Design of an Ultra-Compact and High-Contrast Ratio All-Optical NOR Gate

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Abstract

In this research, an all-optical NOR gate is designed and simulated based on two-dimensional photonic crystals. A square lattice has been used to design this structure. This logic gate has two main inputs, a bias input and an output. Because the output of the NOR gate must be “1” for zero inputs, a bias input is required. One of the characteristics of this structure is its small size for use in optical integrated circuits. Also, in order to reduce the detection error in the output, it has been tried that the outputs have a suitable distance in two “0” and “1” logical states. The use of a small number and simple point defects makes the design of this gate easier. The simulation results show that the proposed structure is suitable for working at a wavelength of $1.55\mu\text{m}$. Also, the amount of optical power at the output is high in the “1” logical mode and low in the “0” logical mode. This indicates that this structure has a reliable output for detecting logical values. In this paper, a photonic crystal structure is proposed to realize the NOR logic gate, which is small in size and uses simple linear and point defects. The use of very few point defects has made the design simpler and thus easier to build this gate. Due to these characteristics, this structure can be suitable for optically integrated circuits.

1. Introduction

Photonic crystals are alternating structures of dielectric material whose refractive index changes alternately in one, two, or three dimensions. Depending on the dielectric material, the shape of the structure, the radius of the rods, and the lattice constant, each structure prevents the propagation of a specific wavelength called the photonic band gap (PBG). The PBG property is used to design a variety of optical devices and logic gates [1–3].

The simplicity of the designed gates, high speed, and small dimensions are important features of photonic crystals. The invention of the transistor had revolutionized the electronics industry in the past, paving the way for the design of integrated circuits and the development of electronic devices, which transformed human life. In recent years, photonic crystals have also revolutionized the optical device industry and are widely used in the design of optical fibers, amplifiers, filters, sensors and, biosensors [4, 5].

In the digital field, logic gates (AND, OR, NOT, NAND, NOR, etc.) can be designed based on photonic crystals, and many papers have been published in this field [6–28]. Structures in the field of optical adders and subtractors using photonic crystals have also been reported [29–35]. Decoders and encoders based on photonic crystals have also been designed so far [36–44].

One of the important goals of photonic crystals is to design all-optical processors that, in addition to their small size, dramatically increase the speed of information processing. A high quality logic gate can play an effective role in the design of a processor. One of the indicators of the quality of the logic gate is the closeness of the output power in logic “1” to the amount of input power in the “on” state, and also the closeness of the output of logic “0” to the amount of zero power. In other words, more distance between

the output power values in the two modes of logic “1” and “0” is one of the design goals. It can be said that the greater power distance, the less possibility of detection error at the output.

In this paper, we have tried to design an all-optical NOR gate based on photonic crystals that has a distance between the power values of “0” and “1” logic states, and also has small dimensions. Reducing the dimensions of the gate can make this gate usable in optically integrated circuits. Also, the simplicity of the proposed gate structure is another design goal. The simpler the designed gate, the easier it will be to build. Simpler defects can be used to have a simple structure. Also, not using ring resonators makes the design simple. If changing the radius of the rods in a structure is used as a point defect, the number of defects should be tried to be small.

In the proposed optical gate, only one of the rods has changed radius and the two rods have moved slightly. Also, no ring resonator is used in this design, so the design of this optical gate is very simple and will be suitable for use in optical integrated circuits.

The proposed NOR gate is designed to work at a wavelength of $1.55\mu\text{m}$. The reason for choosing this wavelength is that it is used in current fiber optic communications. Therefore, the initial structure must be chosen so that this wavelength is in the range of PBG. In this way, light waves with this wavelength do not pass through the periodic structure, and by creating waveguide paths, it will be possible for light to propagate in the desired paths.

To design the NOR optical gate, three input paths and one output path have been used. In addition to the two main inputs, additional input is required. Given that in the optical NOR gate, the output must be equal to “1” for “0” inputs, so we need an additional input called “Bias”. The bias input is considered “on” for all input modes.

2. All-optical Nor Gate

To design an all-optical NOR gate, a photonic crystal structure with a square lattice is first selected. This structure consists of Si rods placed in the air. Si rods have a cylindrical cross section. The refractive index of the rods is 3.48 at the wavelength of $1.55\mu\text{m}$ and the refractive index of the air is equal to 1. The number of rods is considered to be 17×19 . The lattice constant, which is the distance between the centers of the rods, is equal to $0.56\mu\text{m}$, and the radius of the bars is considered to be $0.112\mu\text{m}$.

The results of the band structure for the alternating structure are shown in Fig. 1. The resulting band structure diagram shows that a PBG is generated at the normalized wavelength. The wavelength equivalent to this normalized range is $1.35 < \lambda < 2.00$.

Given that the PBG range has a wavelength of $1.55\mu\text{m}$, this structure is suitable for the mentioned wavelengths. Now to reach the desired NOR gate, paths for inputs and output must be selected. Linear defects are used to propagate light in these directions. In this structure, to avoid the complexity of the

structure and the simplicity of the design, very few point defects have been used. Figure 2 shows the defect paths to achieve the final structure of the all-optical NOR logic gate.

Figure 2 shows that the two inputs A and B are located on the left side of the structure. Using two linear defects named W1 and W2, the light propagation path is created in these inputs. There is also a bias input in the middle of the main inputs. The bias input has a phase difference of 180° compared to the two main inputs. A vertical linear defect is also selected to connect all inputs. Finally, the output path is created with a linear defect along the bias input. A rod is selected at the beginning of the output path as a point defect, whose radius is half the radius of the other rods and is shown in the figure by R_1 . Also, two rods at the top and bottom of the vertical path are moved $0.4a$ to the corners. These rods are shown in Fig. 2 in green. As can be seen, the number of point defects in this structure is very small and this makes the structure less complex during implementation.

Figure 3 shows a diagram of the distribution of optical power in defect paths. Figure 3 (a) shows the power distribution for the zero inputs ($A = B = 0$). In this case, since the bias input is always on, the power generated from this source is directed to the output path, and most of the power is transferred to the output. In this case, a small amount of light power is emitted to the main inputs and will cause power dissipation.

Figure 3 (b, c) shows the optical power distribution for unequal inputs ($A \neq B$). These two figures show that when only one of the main inputs is on, the emitted waves from it have a destructive interference with the emitted waves from the bias input at the point of collision. Therefore the power distribution is very small and the amount of power at the output will be very low.

When both inputs are on, the light waves emitted from them also interfere with the bias source at the point of collision, resulting in a reduction in the amplitude of the wave. That is, the interference of the waves will be destructive. Figure 3 (d) shows the power distribution diagram for this mode.

To analyze the simulation results quantitatively, optical power simulation has been performed for the optical NOR gate for different input modes. In these graphs, normalized quantities are used to better compare the results. This means that the power of the bias source is considered as the basis and the power calculated at the output is considered relative to the power of this source. Output power values are calculated for all four input modes.

Case 1 ($A = B = 0$): In the case where both input sources are off, the bias source is on and provides the power needed to activate the output. Figure 4 shows the normalized power diagram in this case. According to Fig. 4, it can be seen that the optical power at the output is equal to 0.68. In other words, 68% of the optical power of the bias source is transmitted to the output. This power can be considered as logic "1".

Cases 2 and 3. ($A = 0, B = 1$, and $A = 1, B = 0$): When only one of the inputs is on, due to the selection of point defects as well as the path length of the input waveguides and also the phase difference of the bias source, the light waves at the collision point weaken each other and the power propagated to the output is very low. Figure 5 shows the normalized power diagram for these two modes. Due to the symmetry of the circuit for inputs A and B, the power diagram in the outputs will be the same for these two modes of input. Figure 5 shows that the normalized output power, in this case, is 0.07. In other words, only 7% of the optical power of the input source is transmitted to the output. This small value can be considered as a logical “0”.

Case 4 ($A = B = 1$): If both input sources are on, the waves generated by the input sources and the bias source will overlap at the point of collision, resulting in signal attenuation and a very small amount of power being emitted to the output. The simulation results show that the amount of power emitted to the output, in this case, is equal to 0.07. This amount of power is very low and is equivalent to a logical “0”. Figure 6 shows the normalized power diagram for this mode.

The only point defect that has changed radius is a rod with radius R_1 . Now we want to get the optimal value of the radius of this rod so that the output power for the logical “1” and the logical “0” is in the best position. The best situation will be when the logical “1” has high power and the logical “0” has low power. Figure 7 shows the simulation results for the output optical power at different input modes for different values of R_1 .

As shown in Fig. 7, for low values of R_1 , the output power in logic “1” is close to the bias source power and the output has a strong “1”. In this case, the output value in logical “0” modes is close to 0.2. As R_1 increases, the amount of power in logic “1” decreases, but in this case, the value of “0” also decreases. Table 1 shows the output normalized power for radius changes R_1 .

Table 1
Normalized optical power for different values of R_1

R1	Outputs			
	AB = 00	A $\neq$ B	AB = 11	CR(dB)
20nm	1.00	0.19	0.20	7.0
40nm	0.90	0.14	0.14	8.0
50nm	0.77	0.10	0.10	8.9
55nm	0.68	0.07	0.07	9.9
60nm	0.60	0.06	0.06	10
65nm	0.53	0.05	0.05	10.2

According to Table 1, it can be said that with increasing radius R_1 , although the value of logical “0” decreases, the value of logical “1” also decreases. For R_1 values from 50nm to 60nm, the power is acceptable in the logical “1” mode and the value of logic “0” is greatly reduced and therefore the contrast ratio (CR) value is increased. For example, when $R_1 = 55$ nm, the normalized output power in logical “1” mode is equal to 0.68 and its value in logic “0” is equal to 0.07. The value of CR, in this case, is equal to CR = 9.9dB. With further increase of R_1 , the amount of optical power in the logical “1” mode is reduced and is not desirable.

3. Conclusion

In this paper, an all-optical NOR logic gate is designed based on two-dimensional photon crystals with a square lattice. Optical power is used to define the logical values of “0” and “1”. In this way, high optical power is considered as logic “1” and very low optical power is considered as logic “0”. For the desired gate, two inputs are considered as main inputs and one as bias input. To use the proposed structure in optically integrated circuits, the size of the gate has been reduced as much as possible. Also, in the design of this gate, very simple defects have been used so that it can be built easily. The simulation results show that this logic gate has high optical power for logic “1” and low optical power for logic “0”. Therefore, the distance between the upper and lower logic values is large and the detection error at the output will be low.

4. Declarations

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Figures

Figure 1

Band structure for the initial periodic structure

Figure 2

Defect paths for realization of the NOR logic gate

Figure 3

Optical power distribution for a) $A=B=0$, b) $A=0, B=1$, c) $A=1, B=0$ and d) $A=B=1$

Figure 4

Output normalized power for $A=B=0$

Figure 5

Output normalized power for $A=0, B=1$ and $A=1, B=0$

Figure 6

Output normalized power for A=B=1

Figure 7

Output normalized power for different values of R1