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Dual-wavelength-operable all-optical OR gates based on photonic-crystal waveguide

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We propose and numerically investigate a new all-optical OR gate based on a two-dimensional triangular-lattice photonic crystal. The device is composed of a hexagon- shaped ring resonator waveguide with two input ports and one output port in silicon rods embedded in air. Transmission behaviors of the proposed device are investigated by the finite difference time domain method. The logic OR gate can work at two wavelengths of 1.34 and 1.38 μm and is potentially applicable for photonic integrated circuits.

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Keywords: Optical logic gate, Ring resonator, Photonic crystal

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1. Introduction

With the advances of data communication, optical logic gates have been researched intensely due to their promising applications in optical computing and signal processing [1-2]. Many works have been reported to realize optical logic functions like optical fibers [3], semiconductor optical amplifiers [4], and photonic crystals (PhC) [5-6]. As to the device dimension and operation as well as the compatibility to photonic integrated circuits in the existing optical devices, the PhC-based waveguide devices have the benefits of compactness, fast response, low power consumption, and potential for photonic circuit integrations. Wherein, the PhC ring resonator waveguide has been used to demonstrate the applications of add/drop filter in WDM system [7] or optical logic gate in the optical computing [8]. However, the PhC-based logic gates may require a great amount of additional energy to activate the nonlinearity or a complicated device configuration with multiple ring resonators. Furthermore, it has been rarely reported that an all-optical logic gate can have a capacity for operating in more than one wavelength, but multiple operating wavelengths may provide more flexibility in the applications of logic gate in the optical signal processing. In this paper, we thus propose an all-optical OR gate of simple scheme based on triangle-latticed two-dimensional PhCs of silicon rod embedded in air. The device is mainly configured with a hexagonal PhC ring resonator (PCRR), in which the optical OR gate can work at wavelengths of 1.34 and 1.38 μm in the optical communication window. The transmission characteristics of the device are analyzed by using a two-dimensional finite difference time domain (FDTD) numerical method [9].

2. Operational principle and performance analysis

Fig. 1 schematically illustrates a layout of the optical logic gate proposed in the present paper. The main body of the device is a hexagon-shaped PCRR with two input ports (Port A and Port B) and one output port (Port Y). The device is structured in PhC waveguides formed of a triangular lattice of infinite circular silicon rods embedded in air. It is assumed that refractive index of silicon rod and air are 3.4 and 1, respectively, and each rod has a cross-sectional radius of 0.35a, where a denotes the PhC lattice constant. The PhC waveguides are formed by removing lines of the silicon rods from the two-dimensional photonic crystal. Regarding the hexagonal PCRR, its upper arm is parallel to Port A to form an upper directional coupler, its lower arm is parallel to Port B to form a lower directional coupler, and its right-hand arms are joined and connected to Port Y to form a y-branch waveguide. The directional coupler works as a beam splitter, dividing an input light beam from the Port A or Port B into two beams, one of which travels in the 60°-angled output waveguide forward and the other travels in the 120°-angled output waveguide backward.

If a signal light is launched into the PCRR through Port A or Port B, it would be split by the beam splitter into clockwise and counter-clockwise lights with different intensities. When the two lights meet each other at the y-branch connection point, a phase difference has been induced between them. With a proper design for the PCRR's arm lengths, the two lights would interfere with each other in partially constructive at the y-branch connection point to output a high transmission of larger than 85% at Port Y. On the other hand, if two signal lights are launched into the PCRR through Port A and Port B, the clockwise and counter-clockwise lights due to the signal light from either Port A or Port B would interfere in partially constructive with each other at the y-branch connection point to produce a temporary interfered beam. When the two temporary interfered beams from Port A and Port B meet at the y-branch connection point, they would interfere constructively at the y-branch connection point according to the beam superimposition principle, and hence a high transmission can be outputted to Port Y. As a consequence, the device works as an OR gate, which outputs a logic-1 transmission to respond for at least one logic-1 input at Port A and Port B.

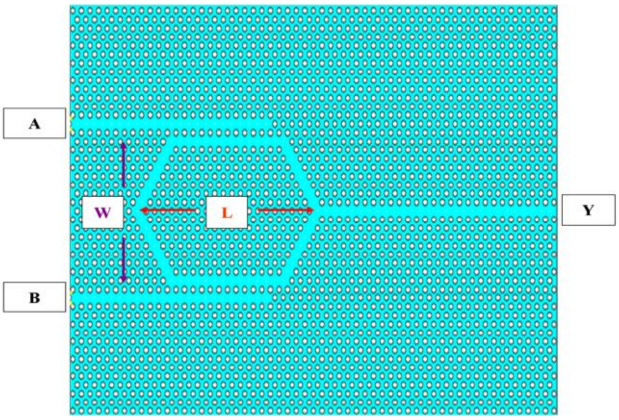

Fig. 1. The proposed PhC logic OR gate.

Fig. 2 shows a dispersion diagram of the triangular-latticed Si-rods-embedded-in-air photonic crystal, which is derived by the plane wave expansion method with its normalized band gap frequency **a**/λ ranging from 0.443 to 0.538. The cross-marked curves represent the possible TM-mode waves. There are two complete band gaps in the proposed PhC triangular lattice, one of which corresponds to a wavelength band ranging from 1.30 to 1.57 μm in the optical communication window. A light with a wavelength in the wavelength band can be confined and transmitted within the PhC waveguides. Since a triangular lattice of circular dielectric rods has a wider operational bandwidth than the conventional square one, we choose the triangular photonic lattice in this work. Also, the TM-mode waves can be emitted into the crystal lattice in the directions of wave vector Γ-M, M-K and K-Γ. Based on the dispersion diagram, we can analyze the wave behaviors, bandgaps, and defect modes to explore operational bandwidth and hence a preferable layout of the proposed device.

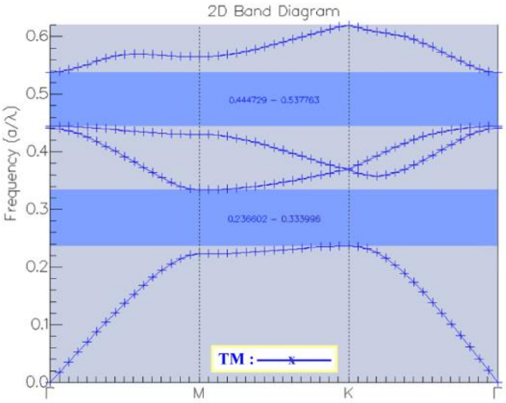

Fig. 2. The band diagram of triangular lattice of infinite circular silicon rods embedded in air.

The FDTD method [9] has been used to numerically analyze the light propagation behaviors of the proposed optical logic gate. The mathematical FDTD model of photonic crystal waveguide can be referred to [10] and it can be performed with simulation software such as the freely opened MEEP by MIT [11] or the commercially available CrystalWave of Photon Design. The latter is used in this study. A continuous TM wave of 1.38-μm wavelength is used to demonstrate OR-gate operations of the device. In the simulation, the Si-rods-embedded-in-air PhC device has a width W = 13**a** and a length L = 21**a**, in which the lattice constant **a** = 0.7 μm and hence the Si rod radius is 0.245 μm. Since the optical logic gate can have a small device dimension, e.g. less than 20 μm, so no loss is assumed in the PhC waveguide in the simulating calculations. In the following, Input (1,0) means that Ports A and B are inputted with logic-1 and logic-0 lights, respectively, while Input (1,1) means that each of Ports A and B is inputted with a logic-1 light. A valid logic signal can be defined with transmission levels of less than 35% as logic 0 and more than 95% as logic 1, which is more stringent than the definition of transmission levels of less than 43% as logic 0 and more than 85% as logic 1 in [12]. Figs. 3-5 show the field evolutions of the optical logic gate at Inputs (0,1), (1,0) and (1,1). When a logic-1 light is launched into Port A and a logic-0 light is launched into Port B, the light beams in the PCRR interfere with each other in partially constructive and transmit to Port Y; thus, the output is logic 1 as shown in Fig. 3. Symmetrically, the same transmission can be obtained when the logic-0 light is at Port A and the logic-1 light is at Port B as shown in Fig. 4. When logic-1 lights are concurrently launched into both Port A and Port B, the PCRR would cause the light beams to interfere each other constructively at the y-branch connection point due to the ring resonance effect and transmit more energy to the output Port Y, so the output is also logic 1 as shown in Fig. 5.

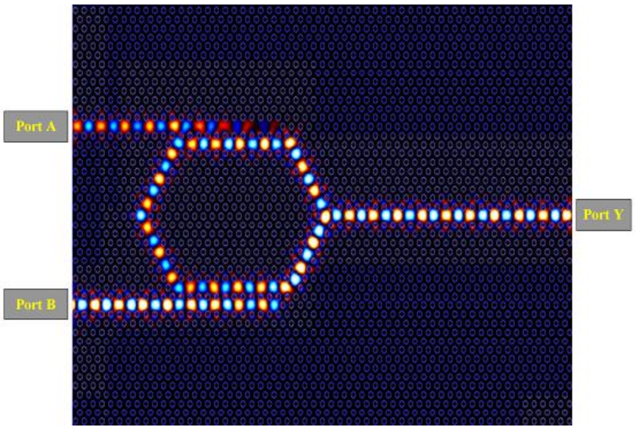

Fig. 3. *Field evolutions of the device for the input (0,1).*

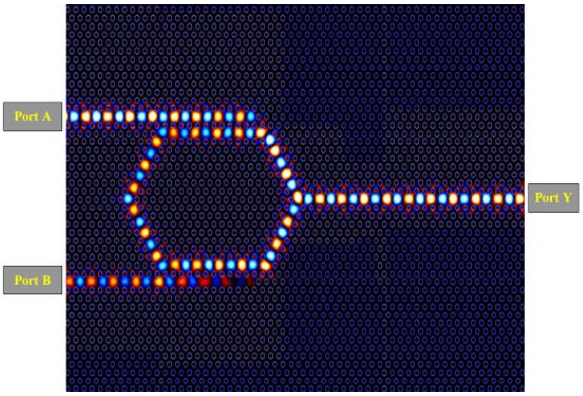

Fig. 4. *Field evolutions of the device for the input (1,0).*

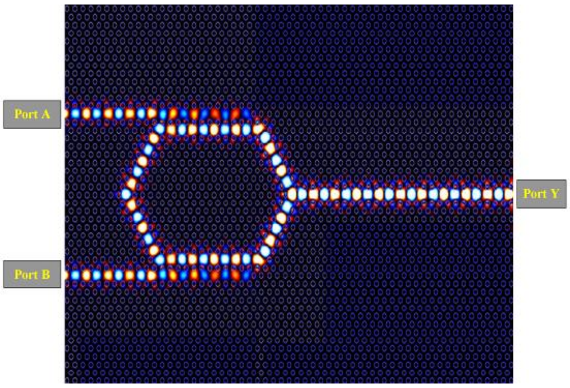

Fig. 5. *Field evolutions of the device for the input (1,1).*

Conventionally, the existing schemes of optical logic gate are reported to function at only one specified wavelength; however, according to the band diagram of the Si-rods-embedded-in-air photonic crystal shown in Fig. 2, the optical OR gate can have more than one operable wavelengths, and thus it may work at various wavelengths in the optical communication windows, so as to provide more flexibility for the wavelength-division-multiplexing (WDM) applications. To verify the WDM capacity of the PhC AND gate, lights of various wavelengths are used as input lights in the calculation. Here we take steps of trial by error to find out possible wavelengths in the 1.3-µ*m* window. Some results are listed as a truth table in Table 1 below.

Table 1. Truth tables of the proposed logic gate corresponding to various wavelengths.

Wavelength	Input	Transmission	Output
λ=1.34 µm	logic	0%	logic 0
	logic	100%	logic 1
	logic	100%	logic 1
	logic	150%	logic 1
λ=1.38 µm	logic	0%	logic 0
	logic	100%	logic 1
	logic	100%	logic 1
	logic	143%	logic 1

The normalized transmission (P_o/P_i) less than 35% is referred to logic 0 and that more than 95% is referred to logic 1 in this paper. At the wavelengths 1.34 and 1.38 µm, the normalized transmission powers (P_o/P_i) for the inputs (0,1) and (1,0) are 100%, functioning as a logic-1 transmission. The normalized transmission power for the input (1,1) is much larger than 100%, providing a logic-1 transmission with a more fan-out capacity. Thus, the device has an OR gate function at both wavelengths. In addition, the response time of the proposed all-optical OR gate can be estimated by the FDTD running time to be about 1.2 ps.

3. Conclusions

In summary, a novel all-optical OR gate has been proposed and numerically investigated based on a two-dimensional PhC silicon grid. The device is composed of a hexagon-shaped ring resonator waveguide with two input ports and one output port in triangular-lattice silicon rods embedded in air. The logic OR gate can operate at wavelengths of 1.34 and 1.38 µm, in accordance with the specification that the logic 0 and 1 are defined as less than 35% and more than 95% of transmission, respectively. These findings would provide the PCRR devices with potential applications for all-optical logic integrated circuits of multi-wavelength operability.

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