An all-optical 1*2 de-multiplexer based on two-dimensional nonlinear photonic crystal ring resonators

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In this work, a new configuration of an all-optical nonlinear de-multiplexer gate based on two-dimensional (2D) photonic crystals (PhC) is proposed. The gate is considered in the double-ring resonator shaped structure of silicon rods. In order to have a more functional structure, some defect rods made of nonlinear materials were positioned in the structure. Considering the functionality of the structure, photonic band gap (PBG), field distribution and transmitted power spectra are investigated. Plane wave expansion and finite difference time domain (FDTD) methods are utilized for extracting the PBG and field distribution diagrams. The remarkable dimension, bit rate, maximum intensity and contrast ratio of 116.64 μm^2, 3.125 Tbit/s, 97% and 40.2 dB are obtained, respectively, which make the gate an appropriate candidate for utilization in optical integrated circuits.

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Nowadays, photonic crystal (PhC) based structures have been of great interest to many researchers around the world. Therefore, many research teams have focused their works on PhC-based photonic structures and technologies[1]. These amazing structures mainly take advantage of their integrability, scalabitly, ease of fabrication and low cost[1,2]. The high efficiencies and precisions make them appropriate options for configuration of photonic integrated circuits (PICs). Therefore, all of the parts in PICs (transmitter, receiver, filter, logic gates, etc) can be considered based on PhC structures. PhCs are formatted in the shape of periodic rods, which are considered based on the combination of different dielectric layers (mostly air-dielectric). The rods are also positioned in the cubic format, rectangle format, etc. Two common PhC structures can be considered as dielectric rods in the air background or air rods in the dielectric background. In most of the applications, dielectric rods situated in the air background are considered. The dielectric materials can be defined by their refractive indices (RIs)[1]. In the design process of PhC structures, lattice constant should also be considered. This parameter indicates the periodicity of the structure or the distance between neighboring rods[3-5]. Photonic band gap (PBG), which indicates the guided or non-guided wavelengths, is an important parameter when the PhC based structure is investigated and studied. By considering the PBG spectrum, the structure's functionalities can be modified for various applications. As a matter of fact, by considering the structure in the guided wavelengths, the light wave can transmit through the rods, forming a dispersed and inappropriate transmission spectrum. On the other hand, by considering the wavelengths in the PBG region, the light wave can be propagated based on the total internal reflection (TIR) effect. In this case, the transmission spectrum and field distribution indicate a very low loss transmission through the structure[6-8]. Wavelengths situated in the PBG in both transverse electric (TE) and transverse magnetic (TM) modes are of great importance in the design process of PhC based devices. Structural and physical characteristics of the PhC can alter the PBG wavelengths (parameters like rod's radius, lattice constant value, refractive index of the rods and background can change the PBG wavelengths). In the PhC-based structures by considering various defects (constructing a waveguide by omitting some rods), light wave can be propagated in defined paths. These paths can be in the forms of straight ring resonator[1,3,6], rectangle, and etc. Through the years, many PhC-based structures have been designed like filters[3,6], logic gates[1,2,7], and etc for PICs. Optical logic gates, as important PIC elements, can be considered based on ring resonator PhCs. In Ref.[9], a three-port PhC power splitter was proposed and considered. In Ref.[10], a multiplexer was proposed by considering nonlinear ring resonator with various switching thresholds. Also in Ref.[11], a majority gate based on nonlinear PhCs was proposed. In another research[1], an all-optical 1*2 de-multiplexer for wavelength division multiplexing (WDM) applications was suggested. In Ref.[12], a structure based on PhC fiber was proposed, which could be utilized for diagnosis of low refractive index analyte with sensitivity factor of 16 400 nm/RIU.

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Also in Ref.[13], NON and NOR gates made of PhC structures in the ring shape with remarkable characteristics were proposed.

In this paper, a new 1*2 de-multiplexer gate based on two-dimensional (2D) PhCs with double-ring resonator (eight-shaped) shaped defects is proposed and considered. For enhancing the functionality of the proposed gate, five nonlinear defect rods (considering Kerr effect) are positioned in the structure. The PBG, field distributions and transmission's power spectra are considered for the 1*2 de-multiplexer gate and are presented in the following parts.

In this work, a PhC-based structure is designed and considered. Therefore (for investigating the functionality of the structure), PBG diagram, transmission's power spectrum and field distribution should be considered. These diagrams can be obtained through Maxwell's equations. In order to investigate the structure, first, the PBG diagram should be analyzed. PBG diagram can be obtained by considering the plane wave expansion (PWE) method[9,11]. Field distribution and transmission's spectra can be obtained based on the finite difference time domain (FDTD) methods. For this purpose, the following Maxwell's equations should be considered

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla * \boldsymbol{E} - \boldsymbol{J}, \tag{1}$$

$$\frac{\partial \boldsymbol{D}}{\partial t} = -\nabla * \boldsymbol{H} - \boldsymbol{J}, \tag{2}$$

where $\boldsymbol{E}$, $\boldsymbol{H}$, $\boldsymbol{D}$, $\boldsymbol{B}$ and $\boldsymbol{J}$ represent the electric field, magnetic field, electric displacement, magnetic induction fields and electric-charge current density, respectively.

The proposed structure is consisted of $20a \times 20a$ arrays of 2D PhCs rods, which is depicted in Fig.1.

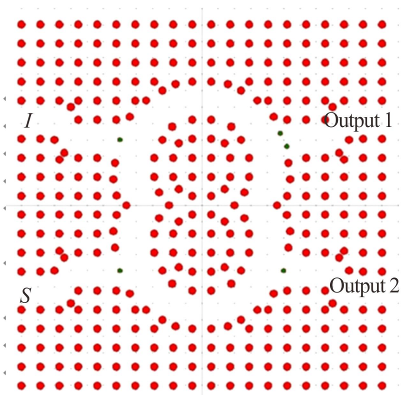

Fig.1 The proposed de-multiplexer based on 2D PhCs

As can be seen in Fig.1, two input ports of *I* (de-multiplexer input) and *S* (select) are forwarded to two output ports (Output 1 and Output 2) through two connected ring resonators (eight-shaped).

In the proposed structure, green nonlinear and red linear rods are considered. Tab.1 indicates the related parameters.

As can be seen, nonlinear (green) rods are considered for connecting input (*I*) and select (*S*) ports to output ports (Output 1 and Output 2) and making various switching thresholds. These rods are implemented via doped-glass rods with n=1.4 (linear part) and N^2=10—14 m^2/W (Kerr nonlinear)[14]. The truth table (logical values) of a 1*2 de-multiplexer can be seen in Tab.2.

Tab.1 Structural parameters of Fig.1

Parameter	Value
Red rod's radius (linear rods)	0.1 μm
Green rod's radius (nonlinear rod)	0.075 μm
Lattice constant (a)	0.45 μm
Refractive index of red rods	3.46

Tab.2 Logical values of a 1*2 de-multiplexer gate

S	*I*	Output 1	Output 2
0	0	0	0
0	1	1	0
1	0	0	0
1	1	0	1

In order to investigate the application of the proposed structure as a 1*2 de-multiplexer gate, the PBG diagram should be considered. As stated, PBG is achieved through PWE method. PBG diagram of the proposed structure can be seen in Fig.2.

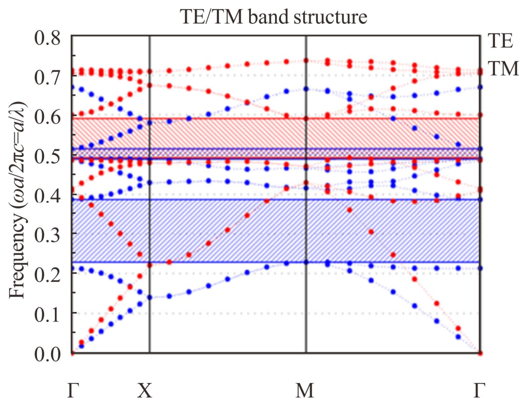

Fig.2 Schematic of PBG of the proposed structure

As can be seen for the TE modes, PBG in the wavelength range of 1.28 μm<λ<2.2 μm and 0.97 μm<λ<1.02 μm are obtained. 0.83 μm<λ<1.02 μm is also obtained for TM mode. TE mode is considered for further simulations due to its wider wavelength range (more dominant in the operation and simulations). In the TE region, TIR effect can help the light wave to be propagated through the structure (without being dispersed). Therefore, for the following simulations, the wavelengths positioned in the PBG range should be considered as the input wavelength (for having the TIR effect). λ=1.58 μm was considered as the incident wavelength due to its very low losses and higher transmission values (it is also appropriate for fiber optic communication application and designations (so close to λ=1.55 μm)). In the following sections, all of the 1*2 de-multiplexer conditions (considering Tab.1) would be investigated and the field distribution and transmission spectrum (for output port) would be considered.

In this section, different conditions of a 1*2 de-multiplexer gate (Tab.2) would be considered by applying the light wave to the *I* or *S* port. For each condition, field distribution and transmitted power spectra would be obtained. It should be noted that logic "1" is considered for values more than 0.6 and logic "0" for values less than 0.2.

In the case of *S*=0, *I*=1, an incident light wave (with the power and wavelength of 1 W and 1.58 μm) is applied to the input port *I* while *S*=0. The field distribution and transmitted power spectra are depicted in Fig.3.

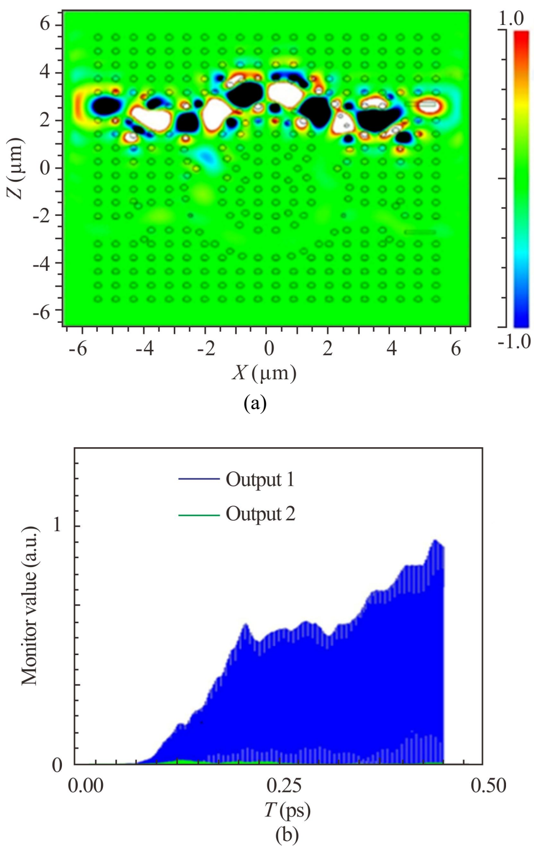

Fig.3 (a) Field distribution and (b) transmitted power spectrum for *S*=0, *I*=1

As can be seen in Fig.3 (for *S*=0, *I*=1), Output 1 moves toward high values (logic "1") and Output 2 gets low values (logic "0"). The obtained result is in accordance with the second line of Tab.2. Therefore, in this condition, high intensity output would be obtained in Output 1 port.

In the case of *S*=1, *I*=0, light wave would be applied to the *S* port while *I*=0. The field distribution and transmitted power spectra are depicted in Fig.4.

In this condition as shown in Fig.4, incident light wave would be only applied to the *S* port. As can be seen, Output 1 and Output 2 would obtain low values (no signal transmitted to Output 1 and Output 2). Therefore, Output 1 and Output 2 indicate logic "0". This conclusion is in accordance with the third line of Tab.2.

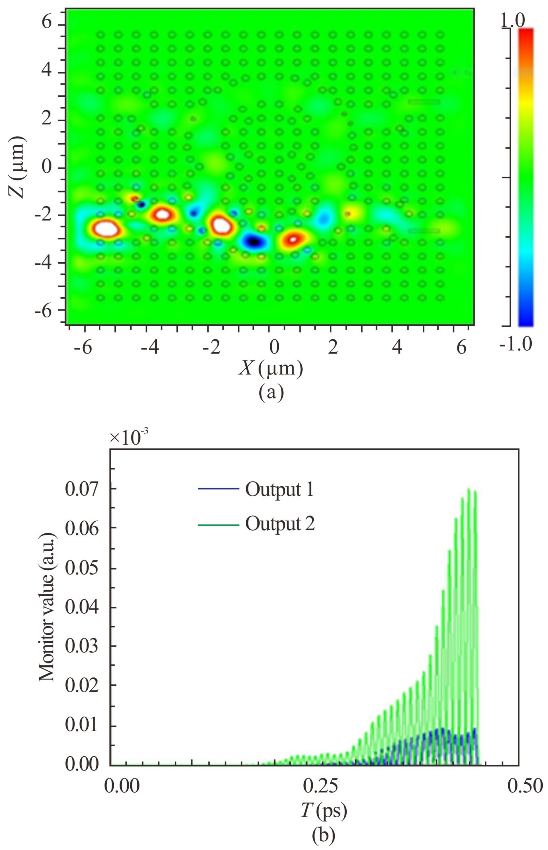

Fig.4 (a) Field distribution and (b) transmitted power spectrum for *S*=1, *I*=0

In the case of *S*=1, *I*=1, incident light waves (with the power and wavelength of 1 W and 1.58 μm) are applied to both *S* and *I* ports. The field distribution and transmitted power spectra are depicted in Fig.5.

In this case, the signal would be transmitted to Output 2. Therefore, Output 1 and Output 2 would indicate logic "0" and "1", respectively. The obtained result for *S*=1 and *I*=1 is similar to the forth line of Tab.2. Finally, an all-optical nonlinear 1*2 de-multiplexer was proposed, if the results of the previous parts would be compared with Tab.2.

For the proposed structure, the contrast ratio can be considered as[15]

$$CR = 10\log(P_1 / P_0)\ \text{dB}, \tag{3}$$

where P_1 and P_0 stand for the minimum output power (in logic "1") and maximum output power (in logic "0"), respectively. As a result, the contrast ratio can be calculated as 40.2 dB. Also as can be concluded[16], the response period of the output power is about 0.32 ps and the bit rate would be about 3.125 Tbit/s. The followng table compares the obtained results of the proposed de-multiplexer gate with some previously published logic gates.

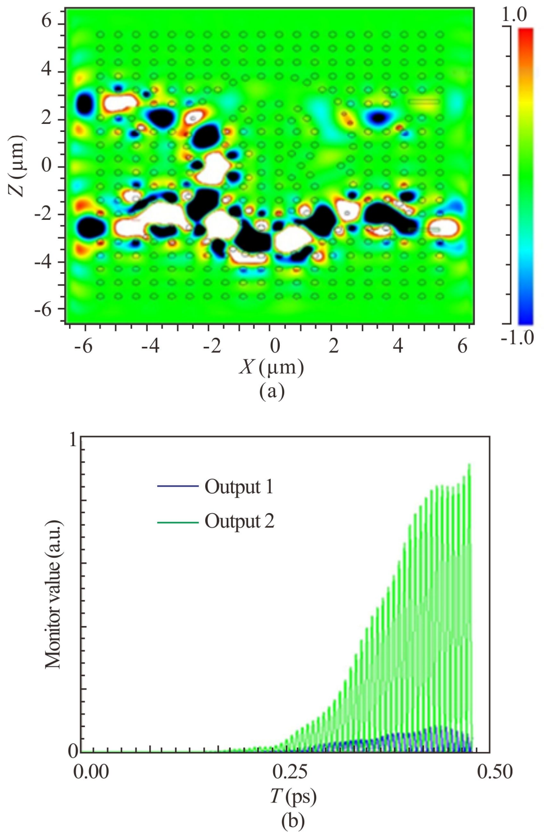

Fig.5 (a) Field distribution and (b) transmitted power spectrum for *S*=1, *I*=1

Tab.3 Comparison of our proposed work with previous works

References	Dimension (μm^2)	Bit rate (Tbit/s)	Maximum intensity (%)	Contrast ratio (dB)
[17]	133.9	2.2	92	13.2
[1]	171		94	9
[18]		0.5	95	19.5
[19]	721		90	
[16]		152		
Our proposed gate	116.64	3.125	97	40.2

In this work, an all-optical nonlinear de-multiplexer gate considering 2D PhCs was presented. The proposed de-multiplexer was based on 20×20 silicon rods in the air background. Five nonlinear defects rods (Kerr effect) were also considered in the structure. Different ports of *I*, *S*, Output 1 and Output 2 were considered as input, select and output ports, respectively. Application of the de-multiplexer gate was completely investigated based on its truth table (considering the field distribution and transmitted power diagrams). Finally, the 1*2 de-multiplexer gate with the dimension, bit rate, maximum intensity and contrast ratio of 116.64 μm^2, 3.125 Tbit/s, 97% and 40.2 dB, respectively was obtained. The proposed gate with its remarkable specifications can be considered as an appropriate candidate for utilization in optical integrated circuits.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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