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All-Optical Switch Based on 2-D Photonic Crystal

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ABSTRACT

In this present paper, was utilized the concept of Photonic Crystals (PhCs) for the implementation of an all-optical NOT logic gate. The new all-optical switch is composed of a Photonic Crystal Ring Resonator (PCRR) in two dimensions (2-D), made of dielectric silicon rods in air substrate. The Plane Wave Expansion (PWE) and Finite Difference Time Domain (FDTD) methods are used to analyze the behavior of the structure. The photonic band gap of the PhC structure is from 0.2654 to 0.3897 (a/λ). The square lattice of gate NOT fabricated is implemented on the operational wavelength of the input ports of the 1700 nm using finite difference on an air wafer of only 12 µm *x* 12 µm. The simulation results show that the proposed structure is applicable for photonic integrated circuits due to its simple structure and principle of operation clear.

Keywords: NOT Logic Gate, Photonic Crystal Ring Resonator (PCRR), Contrast Ratio (CR).

Chave Totalmente Óptica Baseada em Cristal Fotônico Não-Linear

RESUMO

Neste trabalho, foi utilizado o conceito de cristais fotônicos (PhCs) para a implementação da porta lógica NOT totalmente óptica. O novo comutador totalmente óptico é composto por um anel ressoador de cristal fotônico (PCRR) em duas dimensões (2-D), feito de hastes dielétricas de silício no substrato de ar. O método da expansão em ondas planas e o método das diferenças finitas no domínio do tempo (FDTD) são utilizados para analisar o comportamento da estrutura. O intervalo de banda fotônica da estrutura é 0,2654-0,3897 (a / λ). A rede quadrada da porta NOT fabricada é implementada no comprimento de onda operacional das portas, que é 1700 nm usando diferenças finitas em um *wafer* de ar de apenas 12 µm *x* 12 µm. Os resultados das simulações mostram que a estrutura proposta é aplicável para circuitos integrados fotônicos, devido à sua simples estrutura e claro princípio de funcionamento.

Palavras Chaves: Porta Lógica NOT, Anel Ressonador de Cristal Fotônico (PCRR), Razão de Contraste (CR).

I. INTRODUCTION

Photonics is a field of study that is largely focused on the telecommunications sector, however, covers a wide range of applications in the science and technology that are revolutionizing the industry [1].

These applications include all fields of everyday life, among which, we can mention the telecommunications industry, light sensing, metrology, illumination, information processing, military technology, spectroscopy, holography, visual arts, medicine (through surgery for vision correction, in endoscopy, in health monitoring, etc.), the lasers for materials processing, agriculture and robotics and other interesting applications [2].

In recent years, silicon photonics devices has drawn great attention, since they offer a low-cost opportunity to manufacture opto-electronics for applications ranging from telecommunications to applications in new emerging areas such as optical sensing and biomedical applications [3].

Recently, advances and discoveries on the performance of photonic devices have shown that silicon can be considered as a material, which can be used for the construction of future optical devices [4].

While significant efforts are needed to improve the performance of the devices and the "marketing" of these technologies, progress is moving quickly. Thus, the silicon may also potentially affect the optical communications in the same way that has impacted the electronics industry [5].

The demands for all-optical signal processing techniques in telecommunication systems are rapidly increasing, and now is accepted that digital electronics is not able to meet these requirements in the future [6]. The problems of the future of computation and communication are unavoidable since conventional electronic technology will very soon reach its speed limit.

The all-optical logic gates with high performance speed play a main role in large bandwidth signals processing and optical networks [7]. The all-optical signal processing for the networks can handle large bandwidth signals and large information with very high speed. Ultrafast all-optical logic gates based on nonlinear photonic crystal (NPhC) are the key components in the all-optical signal processing systems and future optical networks [7].

In order to recognize the performance of all-optical logic gates, different structures have been proposed. Various gates have been implemented using different techniques such as SOA's (semiconductor optical amplifier), PPLN (Periodically Poled Lithium Noibate), MZI (Mach-Zhender Interferometer), and nonlinear effects of SOI waveguide. Initially, all-optical logic gates based on SOA properties were reported [8]-[9]. However, some limitations of these methods, which such as latency time, low power transmission, high input power, complex designs, heavy cost, speed and size of these complex structures cause it is used less.

The PhCs have interesting properties such as the Photonic Band Gap (PBG) [10], which is a range of frequencies that are not allowed to propagate into the PhC and that can be calculated using the Plane Wave Expansion (PWE) method [11]-[12]. It is possible due to case in controlling the propagation modes, accurate calculation of the photonic band gap, and efficient light confinement [12]-[13].

In recent years, optical waveguide using photonic crystals has received attention because of its small size and low loss in structure [10]. Numerical simulation has been performed through 2-D Finite Difference Time Domain (FDTD) method [14], which is used to simulate electromagnetic wave propagation in any kind of materials in the time domain [15].

II. MATERIALS AND METHODS

In this paper, the 19 × 19 square lattice 2-D PhC is used for designing the structure. The lattice constant, denoted by '*a*', is 0.5943 µm, which is a distance between the two consecutive rods, as shown in Figure 1. The radius of rod is 0.2*a* approximately 0.11886 µm.

The relative permittivity of cylindrical dielectric rods in the structure is ε_r = 11.5 which is equivalent to a 3.39 refractive index. In this structure, the inputs are shown by 'C' and 'I' and the output is indicated by 'B'. The structure is excited in port C with control by the port I and output by port D. When an optical signal is applied to port C and port 'I', no output signal is in port B due to the coupling of Photonic Crystal Ring Resonator (PCRR). On the contrary, the optical signal is transmitted to port B when no signal is applied to port I. The normalized transmission spectra of port B is obtained by conducting Fast Fourier Transform (FFT) [9] of the fields that are calculated by Multiple Scattering Method (MSM) shown in Figure 4 and Figure 5. For the performance analysis, the propagation of the electric field was studied which is calculated by the FDTD method.

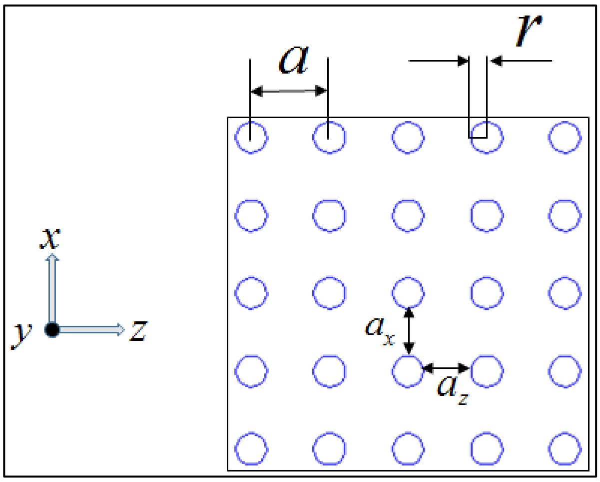

Figure 1 - Two-dimensional square lattice of photonic crystal of silicon rods in air substrate, where r is the radius and a is the lattice constant of the silicon rods.
Source: Authors, (2017).

The all-optical switch shown in Figure 2 designs a novel all-optical NOT logic gate. The diameter of PCRR is 6*a*. The total size of the structure is about 12 µm *x* 12 µm, which is smaller than the conversational PhC-based optical logic gates. One input waveguide is marked as "Control signal" (C) which is shown by upper horizontal waveguide which is made by removing the required number of silicon dielectric rods called as line defects in XZ plane. A sensor is placed at the end of the waveguide.

The input denoted by 'I' is another waveguide of the structure, which is horizontally connected with the PCRR. In the end of the input waveguide was added a defect in the structure, a scatter rod is placed by the shifting of the position of silicon rod by 0.707*a*, which prevents backward reflections due to the curve formed in the waveguide [10]. The scatter rods are placed at each of the four corners in the PCRR with the same lattice constant in order to improve the coupling efficiency.

The material properties of the scatter rods are the same of the other rods. The single circular PCRR shown in Figure 2 is constructed by varying the position of inner rods from of the original position, while the inner rods are built by the varying the position of adjacent rods on the four sides, from their center by the 0.25*a* in both 'X' and 'Z' directions.

The output signal is calculated from port marked as 'B' through observation of the power transmitted in the upper waveguide. The control signal has the same power (P_0) that the input signal I which can be in the 'ON' or 'OFF' state. The switching property between logic '1' and logic '0' of gate is achieved by the light confinement property of PhCs silicon rods [13].

In logic '1' state there should be maximum power transmitted as compared to the power transmitted in case of logic '0'. It was plotted power transmission graphs according to Discrete Fourier Transform (DFT), shown in Figure 4 and Figure 5.

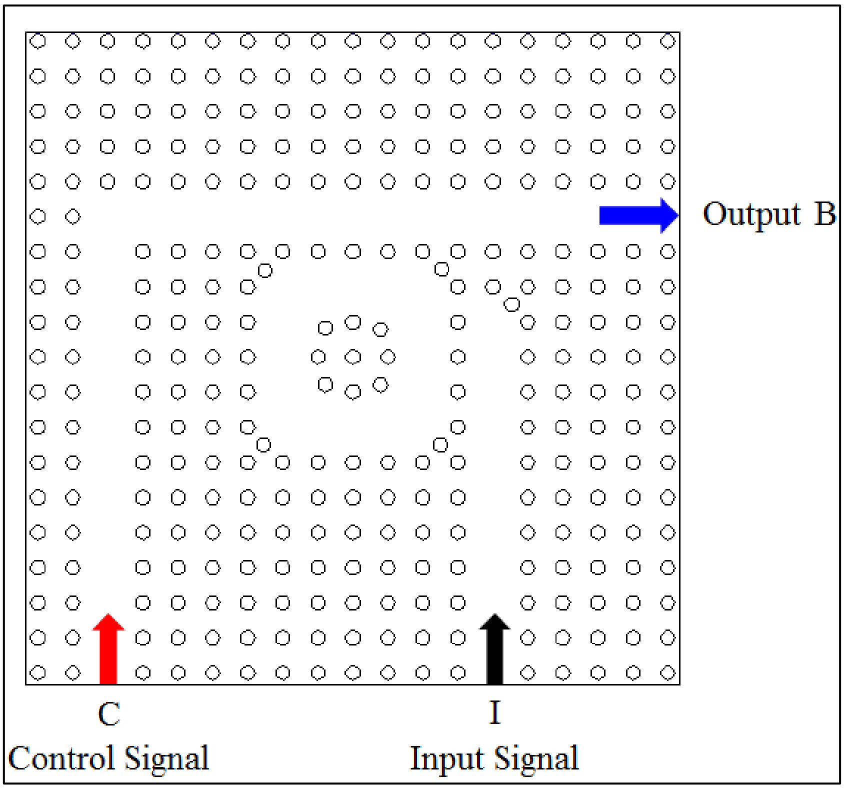

Figure 2: Schematic view of the proposed switch structure.
Source: Authors, (2017).

The band diagram is calculated by the PWE method as shown in Figure 3. The range of band gap is $0.2654 \leq a/\lambda \leq 0.3897$ and band gap width is given by 0.1243. The calculated band gap is for transverse electric mode (TE) photonic band gap and propagation modes in the first Brillouin zone [10]. The light in this range of frequency does not propagate through this structure [12], or we can say that the density of optical states is zero. The frequency range of 0.2654-0.3897 (a / λ), is corresponding to the wavelength range $1525 \leq \lambda$ [nm] ≤ 2239. The waveguides in Γ-X direction are single mode in the whole PhC band gap [11]-[13] shown in Figure 3.

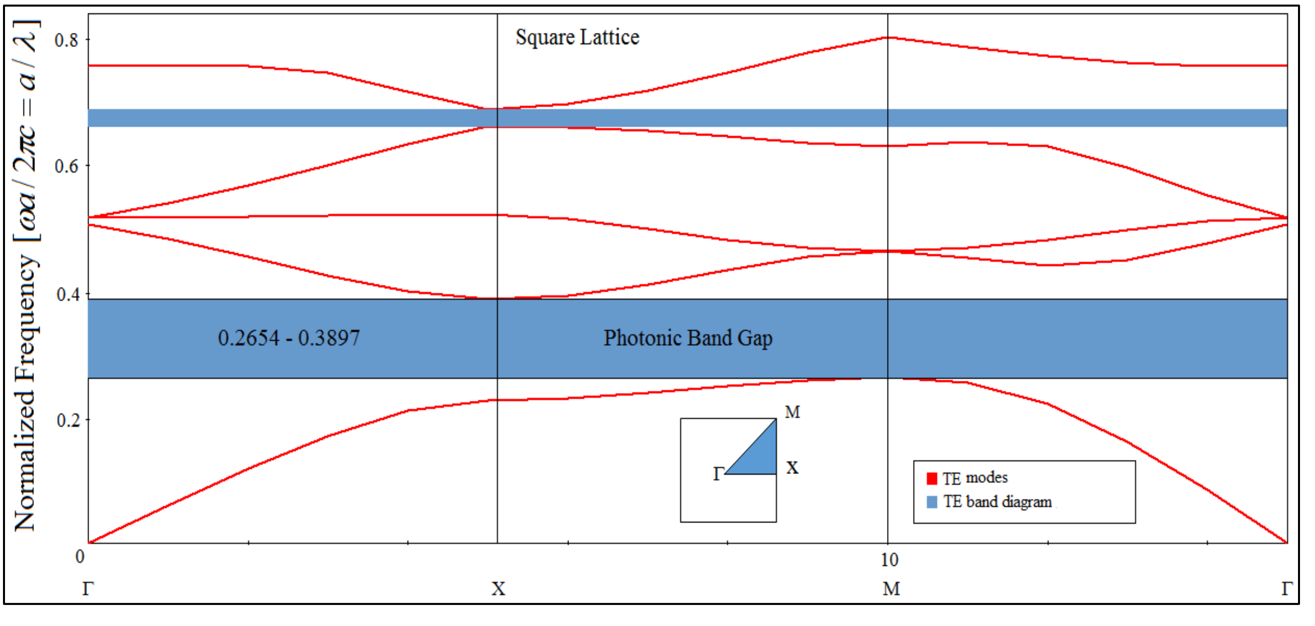

Figure 3: Band diagram in a square lattice of silicon rods in the air substrate for TE modes.
Source: Authors, (2017).

IV. SIMULATION RESULTS

For analyzing the high performance of the implemented logic gate, is calculated the ratio between the two power levels, this is, the high power in 'ON' state and the low power in conditions of the 'OFF' state. The transmission factor is defined as the ratio of average power in 'ON' state with the average power in the state 'OFF'. This relation is known as Contrast Ratio (CR), being obtained using the following expression.

$$CR = 10 \cdot \log\left(\frac{P_{ON}}{P_{OFF}}\right) \qquad (1)$$

In this all-optical NOT logic gate, the contrast ratio is equal to 14.9600 dB approximately 15 dB. The switching nature of NOT logic gate is demonstrated and this structure satisfies the truth table shown in Table 1.

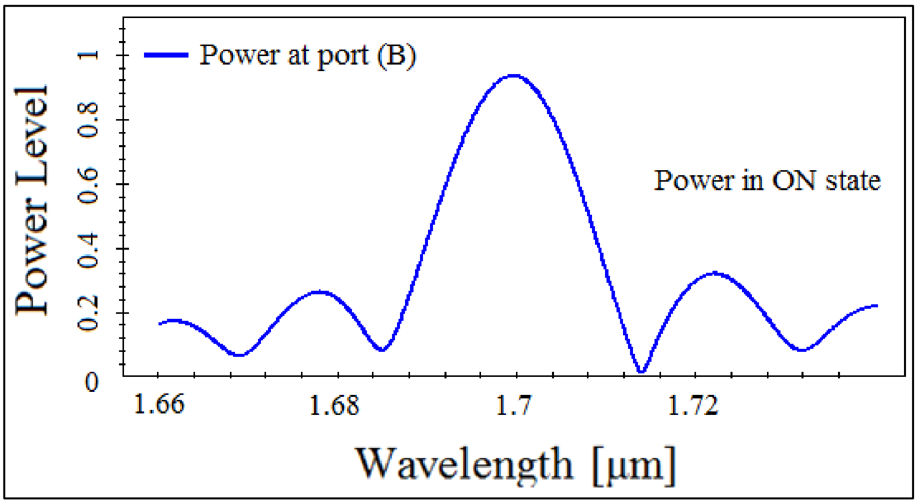

Figure 4: The power transmission (W/m) in 'ON' state.
Source: Authors, (2017).

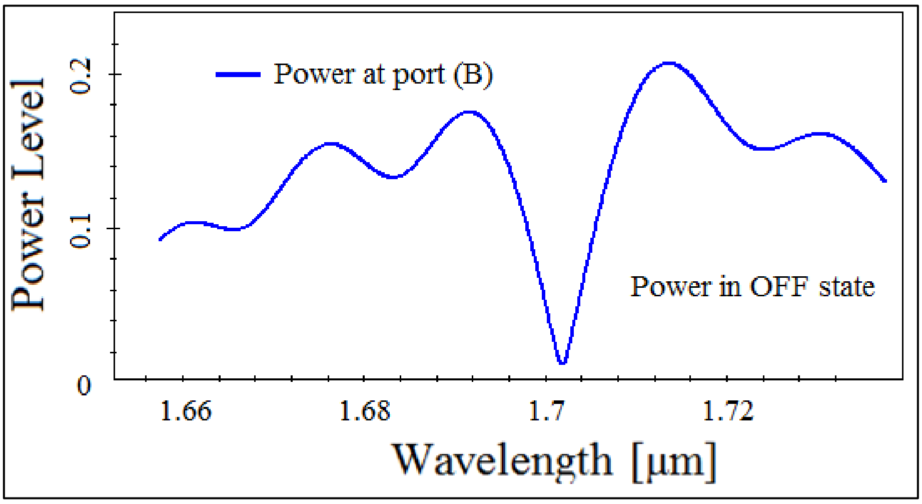

Figure 5: The power transmission (W/m) in 'OFF' state.
Source: Authors, (2017).

Table 1: Logic table of NOT gate.

Control Signal (C)	Input Signal (I)	Output (B)	Power [W/m]
1	1	0	0.03
1	0	1	0.94

Source: Authors, (2017).

V. CONCLUSION

This article describes the design and analysis of an all-optical NOT logic gate fabricated with silicon rods in a substrate air. This all-optical gate shown in this article, has a low dimension compared to the reported literature, and is a very efficient structure in which a high data rate can be transmitted. The operating wavelength used in the simulations of the NOT gate is 1.7 µm with a lattice constant of 0.5943 µm. The results show a high optical performance of the logic gate NOT, which is evidenced by a high contrast ratio value of about 15 dB approximately, producing a high power output. This value is much higher of that values previously obtained in other works. The simulation results show that the proposed all-optical NOT logic gate presented is a potential candidate for ultrafast optical digital circuits and highly advantageous with high transmitting power and simple design. Thus, is beneficial and promising for applications in optical computing, cryptography, digital processing systems among others.

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