Novel All-Optical Logic Gates Based on Photonic Crystal Structure

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Abstract. We have designed AND, NOT, and NOR logic gates based on photonic crystal structure employing cross-waveguide geometry with nonlinear rods using finite difference time domain (FDTD) method. The logical function is based on the frequency resonance shift of the microcavity caused by Kerr nonlinearity. The proposed devices benefit a simple and small structure, and clear operating principle.

1. Introduction
Photonic crystal (PhC) is a promising candidate as a platform on which to construct devices with dimensions of a few wavelengths of light for future photonic integrated circuits. The photonic crystal concept was proposed in 1987 [1,2], and the first 3D experimental photonic crystal with full band gap was manufactured in 1991. The existence of band gap in PhC structures led to many prominent applications in integrated optics. Photonic crystals are nowadays used for different applications such as filters [3], modulators [4–6], switches [7], beam splitters [8-10], and super prisms [11–13] for multiplexing and demultiplexing for example.

All-optical switching is one of the most important targets for photonics. However, this goal has been considered difficult to achieve because of the inefficiency of optical nonlinearity in materials. All-optical switching utilizes the nonlinear refractive-index change as a function of the electrical field intensity.

Nonlinear photonic crystal microcavities offer unique fundamental ways of enhancing a variety of nonlinear optical processes for optical switching. When ultrasmall and high-quality factor cavities are used as switches, the field is enhanced by $Q/V$, where $V$ is the mode volume. By taking into account the reduction of frequency shift required for switching by a factor of $Q$, cavities will generally exhibit a switching power reduction scaled as $V/Q^2$ [14].

Ultra-compact all-optical logic gates are advanced kinds of optical switches which are used as key elements for real-time optical processing and information communications. As a consequence of recent advantages in nanophotonic fabrication, the amount of compactness and low loss of photonic crystal (PC) structures make them one of the best candidates for constructing ultra-fast optical integrated circuits. So far, several schemes have been investigated to realize various all-optical logic functions such as AND, NOT, NOR, XOR, NAND gates [15-20]. In this paper, we have proposed novel all optical AND, NOT, and NOR gate based on cross-waveguide geometry using nonlinear 2D photonic crystal lattice. The prominent features of these gates in comparison to the former designed gates are their fast switching action (about 10 ps), and structure compactness (it has the dimensions in the order of several wavelengths of light). In addition, since the...
same structure has the compatibility to be used as AND, NOT, and NOR gates it offers good candidates for all-optical integrated circuits in contrast to previously designed gates [15-20]. Numerical assessment for the bistable switching action in this geometry has been discussed earlier in [21].

2. Design and Simulation

In this work a 2D photonic crystal lattice with nonlinear rods is used. The structure is based on a $15 \times 15$ square lattice with the lattice constant $a = 575$ nm. The material used for fabrication of nonlinear rods is AlGaAs which provides the refractive index of 3.5 with instantaneous Kerr coefficient of $n_2 = 1.5 \times 10^{-17} \text{ W/m}^2$. In addition, the background material is taken to be air with refractive index of 1. The radius of the rods is set to $0.2a$. As shown in figure 1, two cross waveguides are created by elimination of the rows of rods. These are connected to each other using an asymmetric cavity. Since the radiiuses of the elliptical cavity have been taken different, so, we will have two separate modes in the vertical and horizontal directions. The cavity is considered to have the radiiuses $r_a = 0.27a$ and $r_b = 0.32a$. This geometry provides the resonance wavelengths of 1550 nm in X-direction, and 1649 in Y-direction. Only TM modes are considered in the paper, it is well known that Maxwell’s equations can be described in scalar forms for TM modes as

$$\frac{\partial E_z}{\partial x} = \varepsilon(r) \frac{\partial H_y}{\partial t}$$  \hspace{1cm} (1)

$$\frac{\partial E_z}{\partial y} = \varepsilon(r) \frac{\partial H_x}{\partial t}$$  \hspace{1cm} (2)

$$\frac{\partial H_x}{\partial x} - \frac{\partial H_y}{\partial y} = -\mu(r) \frac{\partial E_z}{\partial t}$$  \hspace{1cm} (3)

We have also applied numerical FDTD method to simulate the light propagation in the designed structure. To analyze the wave behavior, group velocity, bandgaps and defect modes, we have derived the dispersion diagram by the plane wave expansion method (PWE) shown in Figure 1. The input beam frequency is taken about 1.55 µm which is inside the band gap of the structure for TM mode.

![Figure 1. Band structure of the photonic crystal lattice](image)
Figure 2 shows the general structure for proposed logic gates.

![General structure for proposed logic gates](image)

I) AND Gate

Firstly we discuss the AND gate design using this structure. AND gate encompasses of two inputs and an output. As shown in table 1 the output is logically ‘1’ if and only if both of the input values are ‘1’.

| A  | B  | Output |
|----|----|--------|
| 0  | 0  | 0      |
| 0  | 1  | 0      |
| 1  | 0  | 0      |
| 1  | 1  | 1      |

Table 1. Logic table of AND gate

In this gate we use the input signals A and B (No signal is applied via Input C in this case). We take the frequency of signal A such that normally it does not match with the resonance frequency of cavity. So, the output power in this case is about zero. By applying the input signal B, the resonance frequency will change, and signal A fall at the resonance frequency of cavity. As the result, the output power reaches to about 90% of the input power A. Figure 3 demonstrates the resonance frequency shift of the cavity. $\omega_c$ and $\omega_I$ represent the cavity resonance and input signal A frequencies respectively. The resonance frequency shift in cavity causes the output power change. For the input B field amplitude of 450 V/m, the resonance wavelength shift is about 5.7 nm. We have taken the amplitude of input signal A so small that it makes no effective influence in resonance shift. Note that existence of both signals A and B are necessary for making nonzero output power. Thus the system performs as an AND gate.
II) NOT Gate

Now we discuss making a NOT gate with this geometry. NOT gate contains an input (as the control signal) and an output. As shown in table 2 the output is logically complement of input.

Table 2. Logic table of NOT gate

| B | Output |
|---|--------|
| 0 | 1      |
| 1 | 0      |

Like as AND gate structure, in this case we apply input A a fixed signal that it’s frequency matches with the resonance frequency of the cavity. Note that signal A plays a role of a source for the output. Signal B, the controlling input, is used to manipulate the structure as a NOT gate. So, normally when the input power B is zero, the output power is about 90% of input power A. we attribute the logical ‘1’ to this output state. By applying signal B, resonance frequency of the cavity changes, and the frequency of signal A does not match with the resonance frequency, and output power reaches to zero. Thus the system performs as an NOT gate. Figure 4 represents the performance of NOT gate using the resonance frequency shift.
III) NOR Gate

Finally, we investigate the performance of NOR gate using the cross waveguide structure. NOR gate encompasses of two inputs and an output. As shown in table 3 the output is logically ‘1’ if and only if both of the input values are ‘0’.

| B | C | Output |
|---|---|--------|
| 0 | 0 | 1      |
| 0 | 1 | 0      |
| 1 | 0 | 0      |
| 1 | 1 | 0      |

In this case we apply a fixed signal into the input A, that it’s frequency matches with the resonance frequency of the cavity. Note that signal A plays a role of a source for the output. We use the signals B and C as input beams. Both the power and wavelength of the signals A and B are considered equal. When the both input signals B and C are off, the output power is about 90% of input power A (output signal is logically ‘1’). By applying one or both of the signals B and C resonance frequency of the cavity varies, and it does not match with the frequency of signal A. Therefore the output power reaches to zero. Thus the system performs as an NOR gate.

3. Conclusion

In this work we designed AND, NOT, and NOR all optical logic gates based on a cross waveguide geometry using a 2D photonic crystal lattice. The logical function is based on the frequency resonance shift of the microcavity caused by Kerr nonlinearity. Our analyze method for derivation of band structure is based on plane wave expansion, and we used FDTD method to simulate the wave propagation and devices operation. The proposed devices benefit a simple and small structure, and clear operating principle which shows that they can be strong candidates for future photonic integrated circuits.

3. References

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