



All-Optical Photonic Crystal Decoder Based on Nonlinear Ring Resonator

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ARTICLE INFO	ABSTRACT
<p>Article History: Received 2 March 2020 Received in revised form 29 June 2020 Accepted 10 September 2020 Available online 11 September 2020</p>	<p>The rapid evolution of photonic crystal technology has significantly contributed to advancements in optical signal processing, particularly through the integration of nonlinear ring resonators. These advancements have paved the way for the development of all-optical logic devices, which play a crucial role in high-speed optical computing and communication systems. This literature review synthesizes recent research on all-optical photonic crystal decoders, highlighting their potential applications, such as ultra-fast optical communication, optical computing, and secure data transmission. Additionally, the study identifies key research gaps that require further investigation to enhance the efficiency and scalability of such devices. In this paper, a novel photonic crystal structure is proposed for designing an all-optical decoder using a nonlinear ring resonator. The structure utilizes nano-silicon crystal material for optical switching operations, leveraging its nonlinear properties to achieve efficient signal modulation. The performance of the proposed system is analyzed through numerical simulations using the finite-difference time-domain (FDTD) method and the plane wave expansion (PWE) method to evaluate its optical response and efficiency. Simulation results demonstrate that the designed logic gate achieves a high operational speed exceeding 660 gigabits per second, making it a promising candidate for next-generation ultra-fast optical computing and communication systems.</p>
<p>Keywords: Photonic Crystal, Decoder, Nonlinear Ring Resonator</p>	

1. INTRODUCTION

To achieve high bandwidth and speed, as well as high processing power in electronic and telecommunications systems, one effective method is to use all-optical circuits. All-optical logic components and switches are among the most crucial elements for designing all-optical processing circuits and ultra-fast optical networks [1-3]. The ability to guide light in a photonic crystal structure is provided by utilizing the photonic bandgap [4, 5]. Due to the similarity in the manufacturing processes of two-dimensional photonic crystals and integrated electronic circuits, these structures have seen increased use in designing all-optical switches and logic components. Hence, these structures hold greater potential for designing optical devices such as cavities, waveguides, and logic switches [6-9]. Numerous efforts have been made to design all-optical logic gates and photonic crystal components [9-16]. In [2], a NOR logic gate was designed using five resonators, two of which are of the nonlinear Kerr type, within a square photonic crystal lattice with a glass BSC substrate and Si_{0.75}Ge_{0.25} rods having refractive indices of 1.507 and 3.59, respectively.

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An AND logic gate with two nonlinear resonators operating at 120 Gb/s has been designed [12]. Nonlinear silicon material is used to create the resonators. The proposed structure can operate with an input power of 0-45 W as a logical zero and 215-313 W as a logical one. In [10], a method for designing all-optical photonic crystal logic gates and functions based on threshold logic is proposed. By using nonlinear threshold detectors, the threshold level can be changed by altering the rod radii.

This paper proposes an all-optical photonic crystal decoder. Decoders are one of the essential components in designing all-optical circuits and have significant applications in information processing and transmission. A ring resonator and the Kerr nonlinear effect are used for switching operations. The application of nonlinear materials in the photonic crystal structure induces interesting phenomena, such as bistability. In these systems, the output power is a function of the input power. The proposed structure uses a two-dimensional square photonic crystal lattice of silicon rods in the air.

This paper is organized as follows: Section 2 describes the photonic crystal system structure used in the design. Section 3 presents the decoder structure and the simulation results and their analysis. Section 4 concludes the paper.

2. PROPOSED STRUCTURE

This paper utilizes a two-dimensional square photonic crystal lattice of silicon rods in the air, as shown in Figure 1. The refractive index of the silicon material used in the simulation for wavelengths around 1550 nm is 3.46. The rod radius is $r = 0.2a$ (where a) is the lattice constant), and the structure has two photonic bandgaps for TM polarization, with the larger bandgap in the range of $0.2825(a/\lambda)$ to $0.4169(a/\lambda)$, as shown in Figure 2. The photonic bandgap is calculated using the plane wave expansion method.

Simulations are performed using the finite-difference time-domain (FDTD) method, and the simulation region is surrounded by a perfectly matched layer (PML) with a thickness of $1.5a$ to absorb the incident light and maintain constant wave resistance while avoiding unwanted reflections. The lattice constant a is chosen to be 536 nm for a central wavelength of 1550 nm, and the mesh size in the photonic crystal lattice is set to $0.01a$.

By removing a row of rods in the proposed two-dimensional photonic crystal structure, waveguides are created. As shown, a ring resonator is formed by adjusting the radius and refractive index of the material in the photonic crystal lattice, connecting the input and output waveguides. This structure allows for observing the bistability phenomenon, which forms the basis of the switching operation in this paper. A nonlinear Kerr-effect material is embedded in the proposed ring resonator area, where the refractive index of the material changes linearly with the signal intensity [17, 18].

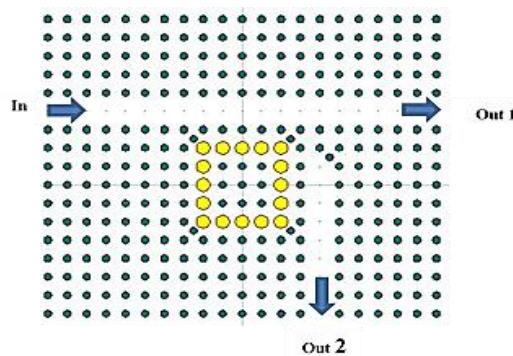


Fig.1. Ring resonator structure for the proposed decoder

The refractive index n in the nonlinear region is given by:

$$n = n_0 + n_2 I \tag{1}$$

where n_0 is the linear refractive index, n_2 is the Kerr nonlinear coefficient, and I is the light intensity. Nano-silicon crystals with a Kerr nonlinear effect are used as the nonlinear material in the proposed structure. This material has a linear refractive index of 1.5 and a nonlinear coefficient of $10^{-16} m^2/W$ at a wavelength of 1550 nm [17, 18].

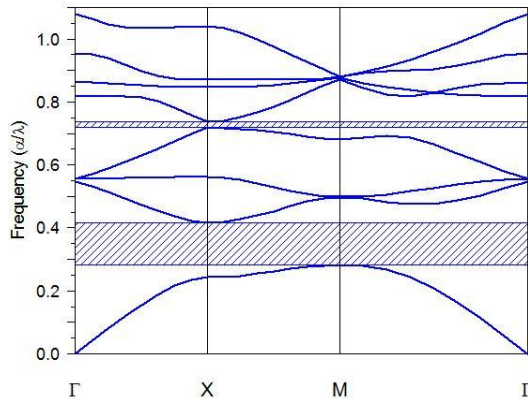


Fig.2. Band structure of a two-dimensional square photonic crystal lattice of silicon rods in the air (TM polarization)

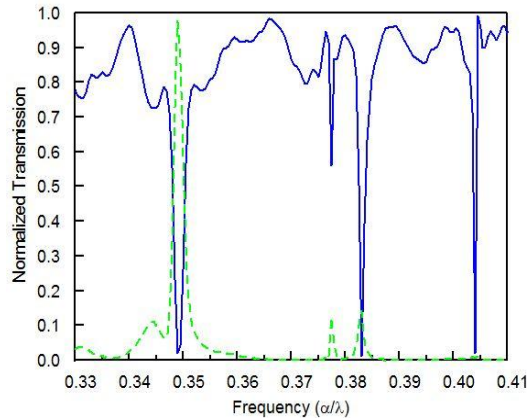


Fig.3. Transmission characteristic curve of the structure

The transmission characteristic of the structure is calculated using the DFT simulation method and shown in Figure 3. As indicated, resonance occurs at a frequency of $0.349(a/\lambda)$, with a significant portion of the input light being transferred to output 2. By applying a continuous wave with power ranging from 1 to 12 watts to the input of the structure, the power transfer to the outputs is measured and shown in Figure 4.

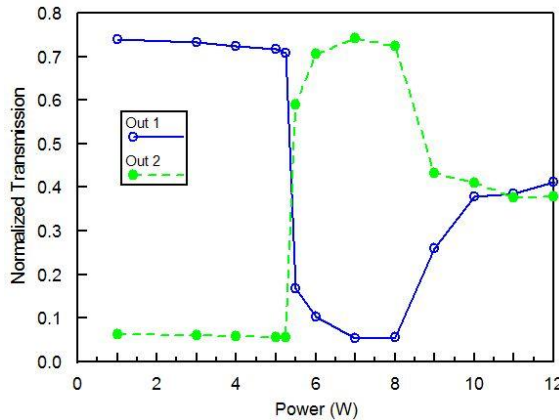


Fig.4. Transmission characteristics relative to input power

3. ALL-OPTICAL DECODER

Photonic crystal structures are suitable for designing all-optical integrated circuits. In this section, a high-efficiency structure for designing an all-optical decoder is proposed. As shown in Figure 5, a 3-input connection at the beginning of the proposed structure designs the decoder. By adjusting the rod radius to 0.05a at the photonic crystal connection output, the amount of light transfer to the input of the resonator is increased. As the light intensity increases, the refractive index of the nonlinear material changes, and the resonator's resonance frequency shifts. By selecting the input light frequency as $0.346(a/\lambda)$ and increasing the input light intensity, the resonance frequency of the resonator shifts to the left on the graph, causing the input light intensity to increase at output port 2 and decrease at output port 1, as shown in Figure 4. When the enable input is off, the power level at the outputs is very low, indicating the decoder is inactive. When the enable input is on, the values of the two output ports depend on the input In value. When input In is off, outputs 1 and 2 will have logical values of 1 and 0, respectively. Thus, the operation of the 1-to-2 decoder shown in Table 1 is correctly implemented.

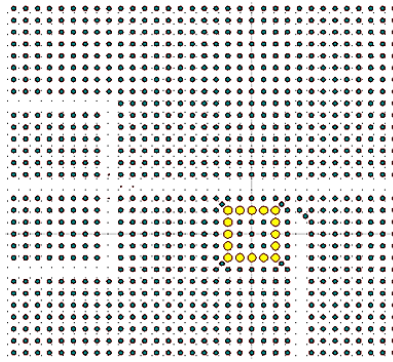


Fig.5. Proposed photonic crystal all-optical decoder structure

Table 1. Truth table of the 1-to-2 decoder

<i>Enable</i>	<i>In</i>	<i>Out1</i>	<i>Out2</i>
0	X	0	0
1	1	0	1
1	0	1	0

By performing simulations using the finite-difference time-domain method, the temporal response of the structure is shown in Figure 6. It is assumed that the input signals have a wavelength of 1550 nm with a Gaussian profile. A continuous wave is applied to the inputs. As shown in Figure 6, when the activation input is off, both outputs 1 and 2 have logical values of 0, depicted from 0 to 3 picoseconds. When the activation input is on and the decoder input is off, outputs 1 and 2 have logical values of 1 and 0, respectively, shown from 3 to 6 picoseconds. Finally, when both the activation and decoder inputs are on, outputs 1 and 2 have logical values of 0 and 1, respectively, depicted from 6 to 9 picoseconds. Thus, the proposed decoder's functionality is correctly demonstrated.

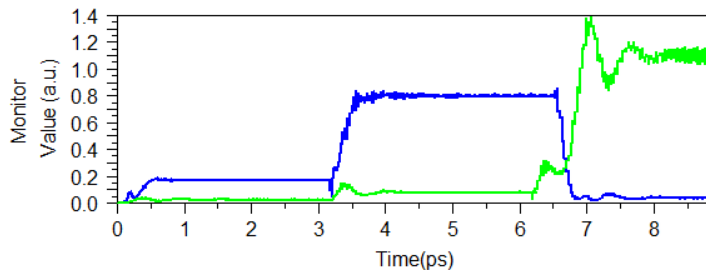


Fig.6. Temporal response of the proposed decoder's outputs

4. CONCLUSION

In this paper, an all-optical decoder is designed and simulated using a two-dimensional square photonic crystal structure composed of silicon rods embedded in air. The proposed structure is developed by integrating a three-input photonic crystal connection with a ring resonator in a cascading configuration, enabling efficient optical signal processing. This design leverages the unique optical properties of photonic crystals to achieve high-speed and low-latency operation, making it suitable for next-generation optical communication and computing systems.

The performance of the decoder is analyzed through numerical simulations, demonstrating its ability to process optical signals with a delay of only 1.5 picoseconds (ps). This ultra-fast response time highlights the potential of the proposed structure in high-speed optical networks and advanced photonic integrated circuits. The findings of this study contribute to the ongoing development of all-optical logic devices, paving the way for more efficient and compact photonic systems.

Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

Acknowledgments

We would like to express our gratitude to all individuals who contributed to this project.

Declaration of Interest

The authors declare that they have no competing interests.

Funding

This research received no specific grant from any funding agency, commercial, or not-for-profit sectors.

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