 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.

$$\mathbf{E} = \mathbf{E}_{sc}e^{-jk(\mathbf{n}\cdot\mathbf{r})} + \mathbf{E}_0e^{-jk(\mathbf{k}\cdot\mathbf{r})} \quad \text{Plane scattered wave} \tag{4}$$

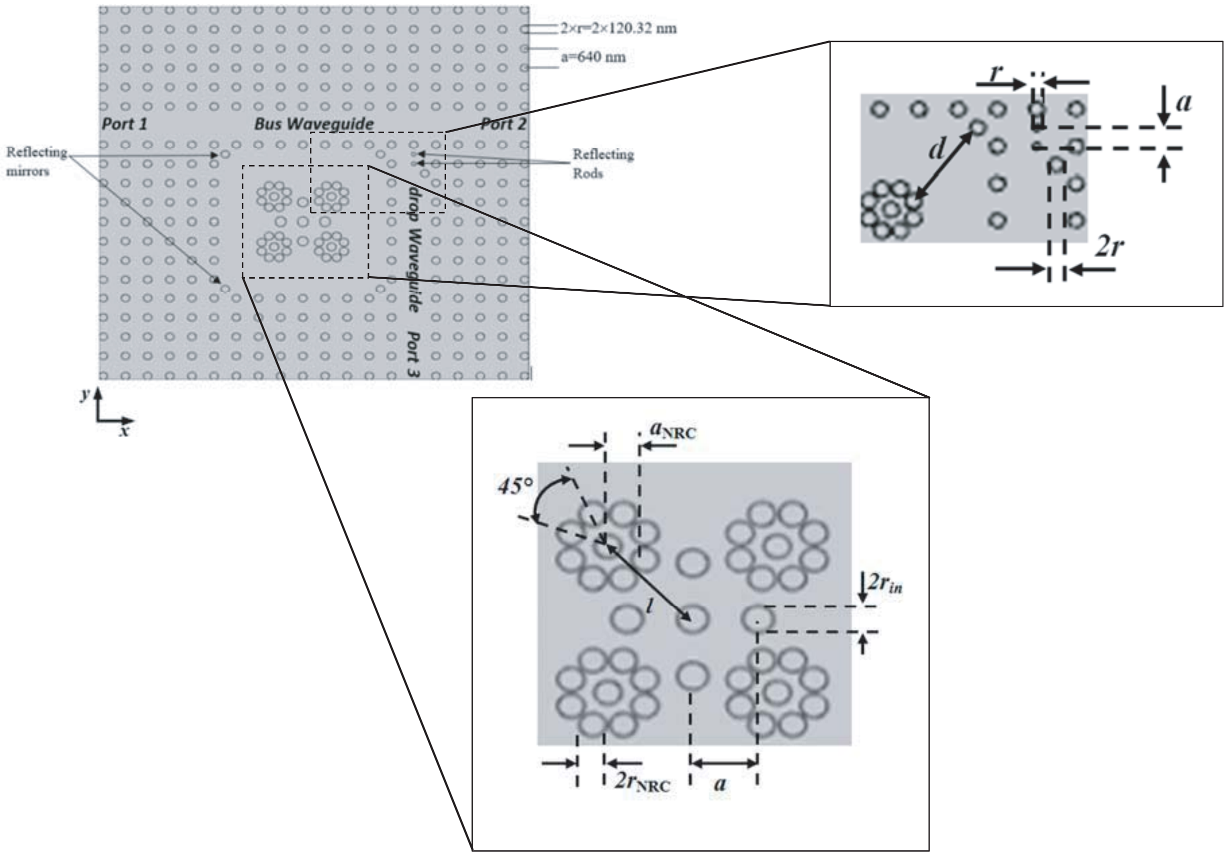
2.3. Design of the Channel Drop Filter

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 $r = 0.188 \times a$, with $a = 640$ nm being the lattice of the photonic crystal structure which is defined as the distance between the centers of two adjacent rods, and a resolution of 20 rods horizontally and 20 rods vertically. Fig. 2 shows the schematic structure of a T-shaped 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 nonuniform, and the type of sequence used is a physics-controlled mesh with scattering boundary condition.

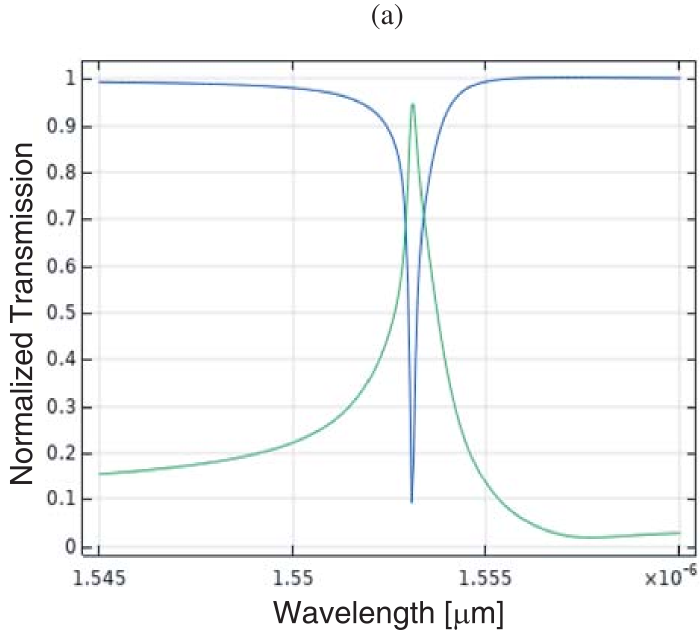
The input bus waveguide is created by removing a complete row of dielectric rods in horizontal direction where the drop waveguide is created by removing a complete row of dielectric rods in vertical direction. In order to ameliorate the extraction efficiency and the spectral selectivity, we will use the technique investigated by Kumar et al. [2]. Four reflecting rods are placed in each corner of the four sides of the resonator with the same radius and same refractive index as all the other rods in the photonic structure. The introduction of localized rods eliminates the modes of counter propagation due to the sharp corners of the resonator; by judiciously choosing their parameters (radius and position), we will have an improvement in the characteristics of the CDF.

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. Fig. 3 shows the electric field pattern of the ring resonator at the wavelength 1.553 µm and 1.556 µm, respectively. At the resonance wavelength $\lambda = 1.553$ µm, the extraction efficiency exceeds 99% with a quality factor of 1411.

The electromagnetic wave transverse component Ez is presented around the wavelengths $\lambda = 1.553$ µm and $\lambda = 1.556$ µm where the positive pulses are in red and the negative pulses in blue.



(a)



(b)

Figure 2. (a) Single ring PCRR. (b) Normalized transmission spectra at two output ports 2 and 3 for PCRR. The designing parameters of the proposed NRC-QSRR: $a = 640\,\text{nm}$, $r = 120.32\,\text{nm}$, $r_{\text{in}} = 151.3\,\text{nm}$, $a_{\text{NRC}} = 551.36\,\text{nm}$, $r_{\text{NRC}} = 130.34\,\text{nm}$, $d = 1608.36\,\text{nm}$, $l = 1169.61\,\text{nm}$.

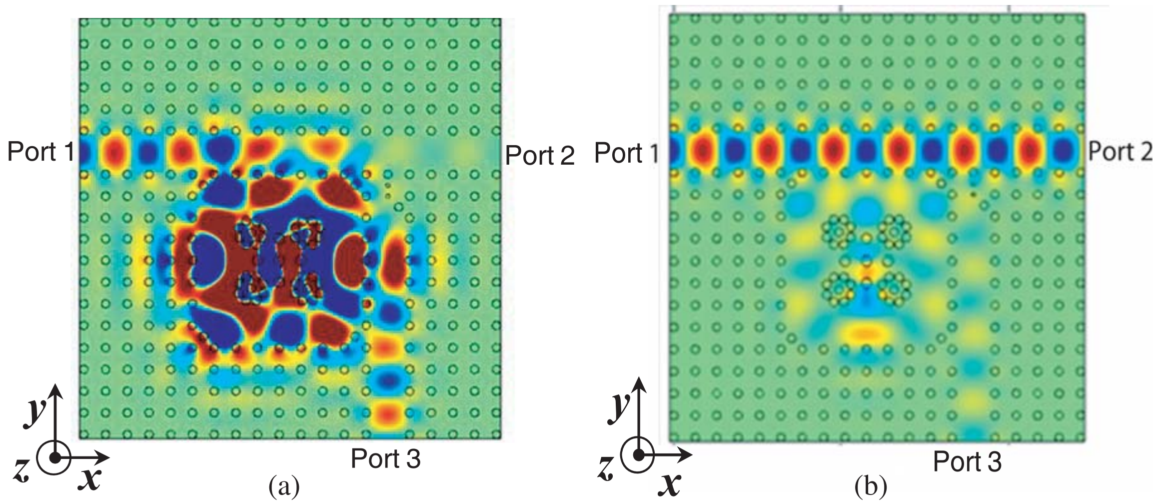


Figure 3. Electric field pattern of the ring resonator at (a) $\lambda = 1.553\,\mu\text{m}$ (the resonant wavelength). (b) $\lambda = 1.556\,\mu\text{m}$ (the off-resonance).

3. APPLICATIONS

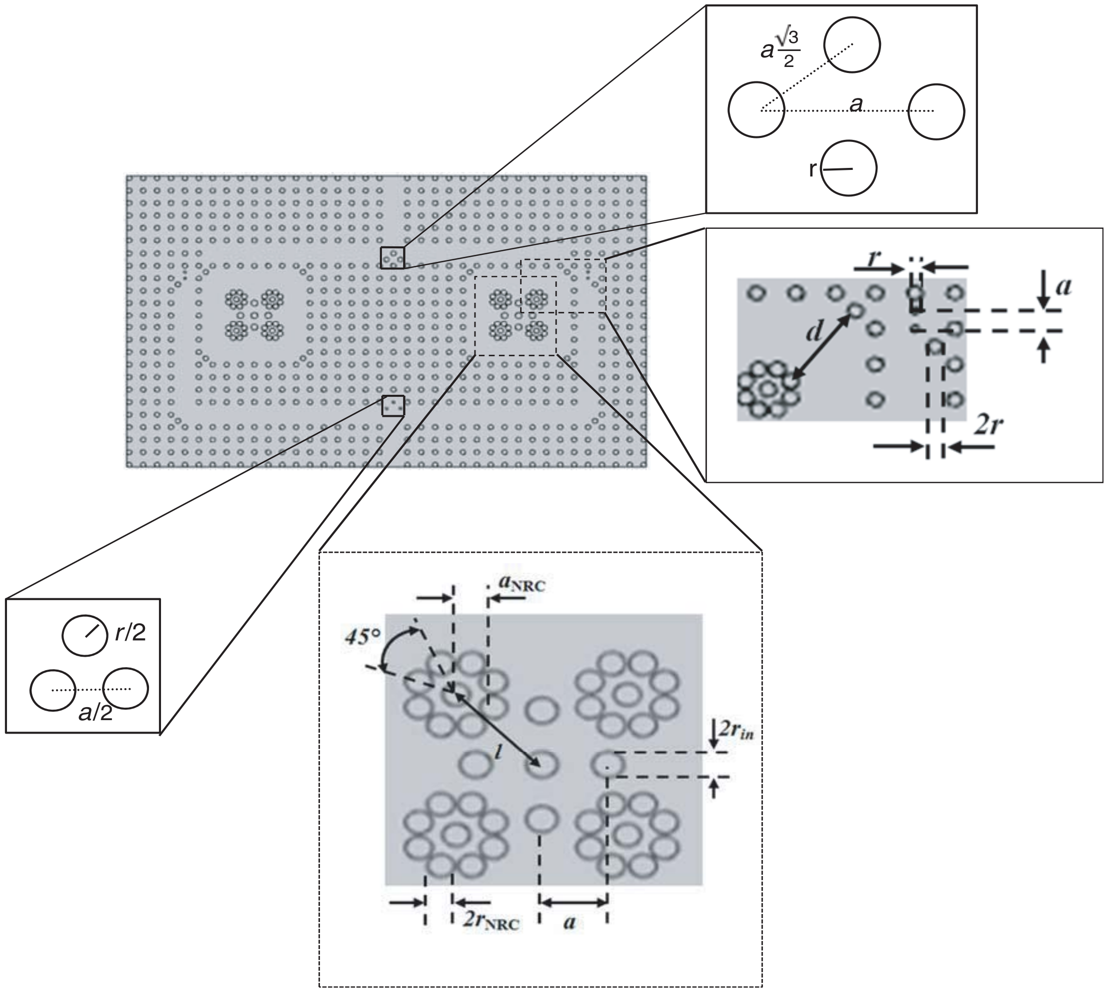
3.1. Double-Ring Photonic Crystal Channel Drop Filter

The previously studied two single-ring resonators are used in combination to compose a double-ring resonator as indicated in Fig. 4(a). In order to optimize the transmission three rods with radii equal to $r/2$ are placed in the junction of the wave guide. It comprises an array of 41×25 rods with the same radii of the resonator. The flower-shaped PCRR is proposed and designed, and its essential parameter such as transmission efficiency, dropping efficiency, quality factor, and resonant wavelength are evaluated.

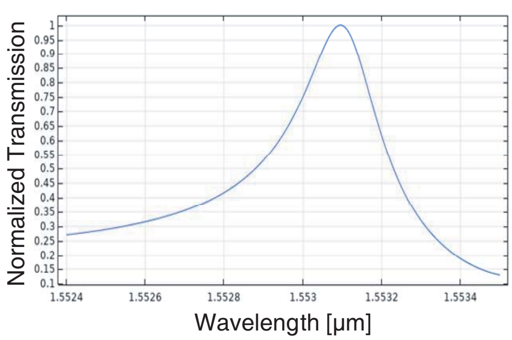
The transmission efficiency of this drop filter is presented in Fig. 4(b). The output efficiency of CDF is approximately 100%. It is observed at resonance that the operating wavelength is $1.553\,\mu\text{m}$. The Q factor can be calculated with $Q = \Delta\lambda/\lambda$ where $\Delta\lambda$ and λ are central wavelength and full width at half power of output, respectively. The value of Q factor for the proposed structure is obtained as 5177.

Table 1. Comparing devices based on PCRRs available in a variety of paper.

References	Transmission of efficiency (%)	Quality factor	Functioning Bands	PhCs Ring Resonator type
Mohammadi and Seifouri [15]	100	9017	Around 1.53 μm	Circular
Ma and Ogusu [16]	95	775	Around 1.55 μm	Diamond
Delphi et al. [17]	96	5159	Around 1.54 μm	Circular
Hsiao and Lee [18]	55	423	Around 1.55 μm	Hexagonal
Andalib and Granpayeh [19]	68	153.6	Around 1.55 μm	Dual curved
Gupta and Janyani [20]	100	7794	Around 1.55 μm	Quasi-square
Radhouene et al. [21]	100	5040	Around 1.51 μm	Line defect filter
Talebzadeh et al. [22]	93.45	4107.3	Around 1.64 μm	Line defect filter resonant cavity
Our work	100	5177	Around 1.55 μm	flower shaped



(a)



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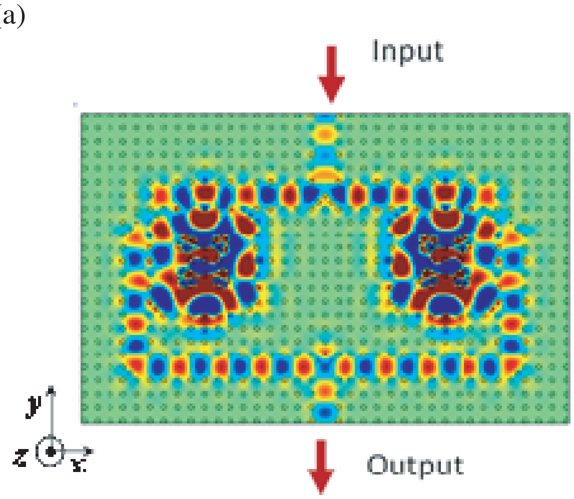


(c)

Figure 4. (a) Double-ring PCRR CDF. The designing parameters of the proposed NRC-QSRR: $a = 640\,\text{nm}$, $r = 120.32\,\text{nm}$, $r_{\text{in}} = 151.3\,\text{nm}$, $a_{\text{NRC}} = 551.36\,\text{nm}$, $r_{\text{NRC}} = 130.34\,\text{nm}$, $d = 1608.36\,\text{nm}$, $l = 1169.61\,\text{nm}$. (b) Normalized transmission spectra. (c) The electric field distribution at (a) $\lambda = 1553\,\text{nm}$ (the resonant wavelength).

Table 1 compares the results of the proposed design with others state of art structures. It is observed that the proposed structure outperforms other designs in both quality factor and transmission of efficiency.

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, are formed along the Γ-M direction by removing two rows of GaAs rods, and two ring resonators are put 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. 5.

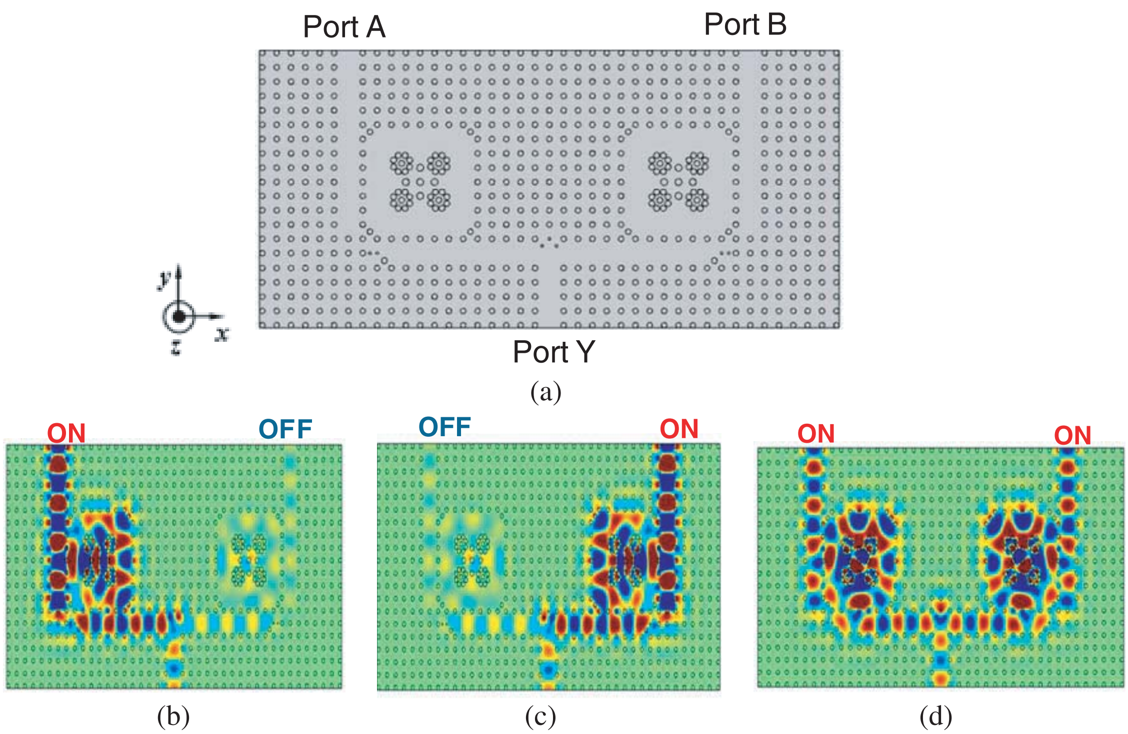


Figure 5. (a) OR gate structure. (b) 1 OR 0 = 1. (c) 0 OR 1 = 1. (d) 1 OR 1 = 1. The OR gate structure parameters are set such as: $n = 3.28$, $r = 0.188 \times a$ and $a = 640$ nm.

The all-optical OR logic gate operation is presented by studying the electric field distribution of the 2D photonic crystal for the 1.553 µm signal light, and the calculated results are shown in Fig. 5. 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. 5(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. 5(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 Fig. 5(d). Thus, an all-optical OR logic gate can be achieved very easily.

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. 6. The optical XOR logic gate operation is presented by studying the electric field distribution of the 2D PCRR device for a particular wavelength $\lambda = 1.553$ µm.

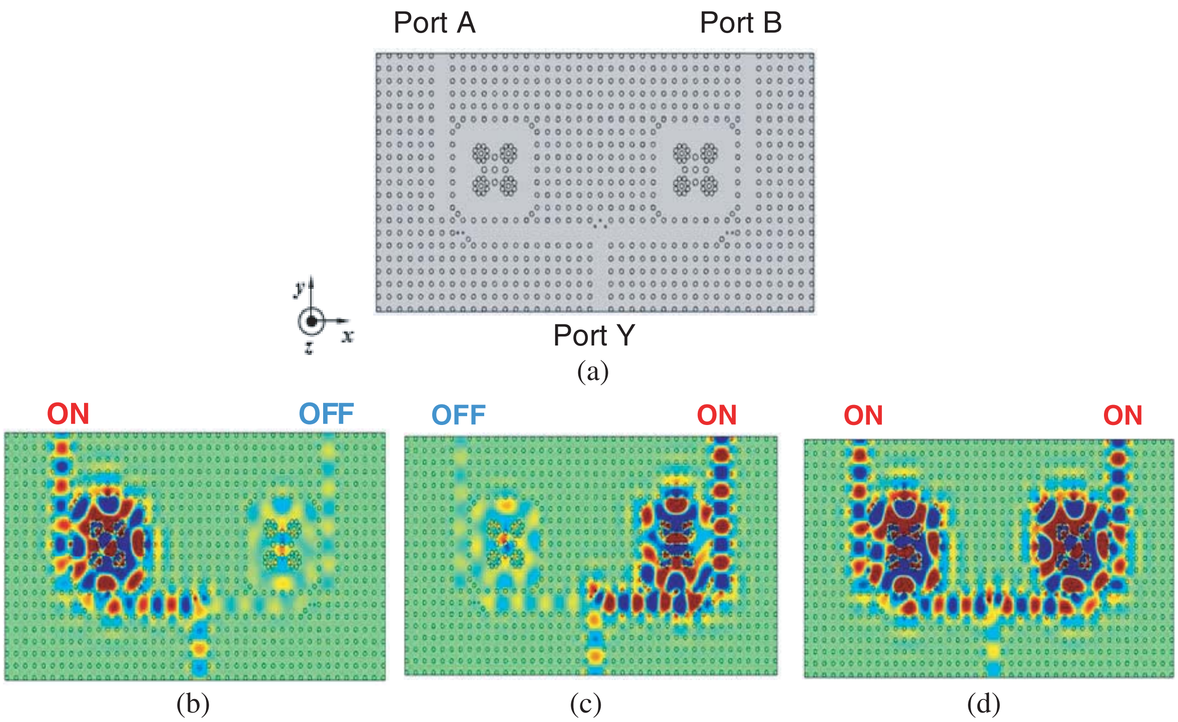


Figure 6. (a) XOR gate structure. (b) $1 \oplus 0 = 1$. (c) $0 \oplus 1 = 1$. (d) $1 \oplus 1 = 0$. The XOR gate structure parameters are set such as: $n = 3.28$, $r = 0.188 \times a$ and $a = 640\,\text{nm}$.

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 "$1 \oplus 0$ gives 1", and it is shown in Fig. 6(b).

A similar situation occurs, when the signal is incident to the B port only, and we get output as 1. This corresponds to the logic operation "$0 \oplus 1$ gives 1" as shown in Fig. 6(c).

When the signals given to the input ports A and B simultaneously, a phase difference occurs 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 "$1 \oplus 1$ gives 0" as shown in Fig. 6(d).

When the two input signals are same ("0", "0" or "1", "1"), the output of XOR gate is zero "0", and when they are different ("0", "1" or "1", "0"), the output is one "1".

3.4. All-Optical Switching

Numerous linear and nonlinear structures have been developed and reported in literature [23–31]. Here all optical switching is demonstrated in nonlinear photonic crystal using Kerr effect. The Kerr effect is generally defined as follows: $n_n(I) = n + \xi \times I$ where n is the linear refractive index, and ξ is the susceptibility of the material, so the refractive index of a dielectric material depends on the applied optical intensity. In order to have a wide filter selectivity and also a fast switching in the field of nonlinearity, we increase the number of ring resonators. The proposed structure is formed from three waveguides and three ring resonators, with a resolution of 37 rods horizontally and 41 rods vertically. The schematic structure of the 2D GaAs photonic crystal is shown in Fig. 7.

The nonlinear ring resonators have been formed by replacing 32 GaAs rods with nonlinear GaAs rods with the same radii as show in Fig. 7. The susceptibility of the nonlinear rods is $\xi = 10^{-16}\,\text{m}^2/\text{w}$.

The optical behavior of the proposed structure at $\lambda = 1.553\,\mu\text{m}$ is shown in Fig. 8. For low intensity input power the PCRR works at linear region, so the input light due to resonant effect of the ring resonator will drop to the drop waveguide, and travel toward port C which is shown in Fig. 8(a).

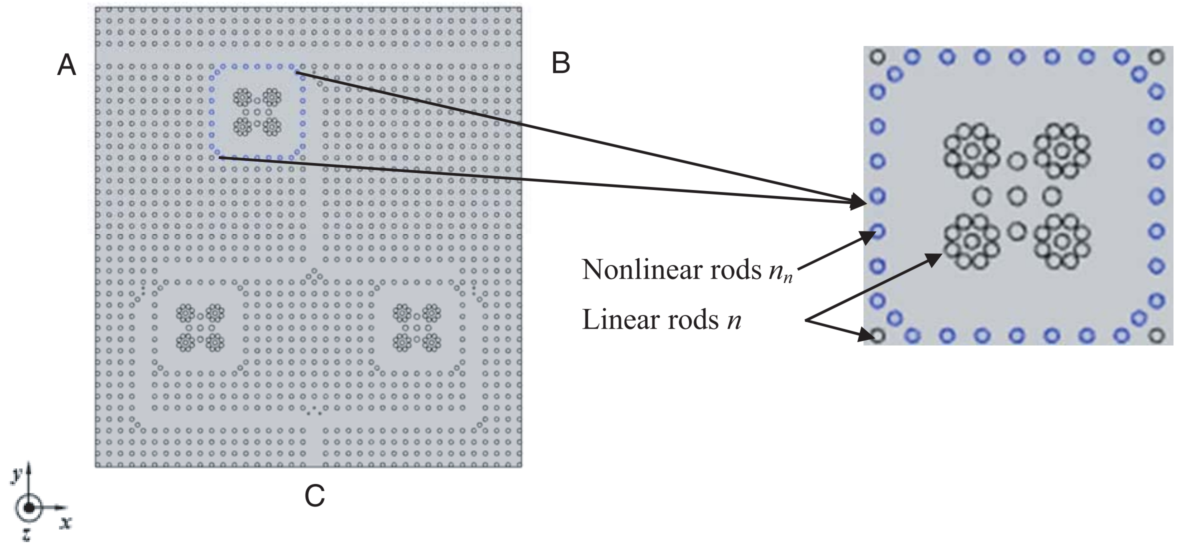
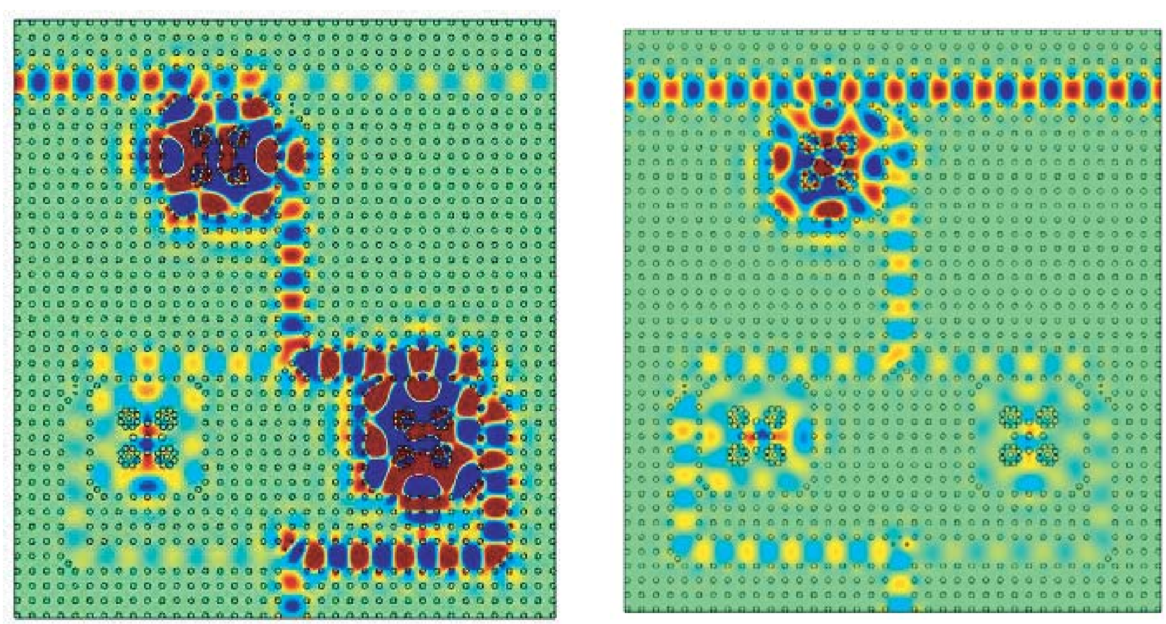


Figure 7. The schematic of a non-linear resonator. The switch structure parameters are set such as: $n = 3.28$, $r = 0.188 \times a$ and $a = 640\,\text{nm}$.



(a) (b)

Figure 8. (a) The optical field pattern and the out power in the low intensity ($I = 0.5\,\text{kW}/\mu\text{m}^2$). (b) The optical field pattern and the out power in the high intensity ($I = 1\,\text{kW}/\mu\text{m}^2$).

When the high-intensity light 'I' enters the ring equal to $1\,\text{kW}/\mu\text{m}^2$, the refractive index of rods is changed based on the Kerr effect, and therefore it tends to change the resonant wavelength of the ring. Therefore, the input light will not drop in the waveguide and will travel toward port B. So the structure shows switching behavior, shown in Fig. 8(b).

4. CONCLUSION

In this article, a 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. After that, we added some nonlinear rods around the ring core, The nonlinear Kerr effect for the nonlinear rods is $10^{-16}\,\mathrm{m}^2/\mathrm{w}$, for high intensity input power equal to $1\,\mathrm{kW}/\mu\mathrm{m}^2$, and the structure shows switching behavior. Finally, it can be concluded that the ring resonator introduced in this study can very well be utilized as a basic and potential component in the design of photonic integrated circuits. Photonic crystal manufacturing is one of the main inconveniences that can be confronted where is expensive in production. Sub 100 nm dimensions need generally employing high resolution electron beam lithography (EBL). Another production technology is the employment of nanoimprint lithography (NIL). Literature has shown manufactured devices with highly smooth and vertical sidewalls even on sub 100 nm scales. Devices as small as 40 nm with aspect ratios of more than 10 were successfully realized [32]. We think that our components will be fabricated by the same process. As perspective, low power can be used by using fano-resonance, and ultra-compact all-optical switches involving fano resonance have been demonstrated experimentally [33].

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