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Interference based square lattice photonic crystal logic gates working with different wavelengths

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ABSTRACT

We propose a new configuration of interference based OR, XOR, NOT and AND optical logic gates on a two dimensional square lattice photonic crystal (PhC) platform. The working of these devices was analyzed by the FDTD method and the operating frequency range was explored using the plane wave expansion method. The XOR and NOT gates have high contrast ratio which is more than 35 dB between high and low logic states, for a particular wavelength. All these devices are operating with multiple wavelengths. The impact of structural parameter like radius on the operating wavelength and Contrast Ratio (CR) was analyzed. It is found that the optimization of structural parameters makes it possible to obtain the operating wavelength allowed by band structure. These proposed devices were made up of linear waveguides and square ring resonator waveguides, without using nonlinear materials, optical amplifiers and external phase shifters.

1. Introduction

Optical logic gates are one of the key components of future all-optical networks, optical computing and optical signal processing [1–4]. By realizing its importance, many optical logic gates operating with different schemes were proposed [5–9]. Among these, PhC based optical logic gates attracted much attention due to its simple structure, low loss, high operating speed and small size [1]. There are many schemes of realizing such devices including nonlinear materials [10–12], self-collimation effect [13,14], interference effect [15–18] etc. The nonlinear material based PhC logic gates have high contrast ratio, but high power consumption, narrow operating frequency and long interaction time limits their applications [8,15]. Due to difficulty in controlling the dispersion, it is difficult to achieve self-collimation effect in PhCs [13,19]. The interference based PhC devices are an alternate possibility, where nonlinear materials are not used. However, interference based structures are limited, due to its difficulty in precisely controlling the phase shift difference for all input signals [20]. To obtain high intensity contrast between logic states of one and zero is also difficult [21]. There are some optical logic gates based on interference which uses external phase shifters for their operation [17,22]. But the use of these external components like phase shifters causes inconvenience and also requires additional space [22].

Most of the interference based optical logic gates are based on triangular PhC lattice [17,18,22]. But in this letter we propose interference based PhC optical logic gates using a new type of structure on a square lattice PhC platform. The square lattice provides effective confinement of light. The fabrication also becomes easier due to its simple geometry [23]. The external phase shifters are avoided and thus made convenient for application. There is no nonlinear materials included and hence it can operate with low power signals. It can also be operated with multiple wavelengths. The size of the proposed devices is small and has a simple structure, which is helpful for optical-integrated circuit design.

2. Theory and operating principle

The proposed PhC based logic gates are working on the principle of interference effect. The designed structure has square lattice of dielectric rods arranged in air background. The band diagram of perfectly periodic lattice gives the information about the Photonic Band Gap (PBG). PBG means, a set of frequencies which are not allowed to propagate through the periodic structure. But these frequencies can be transmitted through the waveguide by introducing proper defects into the perfectly periodic structure. Thus making linear waveguides and ring resonator waveguides based on the defect, we have designed optical logic gates. Depending upon how the signals from a different input interfere at the output, we will get different logic operations.

According to wave theory of optics, there will be a constructive

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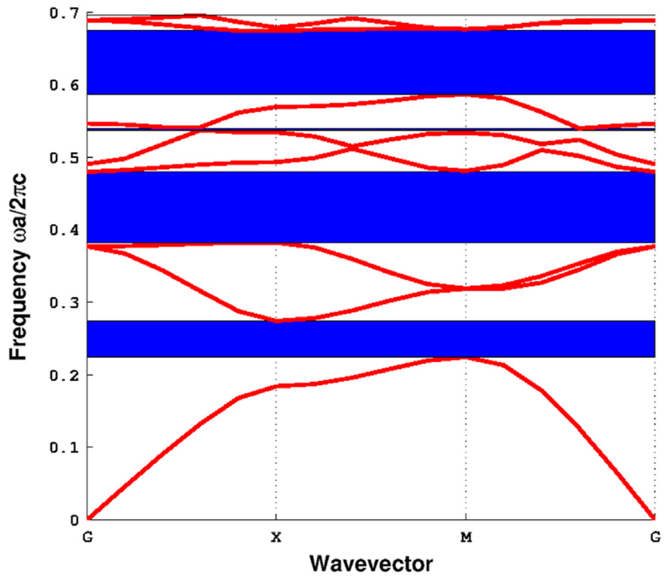

Fig. 1. Band structure for TM mode of perfectly periodic two dimensional square lattice of silicon rods in air.

interference, if the phase difference between two optical waves is $2n\pi$, where $n=0, 1, 2 \ldots$. Then the output will have high power corresponding to logic state of "1 ". If the phase difference is $(2n+1)\pi$, there will be a destructive interference and we will get approximately zero output. This is corresponding to the logic state "0" [20]. The different PhC gates are obtained by introducing the phase difference between the optical beams via precise control of path difference.

In order to explore the operational frequency region of the device the dispersion diagram is used. Fig. 1 shows the dispersion diagram of the two dimensional perfectly periodic square lattice of silicon rods in air for TM mode. For plotting the dispersion diagram we have used the Plane Wave Expansion (PWE) method [24]. The band structure shows, three band gaps of frequency range 0.225–0.274 (c/a), 0.381–0.480 (c/a) and 0.587–0.675 (c/a) for TM mode. We have selected the operating wavelength range as 1354–1706 nm corresponding to frequency range of 0.381–0.480 (c/a). There is no considerable band gap for TE mode. So the device considered here only supports TM mode.

In ordered to get the working frequency and field propagation we have adopted the finite difference time domain (FDTD) method based on MEEP [25] code. To get the operating frequencies, we have calculated the field transmission of the structure. To obtain transmission we have taken Gaussian source with center of frequency and width as 0.42965 c/a and 0.1009 c/a. To get the information about transmitted power, we have used a continuous source with operating frequencies, determined by the transmission calculations. The thickness of the perfectly matched absorption layer is taken as 10 a.

The performance of the optical logic gates can be studied by analyzing the Contrast Ratio (CR). It is defined as [26]

$$CR = 10\log_{10}\frac{P_1}{P_0}$$

where P_1 and P_0 are output power of logic 1 and logic 0 obtained at the output port respectively. Logic 1 is achieved when the output at port has maximum output power. Similarly logic 0 defined when output gives minimum output power.

3. Design and logic operation

The proposed two dimensional photonic crystal device composed of a square ring resonator waveguide with three other linear waveguides which are connected to each other by this ring resonator waveguide. One of the three linear waveguides serves as output waveguide with output port O and the remaining two waveguides are considered as input waveguides with input ports A and B, as shown in Fig. 2. The waveguides are obtained by removing the arrays of dielectric rods from the perfectly periodic structure of this two dimensional PhC. The assumed dielectric rods are of silicon with dielectric constant 11.56 and a radius of $r=230$ nm. The period of lattice of this PhC is $a=650$ nm. The upper and lower side of the square ring resonator waveguide are directly coupled to the two input waveguides, with a line of dielectric rods between each side and the corresponding input waveguide. The output waveguide is connected to the right side of the square ring resonator waveguide.

Considering the case of launching the signal into either input ports A or B, it can be split into two with different intensities, one that travels in clockwise and other in anticlockwise direction in the ring resonator waveguide. These two light signals interfere at output waveguide and give variation of intensity at the output port O. Depending upon whether they interfere constructively or destructively, we get the corresponding logic output 1 or 0 at output port O. This logic states 0 and 1 are distinguished by the threshold values.

In PhCs the light path difference of one lattice constant

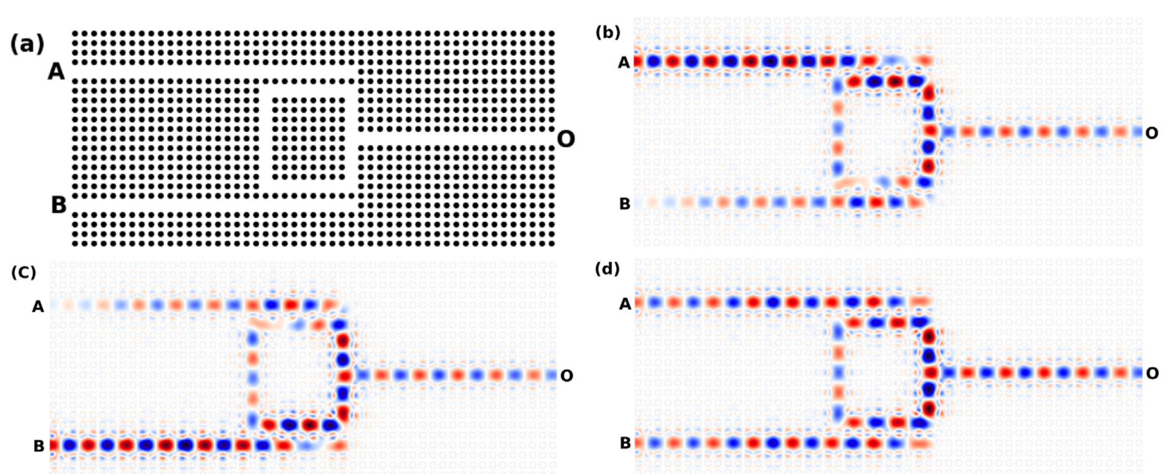

Fig. 2. (a) The designed PhC structure for the OR gate. (b)–(d) represent the field propagation inside the structure corresponding to the logic OR gate operations.