Analysis of the behavior of an all-optical not logic gate in a photonic crystal directional coupler

Análise do comportamento de uma porta lógica not totalmente óptica em um acoplador direcional de cristal fotônico

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ABSTRACT
In the present work, an optical directional coupler (ODC) based on two-dimensional (2-D) photonic crystal (PhC) was analyzed and proposed, through the methods of plane wave expansion (PWE) and finite-difference time-domain (FDTD), which were used with the purpose of analyzing the behavior of a new all-optical NOT logic gate and the electric field distribution in the coupler for linear (bar), non-linear (cross) states and the control signal. The simulation results in OptiFDTD software show that the proposed crystal structure is a strong candidate for use in ultrafast photonic integrated circuits (PICs), being highly advantageous with excellent transmission performance and simple design.

Keywords: photonic crystal directional coupler, not logic gate, fdtd method, cross, bar.

RESUMO
No presente trabalho, foi analisado e proposto um acoplador óptico direcional (ODC) baseado em cristal fotônico (PhC) de duas dimensões (2-D), através dos métodos de expansão de onda plana (PWE) e diferenças finitas no domínio do tempo (FDTD), que foram utilizados com o propósito de se analisar o comportamento de uma nova porta lógica NOT totalmente óptica e a distribuição do campo elétrico no acoplador para estados linear (bar), não linear (cross) e o sinal de controle. Os resultados da simulação no software OptiFDTD mostram que a estrutura cristalina proposta é uma forte candidata para o uso em circuitos integrados fotônicos ultrarrápidos (PICs), sendo altamente vantajosa com excelente desempenho de transmissão e simples design.

Palavras-chave: acoplador direcional de cristal fotônico, porta lógica not, método fdtd, cross, bar.

1 INTRODUCTION

The revolution in telecommunications in recent years has been carried out in order to meet the demands for fully optical signal processing, as electronics are not being able to meet current and future requirements. In this sense Almeida et al. (2017) apud Lee (2008) reinforce that ultrafast all-optical logic gates based on photonic crystal (PhC) are the main components in all-optical signal processing systems and in future optical networks. As stated by SAKODA (2004); CUESTA-SOTO et al. (2004) and LI et al. (2006) semiconductor materials and devices have always dominated the electronics world in the form of gates, transistors, non-linear curves, optical diodes, switches, among others. And also photonic crystals are considered as periodic dielectric structures that can provide photonic band gap (PBG) property and are of great importance due to their unique properties in the integration of all-optical data processing chips.

The concept of photonic crystals was first coined by Yablonovitch in 1987, they are the optical analogues of electronic semiconductors, and exhibit a band structure for photons that propagate in the PhC due to their periodic modulation of the refractive index. In this sense, according to Divya et al. (2017) one of the important characteristics of the photonic crystal is the property of confinement and light control, and it can be used in various logic applications, such as: optical filters, optical multiplexers, optical switches, directional couplers, among others.

There are several ways to design all-optical logic gates, either through the use of semiconductor optical Amplifier (SOA) or PhC. In this sense, several related works have been published over the years. Oliveira et al. (2018a; 2018b; 2018c; 2019b; 2021) presented OR, NOR, AND, NAND and NOT logic gates using semiconductor optical Amplifier based on Michelson Interferometer (SOA-MI) with fiber Bragg Grating (FBG), based on the nonlinear cross properties gain modulation (XGM). All these projects were implemented through numerical simulations using OptiSystem software by Optwave corporation, where all of them achieved excellent performance results for systems with transmission rates of 10 and 20 Gbps. However, according to Divya et al. (2017) SOA performance is limited by spontaneous emission noise and has integration complexity.

Singh et al. (2020) state that due to the growing demand for high speed and bandwidth, it is difficult to design optical computers without designing basic building blocks, that is, all-optical logic gates. They also emphasized that optics is the best possible option over electronics, as it provides parallel data processing with less expense and higher transmission speed, and can be 10,000 times faster than electronic computers.

Therefore, they compared and discussed different PhC-based techniques to build all-optical logic gates based on different parameters, such as contrast ratio (CR) and bit rate.

According to Eshaghi et al. (2008) photonic crystals are of great importance due to their unique properties in the integration of fully optical data processing chips. In addition, non-linear PhCs can be used to manufacture various devices such as: optical diodes, non-linear curves, transistors, switches, switches and directional couplers. In this sense, they presented an all-optical PhC switching structure with a length reduced by 22% in relation to other similar structures. Through the results obtained through the FDTD, PWE methods and the modification of the dispersion curves of the supermodes, they found that the coupler proposed by them obtained low crosstalk and excellent transmission efficiency.

Lima Jr. and Sombra (2012) investigated the physical mechanism of a PhC switching cell based on an ODC using the following methods: Plane Wave Expansion (PWE) by MPB (MIT Photonic-Bands), Finite-Difference Time-Domain by MEEP (MIT Electromagnetic Equation Propagation), Finite Element Method (FEM) by COMSOL Multiphysics and the Binary Propagation Method. The device switching process proposed by them was based on changing the bus state to the crossed state due to the external command signal.

SABINO et al. (2017) simulated an ebium-doped photonic crystal directional coupler based on nonlinear resonance using the Finite Element Method (FEM) in the COMSOL Multiphysics software. They compared the switching performance between an erbium-doped and non-doped Photonic Crystal directional coupler, from the normalized frequency variation, and it was found that the doped coupler was able to operate in the bus and cross states with a higher frequency spectrum.

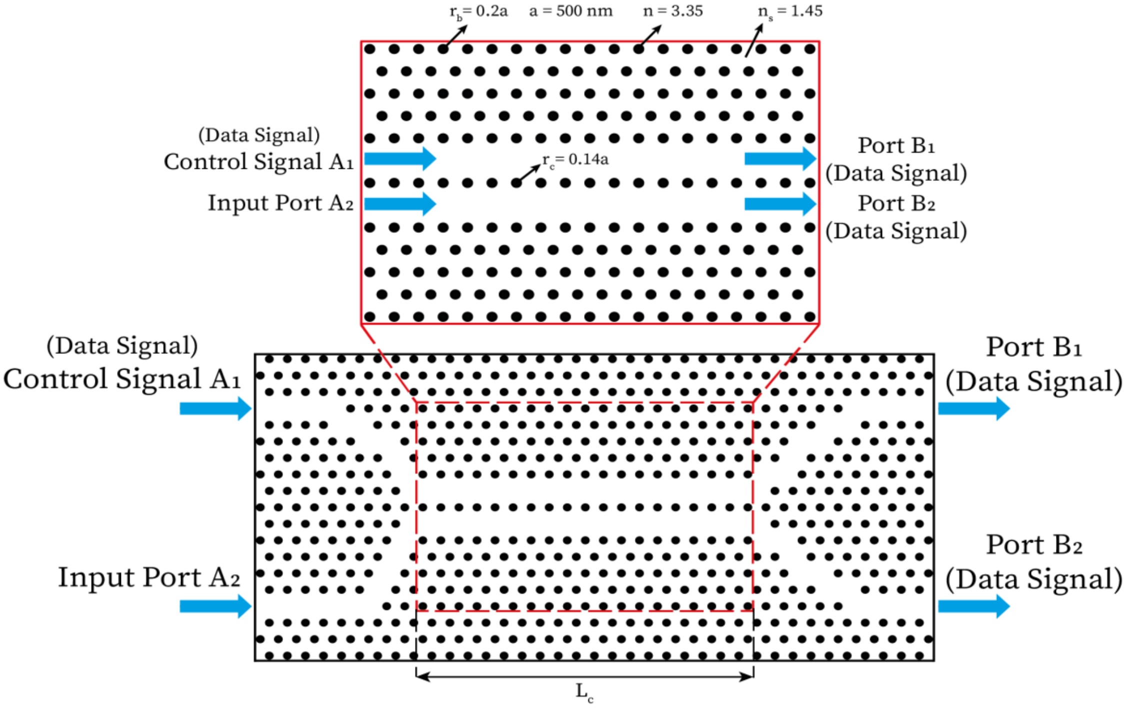
Here we propose a two-dimensional (2-D) PhC ODC for the analysis of the behavior of the NOT logic gate and the bar and cross state change. For this, the PWE and FDTD methods were used through the OptiFDTD software by Optwave Corporation. The PWE method is used to calculate the photonic band gap of the PhC structure. Numerical simulation has been performed through 2-D FDTD method, which is used to simulate electromagnetic wave propagation in any kind of materials in the time domain [7], that is characterized using Maxwell's equations. This work is organized as follows: Section 2 presents the theoretical foundation and working principle of the proposed coupler, section 3 presents the results and analysis of the simulations and finally the conclusions and references.

2 THEORETICAL FOUNDATION AND WORKING PRINCIPLE OF THE PROPOSED ODC

Figure 1 represents the layout of the photonic crystal structure proposed here. The ODC has two fault lines W1 waveguides, and the coupling region is a line of dielectric rods with radius r_c=0.14a. The radius of the dielectric rods was chosen according to the indication of Lima Jr. et al. (2009), who stated that it serves to provide the smallest coupling length before the insertion of the command signal. The crystal structure of the ODC proposed here was designed, simulated and analyzed using the optiFDTD simulation software.

The ODC is embedded in a 13×19 dimensional two-dimensional (2D) hexagonal structure that is composed of high dielectric rods suspended in low dielectric air, which functions as a light switching cell. Furthermore, the high dielectric contrast is responsible for providing a large photonic bandgap (PBG) for the device proposed here. The lattice constant, denoted by ‘a=500nm’, is a distance between the two consecutive holes. The radius of all the rods is given by rb=0.2*a*. The refractive index of the dielectric rods is n = 3.35, which is incorporated into a substrate with refractive index ns = 1.45 and the operating wavelength used in the NOT gate simulations is 1.7 µm.

Figure 1 – (a) Schematic view of the proposed switch structure (b) Coupling region of directional coupler, used in the switch structure.



Source: Almeida et al. (2022).

The working principle of a coupler is explained both by the theory of supermodes, which deals with the interaction of modes in the coupling process, and by the theory of coupled modes, which describes the transfer of energy from one waveguide to another. In this sense, for switching between the coupler waveguides, a minimum coupling length is defined, which is defined by (Eshaghi et al., 2008):

$$L_c = \frac{(2n+1)\pi}{k_{even} - k_{odd}} \tag{1}$$

where k_{even} e k_{odd} are the propagation constants even and odd of the modes respectively and L_c is the coupling length

The theory of coupled modes is defined by the simplified Jensen equation for a non-linear coupler, which considers the two separate waveguides and implemented in a non-linear materia (BERGER et al., 1991):

$$\frac{\partial \alpha_1}{\partial z} = -j\beta\alpha_1 - \left(\frac{\alpha}{2}\right)\alpha_1 + jC\alpha_2 - jn_2k_0|\alpha_1|^2\alpha_1 \tag{2}$$

and

$$\frac{\partial \alpha_2}{\partial z} = -j\beta\alpha_2 - \left(\frac{\alpha}{2}\right)\alpha_2 + jC\alpha_1 - jn_2k_0|\alpha_2|^2\alpha_2 \tag{3}$$

where, α is the energy loss coefficient, C is the linear coupling coefficient, n_2 is the nonlinear refractive index, β is the propagation constant of the guided modes, $k_0 = \frac{2\pi}{\lambda}$ is the propagation constant in free space and α_1 and α_2 are the amplitudes of the complex normalized field of the parallel guides defined by:

$$\alpha_1 = B_1(z)\exp(-j\varphi_1(z)) \tag{4}$$

and

$$\alpha_2 = B_2(z)\exp(-j\varphi_2(z)) \tag{5}$$

Thus, when a high-intensity signal reaches the non-linear coupler, only the refractive index of the central holes, coupling region, is changed according to the following equation (Rahmati and Granpayeh, 2010):

$$\Delta n = n_0 + n_2 I \tag{6}$$

where n_0 is the linear index of refraction having constant value and *I* is the signal strength.

The power required for the operation of the ODC must take into account the increase in the refractive index in the coupling region (□*n*), which is dependent on the PhC structure used and the normalized frequency of the command signal (LIMA JR. et al., 2009):

$$P = \frac{(\Delta n) A_{eff}}{3 n_2 \left(\frac{vg|^u}{vg|^c} \right)} \tag{7}$$

where P is the desired optical power of the command signal, n_2 is the nonlinear refractive index whose maximum value occurs at the adopted wavelength around 1800 nm, *A*eff is the mode effective area [modal volume is given by $(\left(\frac{\lambda}{2n}\right)^3)$], $vg|^u$ is the command signal group velocity in a conventional axial uniform waveguide, and $vg|^c = 0.03 * c$ is the group velocity of the command signal in the coupling region based on *u*=0.283.

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 equation (ALMEIDA, 2016):

$$CR = 10\, log(P_{ON}/P_{OFF}) \tag{8}$$

Typically, the FDTD method is used to calculate the spectrum of the power transmission and field distribution that is based on numerical solutions of Maxwell’s equations, which can be discretized in space and time by so call Yee-cell techniques. The 2-D transverse electric mode FDTD used in this work is (ALMEIDA et al., 2017):

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu}\left(-\frac{\partial E_z}{\partial y}\right) \tag{7}$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_z}{\partial x}\right) \tag{8}$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right) \tag{9}$$

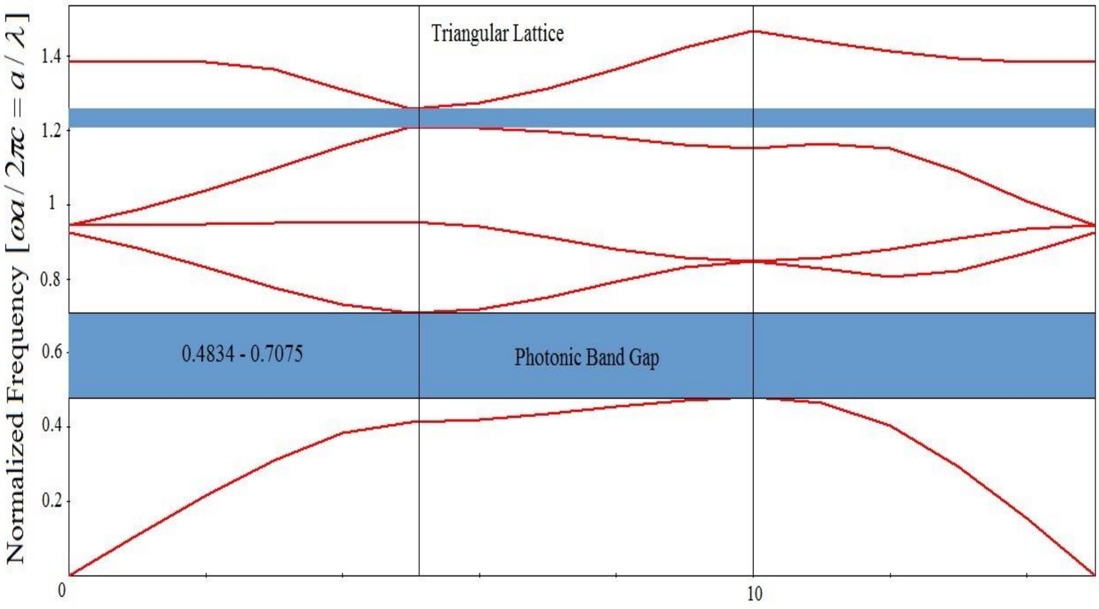
The Gaussian beam is initiated in the grid, travels through, reflects from, refracts in and resonates inside the photonic crystal. Where ε(r), μ(r), σ(r) are permittivity, permeability and conductivity of the material and all are in the function of position. In simulation, structure is surrounded by Perfectly Matched Layer (PML) from all the sides

3 SIMULATIONS AND ANALYSIS

In the simulations, the physical mechanism of an ODC-based PhC switching cell proposed here was investigated. In the ODC coupling region, an external low-power signal was inserted, which was responsible for causing changes in the refractive index of the central holes. In our simulations we used the following methods: PWE and FDTD through OptiFDTD software, the results of the switching process based on the change from bar state to cross state and the analysis of the behavior of the NOT logic gate are shown in the following results.

The PBG consists of the range of frequencies that can pass through the structure, that is, frequencies that are outside this range are defined as forbidden bands. This frequency range is defined by parameters such as refractive index, radius and shape of the rods, lattice structure, lattice constant, etc. Thus, using the ideal values for these parameters, the best PBG region can be reached. The band diagram is calculated by the PWE method as shown in figure 2. The range of band gap is $0.4834 \leq a/\lambda \leq 0.7075$, which is corresponding to the wavelength range $1229 \leq \lambda$ [nm] ≤ 840 in TE mode this region is in normalized frequency domain. Therefore, the proposed structure is suitble for the design of optical comunication devices and it has PBGs only in TE mode, so all simulations were performed in this mode.

Figure 2 – Photonic band structure of 2-D triangular lattice.

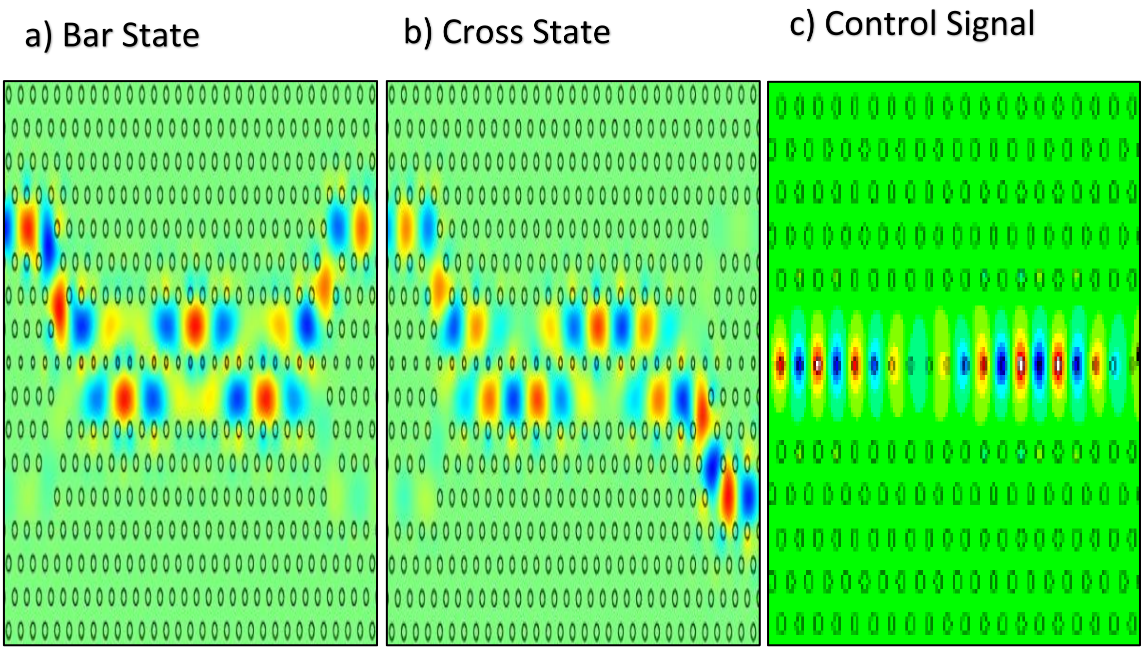


Source: Almeida et al. (2022).

Figure 3 shows the distribution of the electric field inside the OCD, at normalized frequency, obtained through the FDTD method when input A_1 is excited in linear and non-linear state. To demonstrate the switching performance of the proposed ODC, its linear state was simulated, where the refractive index of the central rods of the coupling section was not changed by the pump power and the coupler transmitted the signal in the bar state, where the light came out through the port B_1 as shown in figure 3 (a).

The intensity of the input signal produced variations in the refractive index of the central holes of the coupling section causing a change in the coupling coefficient (non-linear state), so the light left through port B_2, that is, the coupler transmitted the signal in the state cross as shown in figure 3 (b). Thus, depending on the power of the control signal, the signal output can occur in a bar state (linear state) or cross (non-linear state), since the control signal is responsible for exciting the control mode corresponding to the low-frequency region. bandgap frequency, where the switch performance occurs in a frequency range different from the frequencies of the coupled modes.

Figure 3 - Electric field distribution in the coupler for linear (bar) (a), non-linear (cross) (b) and control signal (c) states.



Source: Almeida et al. (2022).

And figure 3 (c) shows that the switch control signal has uniform symmetry and is strongly confined to the central row of rods in the coupling region, showing that it also behaves as a waveguide. Therefore, the switching behavior of the proposed ODC is defined by the Kerr effect, which is induced due to the change in the index of refraction of the rod line between the two waveguides, when a high power level signal is released as a signal control, making it possible to both tune and vary and both tune and vary the power ratio between the ODC outputs.

In the crystalline structure of a PhC, a constructive or destructive interaction of light may occur, this can be seen through the simulations. Figure 3 shows that control port A_1 is always on (A_1=1), and that when port A_2 is off (A_2=0), the output state may be high (1), and that depending on the intensity of the input signal, may occur on port B_1 or on B_2, ie (B_1=1 or B_2=1). However, it was observed that when control gate A_1 and gate A_2 were on (A_1=1 and A_2=1) a destructive light interaction occurred, which resulted in signal scattering, where the output state was low for both. The output ports (B_1=0 and B_2=0), that is, no signal came out in B_1 and B_2. Therefore, by analyzing the results of the signal output, it was possible to extract the fully optical logic gate NOT as shown in the following truth tables.

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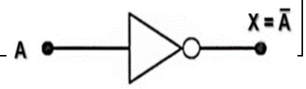
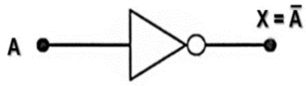
Table 1 - Truth table of logic gate NOT for output gate B_1.

Control Signal A_1	Control Port A_2	Output B_1	NOT Gate Symbol
1	0	1	
1	1	0	

Source: Almeida et al. (2022).

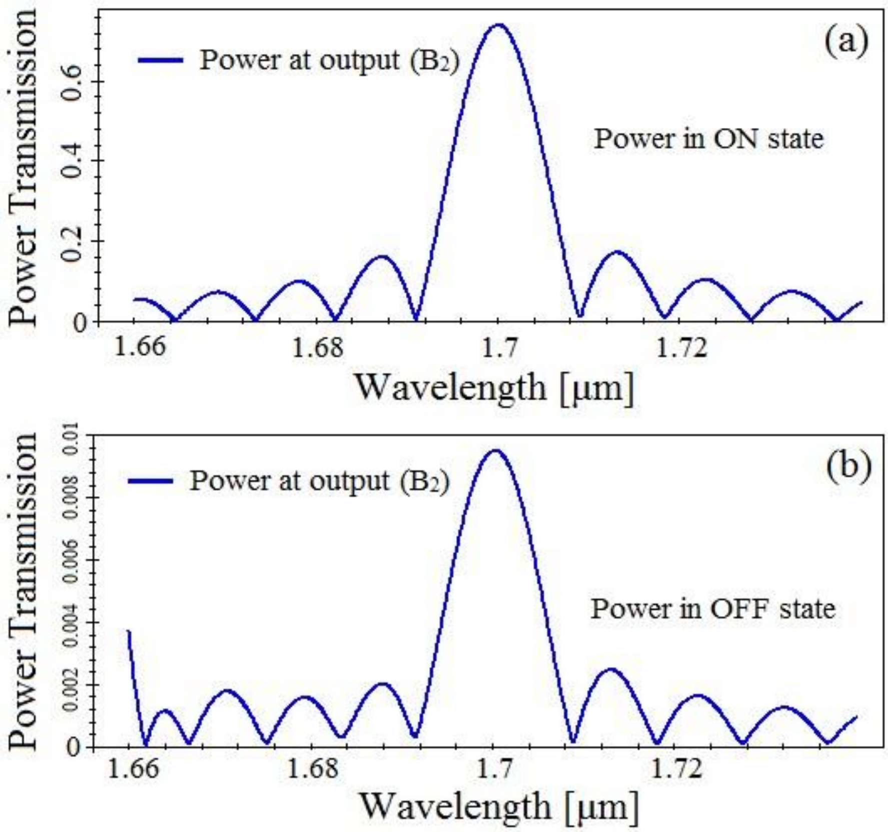
Table 2 – Truth Table of NOT logic gate for output gate B_2.

Control Signal A_1	Control Port A_2	Output B_2	NOT Gate Symbol
1	0	1	
1	1	0	

Source: Almeida et al. (2022).

The switching property between logic ‘1’ and logic ‘0’ of gate is achieved by the light confinement property of PhCs silicon holes. If only one signal is applied in the (A_1) control, then there is no interference and the signal passes directly through the control waveguide. Thus, the transmission power is maximum in the output (B_2) and is represented by logic ‘1’ or ‘ON’ state, as shown in figure 4 (a). Now, when the input signal at port (A_2) is logic ‘1’ there are interferences and therefore the transmitted power is very low, which is characterized by the condition in the ‘OFF’ state, as shown in Figure 4 (b).

Figure 4 – Transmission (W/m) in: (a) ‘ON’ state; (b) ‘OFF’ state.



Source: Almeida et al. (2022).

4 CONCLUSION

The results obtained through the FDTD and PWE methods show that the proposed structure obtained an excellent transmission and that it was able to perform a NOT logic gate. Therefore, it is believed that all-optical logic gates based on PhC can be considered as a viable solution to overcome the technical disadvantages faced in the implementation of communication systems. This all-optical gate shown in this work, has a low dimension compared to the reported literature, and is a very efficient structure in which a high data rate can be transmitted and due to micrometer dimensions of the ODC embedded in photonic crystals structures, it can be used as a switching cell in photonic integrated circuits (PICs).

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