Performance Analysis of All-Optical NOT Logic Gate Based on 2-D Nonlinear Photonic Crystal

Léo César P. de Almeida and Marcos B. C. Costa

***Abstract*—In this paper, a novel scheme for implementation of all-optical NOT logic gate based on two dimension (2-D) photonic crystal (PhC) ring resonator has been proposed, designed and simulated. The new all-optical switch is composed of a nonlinear Photonic Crystal Ring Resonator (PCRR). The PhC structure has a square lattice of 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 PWE method is used to calculate the photonic band gap of the PhC structure, which is from 0.2654 to 0.3897 (a/λ). The square lattice of gate NOT fabricated is implemented on the opera-tional wavelength of the input ports is 1700 nm using finite difference on an air wafer of only 12 µm x 12 µm. The simulation results using two-dimensional FDTD method show that the proposed PhC all-optical NOT logic gate presented here is a potential candidature for ultrafast optical digital circuits and highly advantageous with high transmitting power and simple design.**

***Keywords*—All-Optical NOT Logic Gate, Photonic Crystal Ring Resonator, Finite Difference Time Domain, Contrast Ratio, Quality Factor.**

I. Introdução

Currently, the number of technologies that require advances in all fields is increasing, especially in electronics. 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 [1]. 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 [2]. 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) [15] are the key components in the all-optical signal processing systems and future optical networks [2]. 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), multimode interference, MZI (Mach-Zhender Interferometer), nonlinear effects of SOI waveguide. Initially, all-optical logic gates based on SOA properties were reported [3]-[4]. 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) [5], 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 [6]-[7]. It is possible due to case in controlling the propagation modes, accurate calculation of the photonic band gap, and efficient light confinement [7]-[8]. In recent years, optical waveguide using photonic crystals has received attention because of its small size and low loss in structure [5]. Numerical simulation has been performed through 2-D Finite Difference Time Domain (FDTD) method [9], which is used to simulate electromagnetic wave propagation in any kind of materials in the time domain [10].

II. Materials and Methods

In this paper, the 19 × 19 square lattice nonlinear 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 0.2a approximately 0.11886 µm. The relative permittivity of the nonlinear 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, no output signal is in port B due to the coupling of Photonic Crystal Ring Resonator (PCRR) [12]-[13]-[14]. 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 2. For the performance analysis, the propagation of the electric field was studied which is calculated by the FDTD method as has been reported in [17]-[18].

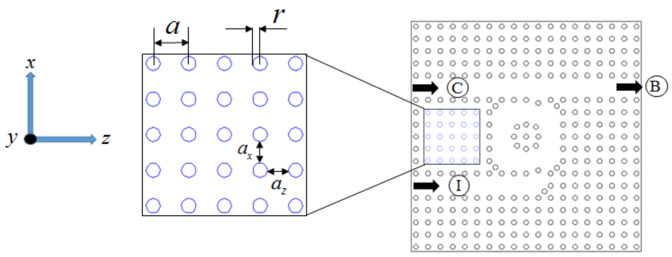

Fig. 1. The basic structure of proposed all-optical NOT logic gate.

The all-optical switch shown in Figure 2 designs a novel all-optical NOT logic gate. The diameter of PCRR is 6a. The total size of the structure is about 12 µm x 12 µm, which is

Léo César P. de Almeida and Marcos B. C. Costa, Programa de Pós-Graduação em Engenharia Elétrica-PPGEE, Universidade Federal do Pará-UFPA, Belém, PA, Brazil, E-mails: leocesarpa@ufpa.br, marcosta@ufpa.br.

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 [5]. 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 rods located inside of the circular PCRR are called of inner 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. To determine a circular microcavity, the outer ring is constructed by shifting the corner rods by 0.25*a*. The coupling rods are placed between the circular PCRR and the waveguides. 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.

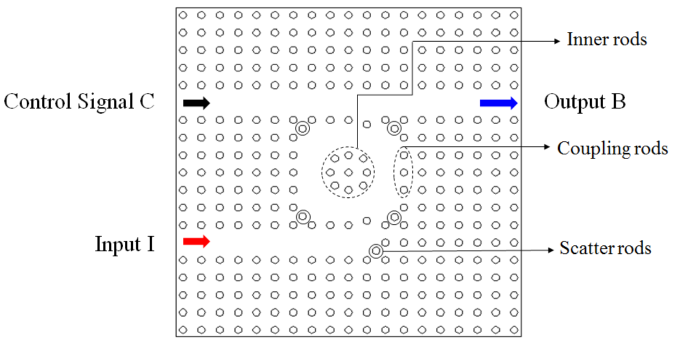

Fig. 2. The schematic structure of all-optical NOT logic gate.

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 [5]. The light in this range of frequency does not propagate through this structure [7], 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 [6]-[8] shown in Figure 3.

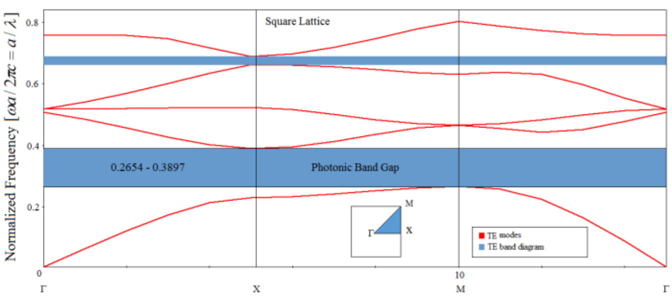

Fig. 3. Band diagram in a square lattice of silicon rods in the air substrate for TE modes.

III. SIMULATION RESULTS AND ANALYSIS

The computational simulation is realized by using the FDTD method. In this work, the logic level high ‘1’ and low ‘0’ are defined. The switching property between logic ‘1’ and logic ‘0’ of gate is achieved by the light confinement property of PhCs silicon rods [8]. In logic ‘1’ state there should be maximum power transmitted as compared to the power transmitted in case of logic ‘0’. The optical field distribution of the proposed all-optical NOT logic gate is obtained by conducting Fast Fourier Transform (FFT) [9] shown in Figure 4 and Figure 5. It was plotted power transmission graphs according to Discrete Fourier Transform (DFT). If only one signal is applied in the (C) control, then there is no interference and the signal passes directly through the control waveguide as shown in Figure 4. Thus, the transmission power is maximum and is represented by logic ‘1’ or ‘ON’ state. In Figure 5 is shown the propagation of the electric field in ‘OFF’ state or logic ‘0’. In this case, there are interferences and therefore the transmitted power is very low, which is characterized by the condition in the ‘OFF’ state.

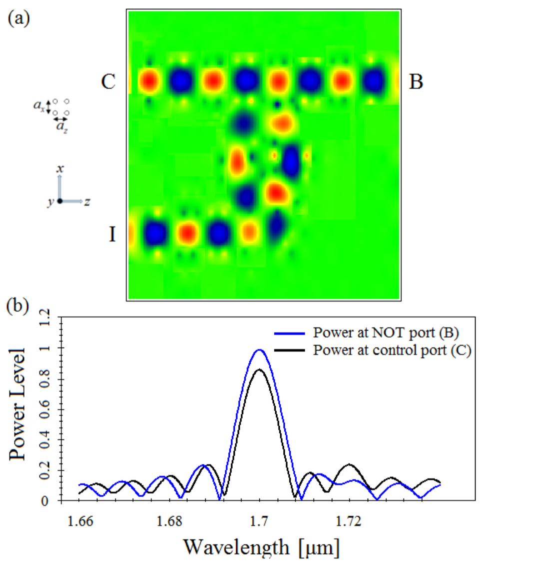

Fig. 4. (a) The propagation of electrical field when the input I is ‘OFF’; (b) Power transmission in ‘ON’ state.

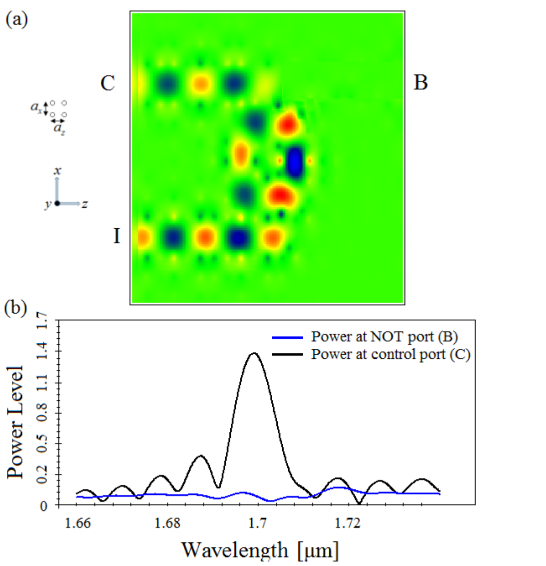

Fig. 5. (a) The propagation of electrical field when the input I is ‘ON’; (b) Power transmission in ‘OFF’ state.

The all-optical NOT logic gate is also known as inverter, because it shows an inverting behavior in the structure [12]. This is a digital logic gate that implements logical negation, according to the truth table shown below. The representation of this logic gate is shown in Figure 6. In the case when the input signal at port B is logic ‘1’, the control signal at port C and input signal interfere destructively and cause the output at port B to be low [5], this is, logic ‘0’. The switching nature of NOT logic gate is demonstrated and this structure satisfies the truth table shown in Table 1.

This paper considers two factors that are used for the performance analysis of all-optical NOT logic gate, namely the contrast ratio and quality factor. For the analysis of these parameters, consider the power transmission graphs only on port B, as shown in Figure 7, characteristic of two conditions: the ‘ON’ state and the ‘OFF’ state.

TABLE I. TRUTH TABLE OF LOGIC NOT GATE.

Control signal C	Input I	Logical Output	Output Power
1	0	1	$0.994P_0$
1	1	0	$0.032P_0$

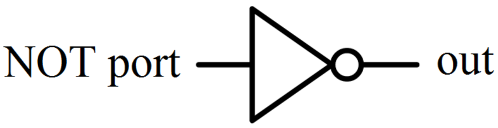

Fig. 6. The digital structure of NOT logic gate.

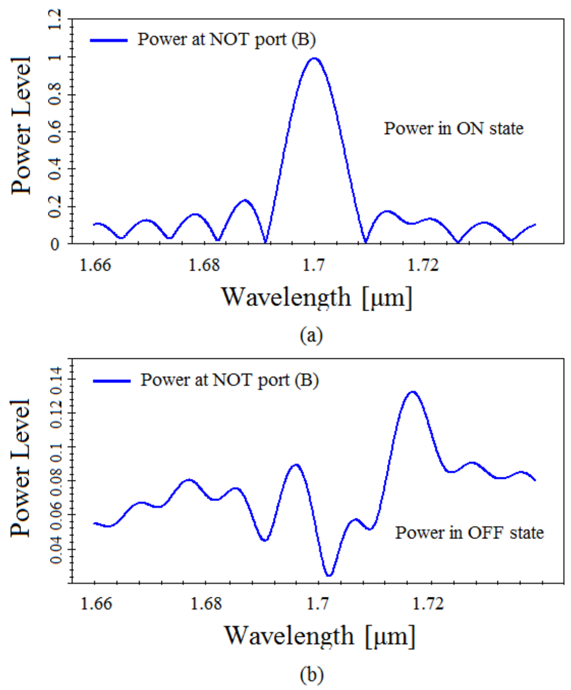

Fig. 7. (a) The power transmission (W/m) in ‘ON’ state; (b) The power transmission (W/m) in ‘OFF’ state.

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

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

In this all-optical NOT logic gate, the contrast ratio is equal to 14.922 dB approximately 15 dB. The power in ‘ON’ state (P_{ON}) is equal to 0.994 and the power for ‘OFF’ state (P_{OFF}) is equal to 0.032 as given in Table 1. The quality of the propagation of electromagnetic waves of a certain frequency depends on spectral width, since, if this is too large, there will be interference from other light rays in the same waveguide. The Quality Factor (Q) can be calculated by the ratio between the wavelength of resonance λ_R and width of spectrum $\Delta\lambda_0$ as shown in expression

$$Q = \lambda_R / \Delta\lambda_0 \quad (2)$$

Therefore, the value of the quality factor is 2598, which is considered as highly beneficial because the PCRR plays an important role in relation to switching capability of the all-optical NOT logic gate presented here. The Figure 8 shows plots of the confined wave in the waveguide after 10000 iterations, where the two states are considered: the ‘ON’ state and the ‘OFF’ state. It can be seen that the amplitude of the field is almost the same from the beginning to the end of waveguide, this is, and the wave is guided with little loss.

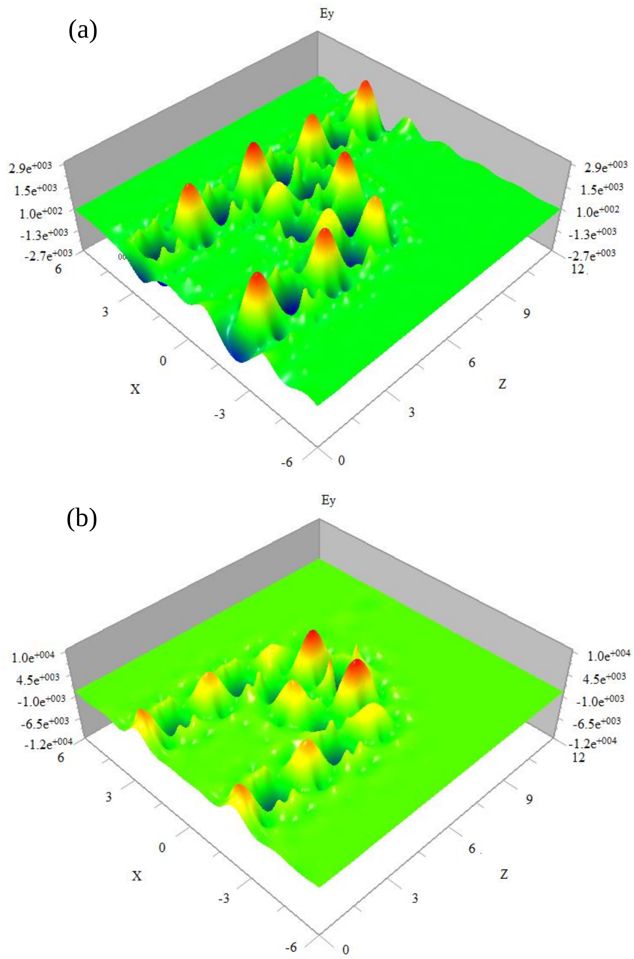

Fig. 8. (a) The propagation of electrical field when the input I is ‘OFF’ in the ‘ON’ state; (b) The propagation of electrical field when the input I is ‘ON’ in the ‘OFF’ state.

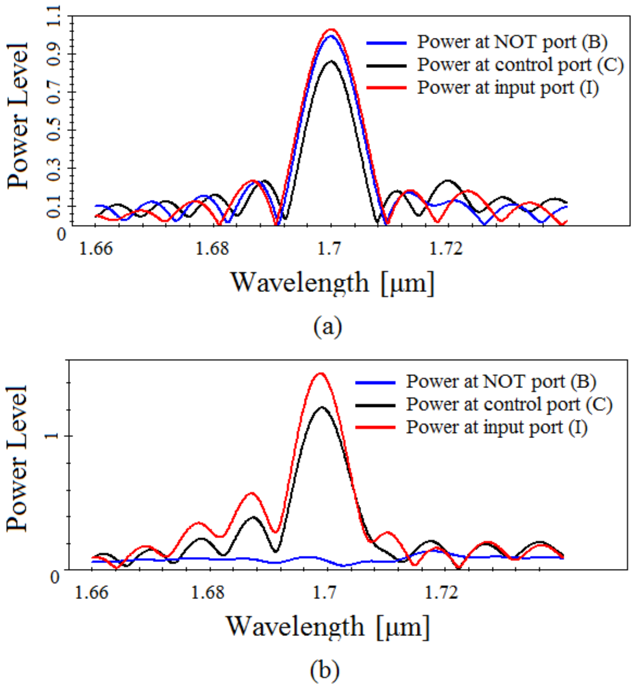

Fig. 9. The power transmission (W/m) on all ports of structure in (a) 'ON' state; (b) 'OFF' state.

For this simulation, the simulated structure needs to be isolated so as not to suffer external interference and internal or related to the physical phenomena that occur during the simulations, such as reflectance occurs when the scattering of the light beam within the cavity. Thus, the Perfectly Matched Layers (PML) [19] were used which are absorbent layers that suppress these phenomena [11]-[12]. In the simulations was possible to see the effects of reflection, diffraction and refraction on the wave during the clash with the PBG structure [5]-[7], besides of the absorption effect of PML simulating the infinity.

The graphs in Figure 9 above shows that the relative power (in W/m) changes with wavelength for all possible combinations in all ports of the structure. The Figure 8 (a) shows the plot of the confined wave in the waveguide after 10000 iterations, in which case input I is 'OFF', and the output 'B' is in the 'ON' state, this is, the transmission power is maximum. Moreover, the Figure 8 (b) shows the distribution of the field when the input 'I' is 'ON', which implies in a transmitted power very low or logic '0'.

IV. Conclusions

This article describes the design and analysis of an all-optical NOT logic gate fabricated with silicon rods in a substrate air. The analysis of the Electromagnetic propagation in periodic structure occurs through the FDTD method, which proved to be very robust and effective. In the simulation, structure is surrounded by perfectly matched layer from all the sides. It is used to avoid reflection from all the sides and absorb waves. 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 quality factor '*Q*', producing a high power output. Furthermore, it was obtained a high contrast ratio value of about 15 dB approximately, indicating a high performance logic gate NOT. This value is much higher of that values previously obtained in other works. Therefore, the analysis of these performance parameters demonstrate that the implemented NOT port is beneficial and promising for a large number of applications in optical computing, cryptography, digital processing systems among others.

References

[1] ZH Zhu, et al, "High-contrast light-by-light switching and AND gate based on nonlinear photonic crystals", *Opt. Express*. 14: 1783-1788, 2006.

[2] E.-H. Lee, "Micro / nano-scale optical network: A new challenge toward next generation", *Proc. Int. Conf. on Transparent Opt. Networks*. 4: 118-119, 2008.

[3] T. Houbavlis, et al "10 Gbit/s all-optical Boolean XOR with SOA fiber Sagnac gate", *Electron. Lett*, 35, 1650-1652, 1999.

[4] J. Y Kim, et al, "All-optical multiple logic gates with XOR, NOR, OR, and NAND functions using parallel SOA-MZI structures: Theory and experiment", *J. Light wave Tech*, 24, 3392-3399, 2006.

[5] K. Sakoda, "Optical Properties of Photonic Crystals", Springer-Verlag Berlin Heidelberg, New York, 2004.

[6] K. M. Leung and Y. F. Liu, "Photon band structures: The plane-wave method", *Physical Review B*, vol. 41, no. 14, pp. 10188-10190, 1990.

[7] R. D. Meade., K. D. Brommer., A. M. Rappe. and J. D. Joannopoulos, "Existence of a photonic band gap in two dimensions", *Appl. Phys. Lett*, 61, 495-497, 1992.

[8] John D. Joannopoulos, Steven G. Johnson, Joshua N. Winn and Robert D, "Meade Photonic Crystals Molding the Flow of Light", Copyright by Princeton University Press, 2008.

[9] S. G. Johnson and J. D. Joannopoulos, "Block-iterative frequency domain methods for Maxwell's equation in a plane wave basis", *Opt. Express*, 11, 173-190, 2000.

[10] Yee K. S, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media", *IEEE Trans Antennas Propag*, 14, 302-307, 1966.

[11] Qui M, He S, "Numerical method for computing defect modes in two-dimensional photonic crystals with dielectric or metallic inclusions", *Phys. Rev. B*, 61: 12871-12876, 2000.

[12] P. Andalib and N. Granpayeh, "All-optical ultracompact photonic crystal AND gate based on nonlinear ring resonators", *J. Opt. Soc. Am. B*, 26: 10-16, 2009.

[13] S. Robinson and R. Nakkeeran. "A bandpass filter based on 2D circular photonic crystal ring resonator," *Proc. IEEE Int. Conf. on Wireless Opt. Commun. Networks* 1, 1-3, 2010.

[14] V. D. Kumar, T. Srinivas and A. Selvaraian, "Investigation of ring resonators in photonic crystal circuits," *Photonics and Nanostructures*, 199-20, 2, 2004.

[15] M. Soljacic, C. Luo, J. D. Joannopoulos e S. Fan, "Nonlinear photonic crystal microdevices for optical integration", *Optics Letters*, Vol. 28, No. 8, pp. 637-639, April 2003.

[16] M. F. Yanik, S. Fan, M. Soljacic e J. D. Joannopoulos, "All-optical transistor action with bistable switching in a photonic crystal crosswaveguide geometry", *Optics Letters*, Vol. 28, No. 24, pp. 2506-2508, December 2003.

[17] T. Fujisawa e M. Koshiba, "Time-domain beam propagation method for nonlinear optical propagation analysis and its application to photonic crystal circuits", *Journal of Lightwave Technology*, Vol. 22, No. 2, pp. 684-691, February 2004.

[18] M. Koshiba, Y. Tsuji e M. Hikari, "Time-domain beam propagation method and its application to photonic crystal circuit components", *IEEE/OSA J. Lightwave Technol*., Vol. 18, pp. 102-110, 2000.

[19] Y. Tsuji and M. Koshiba, "Finite Element Method Using Port Truncation by Perfectly Matched Layer Boundary Condition for Optical Waveguide Discontinuity Problems", *J. of Lightwave Technol*., Vol. 20, No. 3, pp. 463-468, 2002.