

Article

Modeling and Simulation of an All-Optical 1×2 Decoder Based on a Two-Dimensional Photonic Crystal Ring Resonator

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Abstract

In this paper, a simple and compact 1×2 decoder based on a two-dimensional photonic crystal structure is proposed, whose operation relies on total internal reflection and photonic band gaps. The designed structure employs a square-lattice configuration of silicon dielectric rods embedded in air. The decoder consists of two input ports, one acting as a Bias port and the other as a logical input port. Numerical modeling and simulations are performed using the plane-wave expansion (PWE) method and the finite-difference time-domain (FDTD) technique. The proposed coupling-resonator structure increases the coupling efficiency at resonant frequencies. The structure has a relatively small footprint, comprising an 18×18 array of dielectric rods with a total area of approximately $147 \mu\text{m}^2$. A minimum contrast ratio of about 8.4 dB between logical “1” and “0” states is achieved. The decoder operates at $1.55 \mu\text{m}$, making it suitable for photonic and optical communication applications. Due to its compact size, simple architecture, and use of a minimal number of ring resonators, the proposed decoder is well suited for high-speed photonic integrated circuits and future all-optical computing systems. The bit rate of the proposed decoder is estimated to be 2 Tb/s.

Keywords: photonic crystals; all-optical decoder; ring resonator; photonic band gap

1. Introduction

The global semiconductor market is undergoing a significant transformation to meet the ever-increasing demand for ultra-high-speed information processing. As the dimensions of integrated circuits shrink, quantum effects such as electron tunneling significantly impact the performance of electronic devices, posing challenges to the continuation of Moore’s law [1]. To overcome these limitations, researchers have increasingly focused on integrating photonic technologies with existing systems. This approach enhances speed and efficiency while reducing power consumption without compromising compactness [2].

In recent years, photonic integrated circuits (PICs) have emerged as a potential alternative to electronic circuits, finding extensive applications in optical communications, signal processing, and quantum computing [3–6]. Among various photonic structures, photonic crystals (PhCs), introduced by Yablonovitch in 1987 [6,7], have proven to be highly promising dielectric platforms for the design of optical devices. PhCs exhibit a photonic band gap (PBG) resulting from the resonant interaction between optical waves and the periodic dielectric lattice. This property allows precise control, confinement, and guidance of light in extremely small regions [8–11].



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Furthermore, the slow-light propagation phenomenon in photonic crystal waveguides and cavities increases energy density and strengthens light–matter interaction, significantly improving photonic device performance [12–14]. Numerous PhC-based devices have been designed, including optical filters, decoders, demultiplexers, switches, and all-optical logic gates [14,15]. Among them, all-optical decoders/encoders play a crucial role in dense optical networks by reducing the number of switches and connections, thereby enhancing data transfer efficiency [16,17]. Optical decoders also serve as intermediate components in optical routing systems, directing signals between different channels. Efficient waveguide coupling is essential for transferring optical signals to the desired ports and may need to be repeated several times to complete the task.

In this context, all-optical decoders are key components for routing optical signals in processing applications. A logical n input decoder with 2^n outputs allows addressing 2^n memory lines using only n control lines, presenting significant design challenges. Previously, a few 2D PhC-based optical decoders have been reported. One common approach in optical decoder design is to exploit the nonlinear properties of materials, particularly the Kerr effect, which alters the refractive index with input light intensity, thereby enabling precise control of light propagation [18–22]. Additionally, slow-light effects in PhC waveguides can enhance light–matter interaction, improve performance, increase the contrast ratio between logic levels, and reduce operating power. The slow-light phenomenon in photonic crystal structures enables compact and low-power optical devices with enhanced light–matter interaction [23,24]. Krauss investigated the phenomenon of slow-light in photonic crystals and its applications in optical devices, highlighting its potential advantages [25]. Danaie et al. designed photonic crystal double-coupled cavity waveguides in the design of slow-light delay lines using coupled waveguides [26].

Kurt et al. demonstrated slow-light pulse propagation accompanied by light tunneling in photonic structures [27]. Arunkumar and Robinson used a conventional 2×4 decoder design constructed from line and point defects with high efficiency. A nanocavity was incorporated into the structure, thereby reducing leakage power at resonance and increasing the output power (2023) [28]. Askarian et al. designed a 2×4 decoder based on the Kerr effect, reducing the delay time to 2 ps and increasing the contrast ratio to 8.98 [29]. Maleki et al. proposed a structure consisting of two input ports and glass rods with a Kerr nonlinearity, doped with thin silica coated with a graphene oxide layer about 2 nm thick [30]. This led to the creation of a Kerr coefficient and prevented the formation of backward waves in the cavity structure.

Recent works include those of Alipour-Banaei et al. [17], who designed a 2×4 decoder using self-alignment and interference effects with a 29×22 array of chalcogenide rods. Askarian [18] designed a linear optical decoder with an area of $420 \mu\text{m}^2$ on a 2D air-rod PhC platform using interference and threshold switching. Other studies, such as Sharma [21], proposed various linear and nonlinear PhC decoders with point or line defects and ring resonators, sometimes incorporating graphene for enhanced functionality. Naghizade designed a 2×4 all-optical decoder using three nonlinear ring resonators with the aim of reducing rise and fall times [14].

Sirajmohammadi et al. proposed a 1×2 nonlinear all-optical decoder based on a PhC and threshold-switching using a nonlinear ring resonator sandwiched between three waveguides with an area of $238 \mu\text{m}^2$, achieving a switching threshold of $\sim 1.5 \text{ kW}/\mu\text{m}^2$ [15]. Alipour-Banaei et al. suggested a 2×4 rod-based decoder with high-intensity resonant rings for coupling. This structure was arranged in a square lattice. While functional performance was demonstrated, temporal response was often not reported [17].

In all these structures, dielectric rods in air were used, and performance metrics were calculated assuming infinite height. In practical scenarios, however, device height is limited.

Moreover, most previously reported decoders rely on optical nonlinearity, requiring high input power. These limitations motivated the authors to design simple all-optical decoders in a 2D PhC platform [31,32].

In most decoder and other logic circuit designs, Si rods are used in an air background. The rod radius and lattice constant are chosen to be suitable for the wavelength used in fiber-optic communication. Then, line and point defects are used to allow light propagation in the waveguides [33–36].

The proposed simple 1×2 optical decoder employs two single-line defect waveguides coupled to an embedded resonator cavity to realize wavelength-selective transmission. At the resonant wavelength, in-phase signals are combined and transmitted through channel 1, whereas out-of-phase signals propagate through channel 2.

The decoder is implemented entirely in silicon, the most common material in optical integrated circuits. The design features a compact size, a reasonable contrast ratio, and a fast response, achieved by introducing path differences between converging optical signals. The PhC band structure was analyzed using the PWE method, while FDTD simulations [37] were used to study optical behavior and evaluate device performance. The PhC rod height is limited in this design, and an effective refractive index approach was adopted to reduce simulation time. Simulation results indicate high bit-rate operation and a high contrast ratio. The compact size, fast response, and simple design, with the same rod radii, make this device suitable for fabrication and use in future optical computing applications.

Fabrication of photonic crystals currently faces a challenge. This challenge stems from the novelty of the field, as the manufacturing technology has not yet been fully developed. However, the flexibility, low cost, high efficiency, and high speed of photonic crystal-based circuits will drive researchers in the near future to focus on developing fabrication technology for these structures. To date, only a few structures have been fabricated using the limited existing CMOS-compatible technology, in which only two-dimensional structures have been created, and their band structure has been investigated. These efforts have not yet led to the development of waveguides for light propagation and optical applications [38,39].

The remainder of this manuscript is organized as follows. Section 2 describes the proposed decoder structure. Section 3 presents the device performance through FDTD simulations and operational principles. Section 4 concludes with the findings and implications of the proposed structure.

2. Design of a 1×2 All-Optical Decoder

A 1×2 decoder is a combinational circuit that has one input and two outputs. In a photonic crystal optical decoder, when the main input is “0”, one of the outputs must be in the logical “1” state; therefore, a secondary input called Bias is required. In other words, for the decoder to operate, the Bias source must be ON. If this source is OFF, the output values are not relevant. So, assuming the Bias source is ON, if the main input is in the logical “0” state, the output D_0 will be active (“1”), and the other output will be “0”. If the main input is in the logical “1” state, the output D_1 will be active and the other output will have the value 0. Table 1 shows the different logic states for the 1×2 decoder.

Table 1. Truth table of different logic states for inputs and outputs.

Bias	Input	D_0	D_1
0	×	×	×
1	0	1	0
1	1	0	1

With the increasing demand for high-speed and compact optical signal processing systems, the design of efficient all-optical logic components has become a critical research area. Key challenges include reducing device footprint, improving switching speed, lowering power consumption, and achieving high integration capability within photonic integrated circuits.

In this work, we propose a 1×2 all-optical linear decoder based on a two-dimensional (2D) photonic crystal (PhC) and a ring resonator. The schematic of the proposed switching decoder is shown in Figure 1. It consists of a waveguide coupled to a ring resonator. The ring resonator serves as a coupling element between waveguides and is characterized by a specific resonance wavelength. Optical waves at the resonant wavelength are trapped within the ring, allowing controlled propagation to other waveguides [40–43].

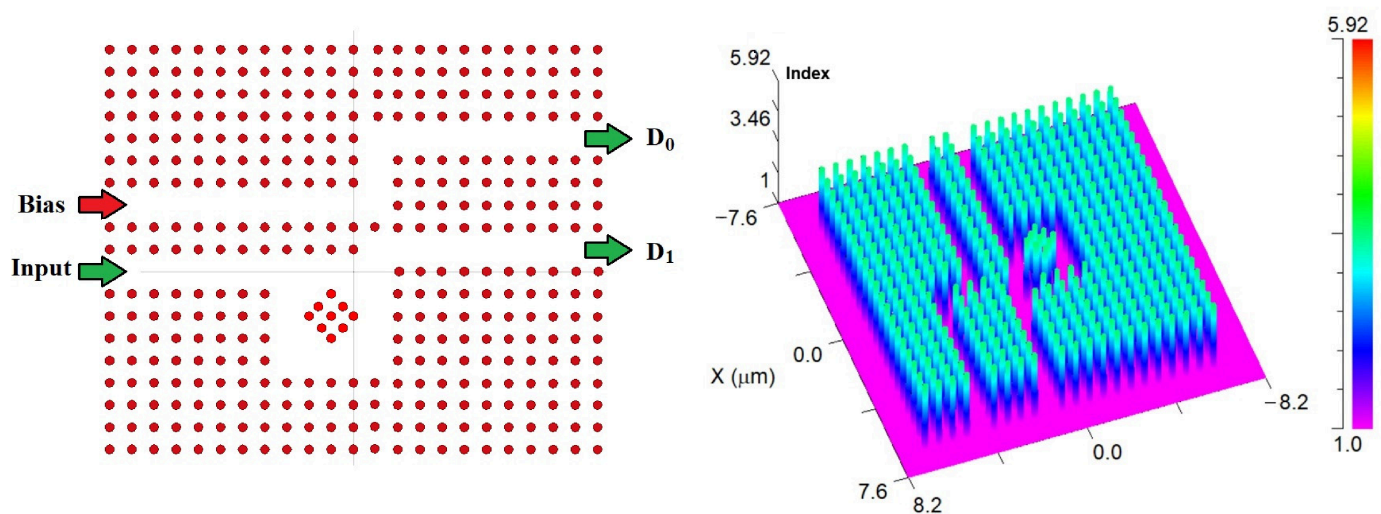


Figure 1. The structure of photonic crystal decoder.

The photonic crystal lattice has a square configuration consisting of 23×19 dielectric rods, each with a refractive index of ($n = 3.23$) embedded in an air background ($n = 1$). The rod radius is $0.18 \times a$, where the lattice constant is $a = 0.58 \mu\text{m}$. The ring resonator is designed to operate at a resonant wavelength of $1.55 \mu\text{m}$, which corresponds to a rod radius of $0.18 \times a$.

The photonic band structure of the crystal was calculated using the plane wave expansion method. To form the decoder, a waveguide is first created by removing a complete row of dielectric rods within the PhC. Subsequently, a 5×5 square array of dielectric rods adjacent to the waveguide is removed, and a nine-rod ring resonator is placed at the center of the square to achieve resonance at $1.55 \mu\text{m}$.

The proposed 1×2 decoder includes an input light source and a Bias line, which determines which input is directed to the output channel 1. An input waveguide connects the logical input port to the decoder, while the Bias port introduces a reference optical signal. As mentioned, the proposed all-optical device operates based on the interference of optical beams, which is governed by wave optics theory. Constructive or destructive interference occurs depending on the initial phase and the propagation paths of the incoming optical signals.

It should be noted that when an optical signal is applied to the input port, its propagation through the waveguides requires a finite time due to intrinsic system delays. The total response time of the structure is given by the sum of the transit time and the steady-state time. For a given output port, the transit time is defined as the time required for the output

signal to reach 1% of its steady-state power, while the rise time corresponds to the time taken for the output to increase from 1% to 90% of its steady-state power [43–47].

Temperature-induced variations in the refractive index of the constituent material can lead to a shift in the photonic band gap (PBG), thereby potentially affecting the overall performance of the system. In the proposed structure, Si is employed as the base material, which exhibits a relatively low thermo-optic coefficient. Moreover, as illustrated in Figure 2, the PBG width is sufficiently broad, and the operating wavelength of $1.55\ \mu\text{m}$ is located well within the band gap and away from the band edges. Consequently, even if minor refractive index fluctuations—caused by temperature changes—result in slight shifts in the PBG range, the operating wavelength remains within the band gap. As a result, light propagation through the waveguides is preserved at this wavelength.

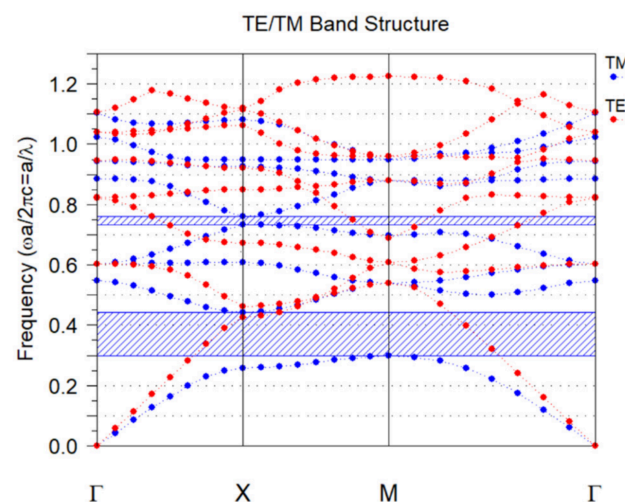


Figure 2. The photonic TE-TM band gap diagram.

Manufacturing tolerances present another challenge that can adversely affect the bit rate. The impact becomes more pronounced as the rod dimensions are reduced. In the proposed design, rods with a radius of $0.18 \times a$ are employed, while the use of extremely small defect radii is avoided. This approach effectively mitigates the influence of fabrication tolerances and process limitations on the bit rate. Naturally, with continued technological advancement and the feasibility of fabricating rods with even smaller radii, this challenge is expected to diminish further.

2.1. FDTD Method

The FDTD method enables the visualization of wave propagation in structured media such as photonic crystals. It provides an intuitive understanding of propagation dynamics as well as detailed information about electromagnetic field behavior within the structure. The method constitutes a direct time-domain solution of Maxwell's equations using numerical finite-difference techniques, allowing the simultaneous analysis of TE and TM modes. This capability facilitates the mapping of the electromagnetic field at any spatial location and time instant.

Time-resolved field evolution also offers insights into the structure's spectral response. In photonics, FDTD allows the simulation of an optical excitation in a photonic crystal and the monitoring of its interaction over time, including transmission characteristics.

The purpose of this work is to present a set of simulations for calculating light propagation in waveguides with arbitrary geometries. In this analysis, the meshing scheme sets Δx and Δz as the minimum spatial step sizes in the x and z directions, respectively, both

chosen to be equal to $\lambda/16$. In this context, the following equation determines the allowable time step Δt [44–46].

The Courant condition is a necessary condition for the convergence of the structure's response. The CFL condition is given by:

$$\Delta t \leq 1 / c \times \sqrt{\left(\frac{1}{\Delta x}\right)^2 + \left(\frac{1}{\Delta z}\right)^2} \quad (1)$$

2.2. PWE Method

The plane wave expansion (PWE) method is a well-established mathematical technique widely used in physics and engineering, particularly for analyzing periodic structures such as photonic crystals and diffraction gratings. In this approach, the linear wave equation is solved in the frequency domain by expanding the electromagnetic fields into a set of plane waves.

This method is widely used to calculate photonic band gaps. The governing equations of the PWE method are as follows:

$$\nabla \times (1/\epsilon_r \nabla \times H) = (\omega/c)^2 H \quad (2)$$

$$(1/\epsilon_r) \nabla \times \nabla \times E = (\omega/c)^2 E \quad (3)$$

One of the key features of photonic crystals is their ability to prohibit the propagation of specific wavelengths of light, which can be exploited to block a wide spectral range. By properly designing the photonic crystal structure, a PBG can be formed, in which light of certain wavelengths is prohibited from propagating. The PBG characteristics, such as its wavelength range, can be tuned by adjusting the structural parameters of the photonic crystal, including rod radius, lattice constant, refractive index, and material type.

For the proposed decoder, the photonic crystal was designed to create a TM-mode PBG in a normalized frequency range of $a/\lambda = 0.3$ to 0.45 , corresponding to wavelengths of approximately $1.28 \mu\text{m}$ to $1.93 \mu\text{m}$, as illustrated in Figure 2. Within this bandgap, a specific operating wavelength of $1.55 \mu\text{m}$ was selected for device operation.

The proposed structure consists of two parallel input waveguides, where the waveguide logical input and the Bias act as the input port. The Bias port introduces an optical signal with the same power as the logical input. A ring resonator is coupled to the logic input waveguide, while the output ports D_0 and D_1 collect the transmitted signals. A phase difference of 120° is introduced between the logical input and Bias signals.

The coupled ring resonator operates as a 3 dB optical splitter/combiner. This configuration enables constructive and destructive interference, allowing controlled routing of optical signals to the output ports D_0 and D_1 , as illustrated in Figure 1.

3. Simulation and Results

After completing the design of the proposed decoder, the structure was simulated to investigate its optical behavior and switching performance. For this purpose, the FDTD method was employed, as described in the previous section. The ring resonator was specifically designed to exhibit resonance at a wavelength of $1.55 \mu\text{m}$.

In the following, the performance and operational characteristics of the proposed decoder are analyzed for two different input conditions. The analysis focuses on the output power distribution, logical state discrimination, and the impact of phase-controlled interference on the decoder operation.

Case 1: Figure 3 illustrates the operating condition in which the logical input is set to 0, while only the Bias input is active (Bias = 1). In this case, an optical signal with

power intensity $P_i = 1 \text{ mW}/\mu\text{m}^2$ and a central wavelength of $1.55 \mu\text{m}$ is launched into the structure and propagates through the Bias waveguide.

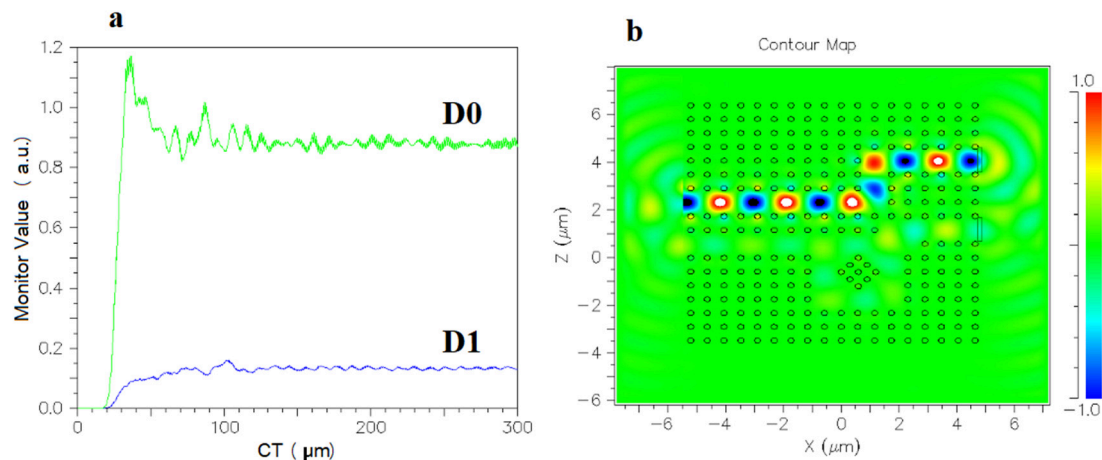


Figure 3. Outputs when Input = 0 and Bias = 1. (a) Normalized output power; (b) power distribution in the waveguides.

Since the optical power is below the threshold required to switch the resonant ring, and the input wavelength does not match the ring's resonant wavelength, the optical signal is not efficiently coupled into the resonator. Consequently, the light is transferred through the ring to the L-shaped waveguide connected to output port D₀.

As a result, in this operating state, the Bias input and output ports D₀ are ON, whereas the logical input and output ports D₁ remain OFF. Figure 3a shows the temporal response of the output power. In this case, the output power at port D₀ is equal to 0.9, whereas the output power at port D₁ is 0.13.

Case 2: The second operating condition occurs when the Bias input is ON and the logical input port is also turned ON. The optical power intensity injected into the logical input port is assumed to be $P_i = 1 \text{ mW}/\mu\text{m}^2$.

In this scenario, both input signals interact in the vicinity of the ring resonator. Due to the introduced phase difference, constructive and destructive interference occurs, which significantly alters the propagation behavior of the optical fields. As a result, the optical power is redirected toward the second waveguide.

The light then propagates through the Bias waveguide toward output port D₁. In this operating state, output port D₁ is in the ON state, while output port D₀ is OFF, as illustrated in Figure 4b. It should be noted that the decoder outputs are valid only when the Bias input is active. Figure 4a shows the temporal response of the output power. In this case, the output power at port D₀ is 0.13, whereas at port D₁ it is 1.1.

The logical states of the input and output ports, along with the corresponding output power levels for different decoder input conditions, are summarized in Table 2.

Table 2. Logic and power levels at various ports of this 1×2 linear decoder.

Bias Power	Input Power (Logic Level)	D ₀ (Logic Level)	D ₁ (Logic Level)
P_i	0 (0)	0.9 P_i (1)	0.13 P_i (0)
P_i	P_i (1)	0.13 P_i (0)	1.1 P_i (1)

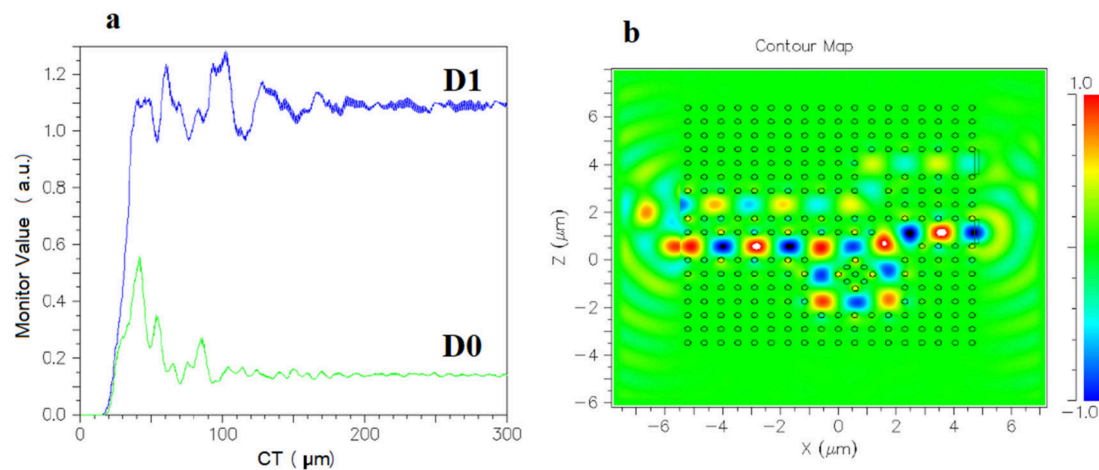


Figure 4. Outputs when Input = 1 and Bias = 1. (a) Normalized output power (b) power distribution in the waveguides.

For Input Signal “0”:

Under this operating condition, a negligible portion of the optical signal is transmitted through the resonator to the output port D₁, resulting in a low logical level at this port. The electric field distribution corresponding to this state is illustrated in Figure 3. The output power measured at port D₁ is 0.13 P_i, while the output power at port D₀ is considered to be 0.9 P_i.

For Input Signal “1”:

In this case, the input port is excited by a continuous-wave (CW) optical signal with a power of P_i and a phase shift of -120° relative to the Bias signal.

The optical signal entering via port I undergoes interference at the ring resonator’s coupling region, preventing significant power transfer to output port D₀. Consequently, the logical level at port D₀ remains low. The corresponding electric field distribution of the device under this condition is shown in Figure 4. The output powers at ports D₀ and D₁ are measured to be 0.13 P_i and 1.1 P_i, respectively.

In addition, some parameters of the proposed structure, including contrast ratio, data rate, and response time, are extracted using FDTD simulations.

The contrast ratio is defined as the ratio of the optical power at the output port when the device is in logical state “1” to that when it is in logical state “0”. The contrast ratio is a key parameter in the design of optical logic devices and is typically maximized. Moreover, the contrast ratio is inversely proportional to the bit error rate (BER), while BER itself is inversely related to the noise margin of the structure. Therefore, the contrast ratio is directly associated with the system’s noise margin. The contrast ratio (CR) can be expressed as:

$$CR = 10 \times \log \left(\frac{P_{1,Min}}{P_{0,Max}} \right)$$

where P_{1,Min} and P_{0,Max} denote the worst-case optical power for logical states “1” and “0”, respectively.

From Table 2, P_{1,Min} = 0.9P_i and P_{0,Max} = 0.13P_i are obtained, and consequently, CR = 8.4 dB has been computed.

To calculate the decoder bit rate, a pulse is applied to the input. The pulse duration is chosen to ensure that the output has sufficient time to reach a steady state. After the pulse is interrupted, the output gradually approaches the zero state. If the time to reach the final

state of 0 is denoted by T, the bit rate can be calculated as $BR = 1/T$. Figure 5 shows the time to reach a steady state for the outputs in state 1.

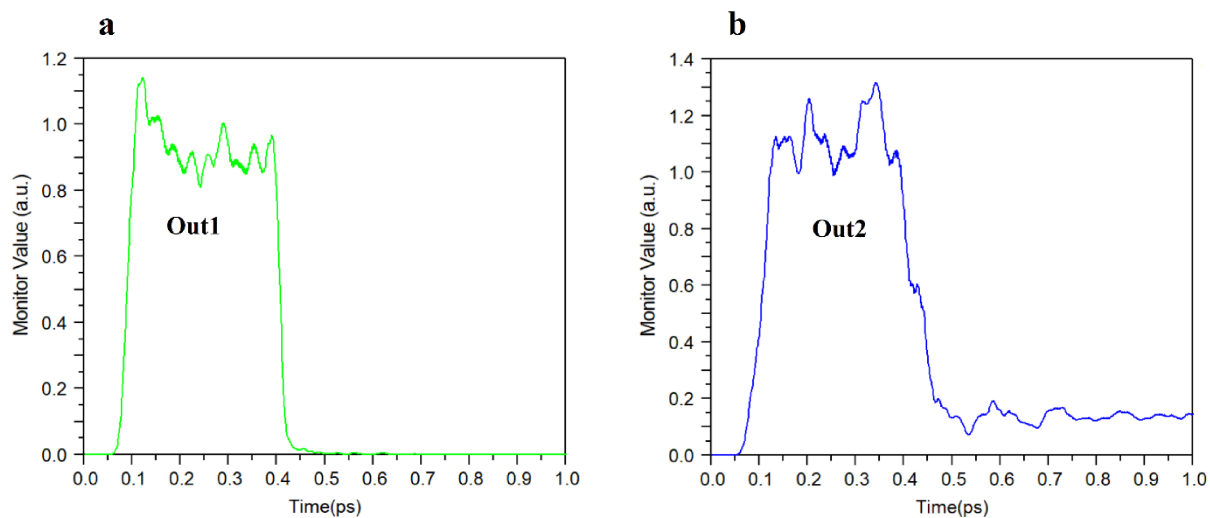


Figure 5. Response time to input pulse for calculating BR for (a) output D_0 and (b) output D_1 .

Figure 5a shows the output of D_0 in state “1”. As this figure shows, the output first reaches a stable state (approximately 2 ps). Then, when the input pulse is cut off, the output quickly reaches zero. The time required for the output to reach state “0” is 0.45 ps. Figure 5b also shows the D_1 output when $D_1 = 1$. In this case, the time to reach a stable state in state “0” is approximately 0.5 ps. Considering these times, the worst-case BR for the proposed decoder is 2 Tb/s.

4. Comparative Analysis

The performance characteristics of the proposed decoder are summarized in Table 3. A comparative analysis with several previously reported decoders, mainly based on nonlinear optical effects, is also presented. In such nonlinear designs, a threshold optical power is required for proper operation, which represents a significant limitation for practical implementations.

Table 3. Comparison of the proposed structure with previous works.

Reference	Lattice Type	Footprint (μm^2)	Wavelength (nm)	Bit Rate (Tb/s)	Contrast Ratio (dB)	Material	Response Time (ps)
[32]	Square	850	1550	0.45	10.6	Si	2.2
[48]	Square	228	1550	0.22	--	Si	4.5
[49]	Hexagonal	110	1550	1.0	13.4	Si	--
[50]	Triangular	243	1550	1.44	20.0	Si	--
[51]	hexagonal	215	1550	0.70	10.0	Si	0.88
[52]	Square	561	1550	0.67	9.12	Si	--
[53]	Hexagonal	561	1550	0.5	9.3	Si	2
[54]	Hexagonal	228	1550	2.8	2.9	Si	--
This work	Square	147	1550	2.0	8.4	Si	0.2

In contrast, the proposed decoder has a relatively compact footprint compared with prior work, making it a promising candidate for dense integration in photonic integrated circuits (PICs). Furthermore, the contrast ratio achieved at the decoder output ports in this work exceeds that reported in previous studies listed in the comparison table, thereby minimizing the bit error rate in optical communication channels [32,48–54].

As a result, the comparative evaluation demonstrates that our design achieves a high bit rate and a low bit-error rate without imposing the limitations associated with threshold optical power requirements.

5. Conclusions

In this paper, the design and simulation of a 1×2 decoder based on a ring resonator on a two-dimensional photonic crystal platform have been presented. The proposed structure has been developed to achieve a compact footprint, simple design, and high-speed operation. The decoder consists of a ring resonator and two linear waveguides as its main components, thereby reducing fabrication complexity and improving integrability in photonic integrated circuits. The photonic crystal structure is specifically designed for operation at a wavelength of $1.55 \mu\text{m}$, which is widely used in optical fiber communication systems. Simulation results demonstrate that the proposed structure provides a clear distinction between logical “0” and “1” states and exhibits reliable performance in routing the output signals. These features make the proposed design a strong candidate for applications in optical logic processing systems and advanced photonic integrated circuits.

Author Contributions: F.P.: supervised, designed and performed simulations, and analyzed data; M.P.: investigated and simulated the proposed structure; S.O.: verified, edited, and prepared the final draft of the manuscript. All authors have read and agreed to the published version of the manuscript.

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