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Photonic Crystal Resonators in Designing Optical Decoders

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Abstract

New design in photonic crystal structures has provided a great opportunity to employ optical decoders with high contrast ratio and low response time. Based on the last published articles, photonic crystal-based decoders result in a contrast ratio higher than 20 dB and a response time of 200 fs which is proper to use in optical circuits. Changing the path of a signal may occur with the help of a resonator in the form of a cavity or ring. Dropping a signal at a wavelength makes a possible to direct it toward the desired path. We present an introduction to the decoding operation and its advantages in different applications, followed by an explanation of the excellent features of photonic crystals including forbidden bandgap and the optical Kerr effect. Furthermore, we discuss the key role of the resonance phenomenon in photonic crystal structures. Then, we investigate the valuable designs in approaching the decoding. It has been tried to present an algorithm to design photonic crystal-based decoders which is so needed for research.

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1. INTRODUCTION

High-speed processing requires careful optical circuit design due to the rapid movement of optical waves compared to electrons. While quick data transmission via optical waves is a major advantage of optical systems, ensuring optical confinement poses a significant challenge in circuit design. Optical confinement can be achieved by creating a refractive index contrast between two layers. Optical circuits consist of optical waveguides, which typically consist of a core surrounded by a clad. In these circuits, planar waveguides are composed of three layers, with the middle layer having a higher index than the others. Proper layer matching and interface quality are important factors to prevent power leakage to the clad. The lattice constant and doping concentrations of the layers play crucial roles in the design and fabrication of optical waveguides. In recent years, different structures such as Mach-Zehnder interferometers (MZIs) and graphene-based waveguides with metal-insulator-metal and insulator-metal-insulator configurations have been developed to guide and control optical waves. MZI structures require multiple arm lengths to achieve desired interferences, which makes them incompatible with integrated circuits. Although plasmonic-based structures are designed in a small area, the transmission efficiency for coupling with other blocks is not very high [1]. Additionally, the transmission efficiency of waveguides depends on the graphene chemical potential, which is adjusted using a gate voltage. However, these waveguides operate electro-optically rather than all-optically, limiting their electrical switching capabilities.

Designing optical systems with all-optical processing capabilities is an interesting feature. All-optical processors enable optimal data transmission among blocks. Photonic crystal structures have shown potential for designing all-optical components of optical processors [2-6]. These structures create a photonic bandgap that prevents the propagation of optical waves at specific wavelengths. The bandgap is created through the reflection of Bragg layers, where the contrast of indices between adjacent layers leads to partial reflection and the construction of multiple reflections forms a complete reflector. As a result, photonic crystals can have a forbidden range of wavelengths for wave propagation. Photonic crystals offer high transmission efficiency and all-optical mechanisms, making them suitable for designing fundamental blocks in optical processors. They allow more than 90% of the input light to pass through the output of the optical devices. Additionally, their scalability feature enables the fabrication of devices with desired outputs of various sizes. Photonic crystal-based decoders have attracted significant attention due to their ability to guide waves in all directions and over a wide range of angles. Guiding waves through resonators helps achieve high-performance optical decoders.

Compared to other structures like semiconductor optical amplifiers, Mach-Zehnder interferometers, and plasmonic decoders, photonic crystal-based decoders offer advantages such as all-optical processing, simple fabrication processes, and high transmission efficiency. Based on their ability to control and manipulate optical waves, photonic crystal-based structures are considered a suitable medium for decoding operations. This study explores various structures and ideas for designing optical decoders within photonic crystal structures. It also discusses the role of the optical Kerr effect and the implementation of cavity and ring resonators in decoders.

2. OPTICAL DECODER

Digital circuits can be categorized into combinational and sequential circuits. Combinational circuits produce outputs solely based on the current inputs, without any influence from past outputs. On the other hand, sequential circuits generate outputs based on the current inputs as well as the previous outputs. Binary codes are used to represent discrete data in digital systems. An n-bit binary code can represent up to 2^n discrete information elements. A decoder is a combinational circuit that takes binary information from n input lines and converts it into a maximum of 2^n output lines [7]. In an n-input decoder with 2^n outputs, each output corresponds to a unique combination of inputs. In some cases, certain input combinations may be unused, resulting in the number of decoder outputs being less than 2^n.

A decoder circuit can also include an enable signal. When the enable signal is inactive, the decoder circuit is disabled and does not function. One application of decoders is in code converters like BCD to 7-segment converters. Decoders can be designed in various configurations depending on the number of inputs and outputs, such as 1-to-2, 2-to-4, 3-to-8 decoders, and so on. The simplest decoder is the 1-to-2 decoder, which has one input and two outputs, denoted as x for the input and O0 and O1 for the outputs. The behavior of this decoder is as follows: if x=0, only the O0 output is active, and if x=1, only the O1 output is active.

Decoders possess the flexibility to construct larger decoders by utilizing smaller ones. As an illustration, by combining two 2-to-4 decoders, a 3-to-8 decoder can be created. The design process for this decoder is visually presented in Figure 1 [7].

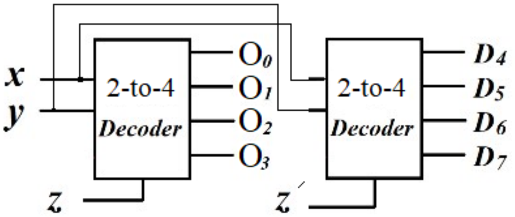


Fig. 1. A 3-to-8 decoder based on two 2-to-4 decoders using the enable port [7].

In Figure 1, both inputs of the 2-to-4 decoders are linked to x and y. The third input is generated through the enable input. Consequently, the complement of this input is connected to the right decoder (which includes outputs with higher values), while the input itself is connected to the left decoder (which includes outputs with lower values).

Code converter circuits are among the various applications of decoders. An instance of this is its usage in analog to digital converters. Additionally, in-memory systems can employ decoders to reduce the impact of system decoding. An essential application of decoders lies in implementing and designing logical functions. Put differently, instead of employing logic gates, one can utilize a decoder to design the logic function. With this in mind, decoders can be used to design various logic circuits, such as adders and reducers.

3. PHOTONIC CRYSTALS

Photonic crystals are structures with a periodic arrangement that manipulate and control the movement of light or electromagnetic waves. Just like regular crystals have repeated atom patterns, photonic crystals have alternating regions of different refractive indices [8]. This unique design creates a photonic bandgap, a range of wavelengths where specific frequencies of light cannot propagate. The photonic bandgap acts as a barrier for certain light wavelengths, resulting in optical effects like reflection, refraction, diffraction, and localization. Researchers can customize the bandgap properties of photonic crystals by adjusting their composition and geometry, allowing them to selectively permit or block particular light wavelengths. The ability to manipulate light using photonic crystals finds extensive applications in optics and photonics. They are utilized in the development of lasers, optical fibers, waveguides, lenses, filters, sensors, and various other photonic devices. Photonic crystals are also employed in telecommunications, integrated circuits, quantum optics, and energy harvesting. The study and design of photonic crystals involve advanced techniques such as nanofabrication and self-assembly methods, enabling the creation of precise patterns and structures on a nanoscale. This precision facilitates fine-tuning of the photonic properties and exploration of new optical phenomena and interactions between light and matter.

The properties and behavior of photonic crystals depend on several important factors. One crucial aspect is the lattice structure, which refers to how the constituent materials are arranged in a periodic fashion. The lattice structure can take various forms, such as cubic, hexagonal, or others, and it establishes the crystal's symmetry and spacing. Another significant parameter is the refractive index contrast, which measures the disparity in refractive indices between the materials composing the photonic crystal. A higher contrast leads to a more pronounced photonic bandgap, enabling better control over the propagation of light. The dielectric constant, also known as permittivity, describes how a material responds to an electric field. In the context of a photonic crystal, it affects both the speed and polarization of light within the crystal. Periodicity relates to the repetition of the photonic crystal structure in space. It determines the specific range of wavelengths affected by the photonic bandgap, as well as the angular dependence of the bandgap. The band structure of a photonic crystal represents the allowed and forbidden energy states for photons within the crystal. It defines the range of frequencies or wavelengths that can either propagate through the crystal or are prohibited from doing so. By introducing defects or impurities into the photonic crystal structure, engineers can create localized states or modify the band structure. These engineered imperfections enable various applications, including waveguiding, cavity resonances, and efficient light emission. Researchers can customize the properties of photonic crystals according to specific applications and desired functionalities in the field of optics and photonics. This is made possible by considering the aforementioned parameters and utilizing various design and fabrication techniques.

3.1. Various forms of the photonic crystal structures

Photonic crystals exist in various forms, each with its own distinct characteristics and properties. One-dimensional structures, also known as photonic crystal slabs, possess periodicity in one dimension while extending infinitely in the other two dimensions. They are comprised of alternating layers or rods with different refractive indices. Through the manipulation of these one-dimensional photonic crystals, researchers can control the propagation of light and observe intriguing phenomena like Brewster's angle reflection and resonant tunneling. Two-dimensional structures exhibit periodicity in two dimensions and extend infinitely in the third dimension. These structures consist of regularly arranged scatterers or holes on a flat substrate. They enable the manipulation of light in two dimensions and exhibit behaviors such as diffraction, refraction, and the formation of bandgaps. In contrast, three-dimensional structures demonstrate periodicity in all three dimensions. They feature a precise arrangement of scatterers or voids within a bulk material. These three-dimensional photonic crystals offer meticulous control over light propagation in all directions and can exhibit complete bandgaps, which effectively block the transmission of light across a range of frequencies.

There are two common types of photonic crystals based on the arrangement of constituent elements (dielectric materials) within the crystal structure: hole-type and rod-type. In hole-type photonic crystals, a higher-index host material surrounds a periodic array of air or low-index material. This arrangement creates regularly spaced holes or voids within the crystal lattice. The presence of the air or low-index regions introduces a photonic bandgap, which prevents the propagation of specific wavelengths or ranges of light. The bandgap arises from the periodic refractive index contrast between the high-index host material and the low-index regions. This unique structure blocks certain frequencies of light, resulting in distinctive optical properties. In rod-type photonic crystals, high-index rods or columns are periodically arranged within a lower-index background material. The rods constitute the dielectric elements of the crystal lattice, while the surrounding lower-index material serves as a host. Similar to hole-type crystals, rod-type crystals possess a photonic bandgap resulting from the periodic variation in refractive index. The presence of the high-index rods modifies the effective refractive index of the crystal structure and influences the propagation of light. This leads to the formation of bandgaps that selectively inhibit the transmission of specific wavelengths of light through the crystal.

By designing the geometry, radius, and spacing of the rods or holes, the behavior of light within a photonic crystal can be manipulated through the tuning of the photonic bandgap. This enables control over various optical properties, including light confinement, enhancement, and guidance. As a result, photonic crystals have found valuable applications in optical circuits and sensors.

Photonic crystals possess distinct characteristics that make them unique and useful in a variety of applications. Photonic crystals have a photonic bandgap, which is a range of frequencies or wavelengths where the propagation of specific light modes is prohibited. This property allows for the selective blocking or guiding of specific wavelengths, granting control over the flow of light. The geometry and refractive index contrast of photonic crystals can be tailored to engineer precise dispersion properties. This refers to how the phase velocity of light changes with its frequency or wavelength. By modifying dispersion, light propagation can be manipulated to achieve desired effects such as slowing down or enhancing its movement. Photonic crystals can confine and localize light within designated regions or channels called waveguides. These waveguides guide light along predetermined pathways, ensuring efficient data transmission, integrated optics, and optical circuitry. Photonic crystals enhance the interactions between light and matter. They can increase the strength of interactions between photons and atoms, molecules, quantum dots, or other nanoscale structures embedded or coupled with the crystal. This property holds significance in sensing, quantum information processing, and nonlinear optics. Photonic crystals can be designed and fabricated with tunable properties. By adjusting parameters such as lattice structure, refractive index contrast, or fill factor, the bandgap characteristics and optical responses of the crystal can be modified. This tunability enables dynamic control over light propagation and facilitates the creation of reconfigurable photonic devices.

3.2. Nonlinearity in refractive index

Photonic crystals have a structured arrangement of dielectric or semiconductor materials that create a bandgap, affecting how light travels within the crystal. When a strong beam of light interacts with the photonic crystal, there is a notable change in its refractive index, altering its optical properties. This change occurs due to the optical Kerr effect, which happens because of the material's nonlinear response to intense light. The optical Kerr effect involves the simultaneous interaction of three photons with the material, resulting in its third-order nonlinearity. The optical Kerr effect in photonic crystals leads to varying phenomena like self-focusing, self-phase modulation, and optical switching. By leveraging this effect, researchers can control and manipulate the propagation of light at the nanoscale. This capability opens up potential applications in optical communication, all-optical signal processing, and the development of nonlinear optics-based devices such as switches, modulators, and sensors. The optical Kerr effect equation relates the change in refractive index (n') of a material to the applied electric field (E) and the material's Kerr constant (P_{nl}). The equation can be written as [9]:

$$n' = P_{nl} E^2 \qquad (1)$$

The Kerr constant is determined by the molecular structure and composition of a material. A higher value for the Kerr constant signifies a more pronounced reaction of the material's refractive index to the electric field it encounters. In the equation, the electric field is squared, indicating that the change in refractive index is directly proportional to the square of the electric field.

3.3. Resonance of signals

Resonators are integral components within photonic crystal structures, serving to manipulate and govern the propagation of light. They are localized regions within the photonic crystal, designed to confine and trap light at distinct frequencies or wavelengths. Resonators achieve this by adopting specific geometries and patterns using dielectric or metallic materials, thus forming optical cavities with unique properties. The resonant frequency or wavelengths of a resonator are determined by factors such as the size, shape, and arrangement of materials within it. When the wavelength of incident light aligns with the resonator's resonant wavelength, constructive interference occurs, resulting in intensified field intensity and extended interaction time between light and matter. This phenomenon enables a wide array of applications, including filtering and switching. Resonators in photonic crystal structures can take various forms such as cavities, micro disks, nanowires, or waveguides, each offering distinct characteristics and advantages for specific purposes. Meticulously engineering these resonators empowers researchers to manipulate and control light in ways previously challenging with traditional optical devices. Cavity and ring resonators have garnered significant attention in the design of optical devices, including decoders. Consequently, let's provide a brief introduction to these types.

A ring resonator is a device employed in photonic crystal structures to confine and manipulate light waves within a circular path. Constructed from photonic crystal materials, it consists of a circular or annular waveguide. Photonic crystals entail engineered materials with periodic variations in refractive index, facilitating precise control over light propagation. In a ring resonator, the structure is designed to form a closed loop with a gap or defect region where light is confined. This gap can be created by removing lattice points from the photonic crystal or introducing localized defects within the crystal lattice. Once light enters the ring resonator, it circulates around the loop due to total internal reflection. The periodic variation in refractive index guides the light along the desired path, preventing its escape. As light propagates through the resonator, it undergoes multiple round trips, resulting in constructive interference between incoming and reflected waves. The underlying principle governing ring resonator operation is resonance. The circumference of the ring resonator is precisely chosen so that the optical path length of the circulating light becomes an integer multiple of the light's wavelength. This condition allows wavelengths satisfying the resonance criteria to accumulate constructive interference, generating high-intensity standing waves within the resonator. Ring resonators find diverse applications in photonics and integrated optics, serving as filters, modulators, sensors, and foundational components for intricate optical circuits. By manipulating the design parameters of the photonic crystal structure, such as the lattice constant and defect size, the properties of the ring resonator - such as its resonance wavelength and quality factor - can be tailored to meet specific requirements for various applications.

A cavity resonator within photonic crystals consists of a localized defect or region within a periodic arrangement of dielectric materials, forming a photonic crystal. In the context of cavity resonators, a photonic crystal is intentionally designed to include a region where the refractive index is modified or disrupted, leading to a defect or discontinuity in the periodic lattice. This defect acts as a miniature optical cavity with the capability to confine and manipulate light at specific frequencies or wavelengths. The confined electromagnetic waves within the cavity resonate and create standing wave patterns, akin to the behavior of sound waves in an acoustic resonator. These standing waves possess discrete resonant frequencies where constructive interference transpires, resulting in intensified optical intensity within the cavity. The resonant frequencies of the cavity are determined by the size, geometry of the defect region, and the surrounding periodic structure of the photonic crystal. Precision design of the photonic crystal parameters enables the creation of cavity resonators with specific resonance properties, granting control over the wavelengths or frequencies at which light is trapped and amplified.

4. DESIGNING OPTICAL DECODERS

When designing a decoder based on photonic crystals, the initial step is calculating the photonic bandgap. This calculation involves considering the contrast between the rod (or hole) and the surrounding medium, as it greatly influences the width of the bandgap. Higher contrast generally results in a wider bandgap, so careful material selection is crucial. Previous research suggests that the ratio of rod (or hole) radius to the spatial period should be around 0.2 to achieve a wide bandgap. Two arrangements, triangular and square, can be utilized for the positioning of rods and holes. The triangular arrangement typically offers higher transmission efficiency compared to the square arrangement, thanks to lower waveguide loss in the corners. On the other hand, the square-based form results in a more compact structure. Therefore, the selection of the arrangement depends on the desired transmission efficiency and area limitations.

After determining the arrangement, the next step is designing a fundamental switch to redirect the waves towards the desired ports. This switch can be implemented using either ring or cavity resonators. Generally, a ring resonator provides higher transmission efficiency than a cavity resonator, but the cavity-based structure offers a smaller size. The choice between them depends on the specific requirements and working conditions of the decoder. Furthermore, to differentiate between different cases and provide sensitivity to incoming power, nonlinear rods (or holes) can be placed at the center of the resonators. The dropping of waves can be controlled based on the optical intensity, allowing proper tuning of the resonator operation for decoding the input waves. Studies recommend a 3×3 array of nonlinear rods (or holes) to achieve high transmission and a compact size. By adjusting the radius of rods and the lattice constant while maintaining their ratio, transmission efficiency can be enhanced.

Once the fundamental switch is designed, the necessary waveguides for incoming and outgoing waves are determined based on the number of inputs and outputs. Various methods can be employed to connect the resonators to the waveguides, providing flexibility to designers. In the following section, some design ideas for photonic crystal-based decoders are further explored.

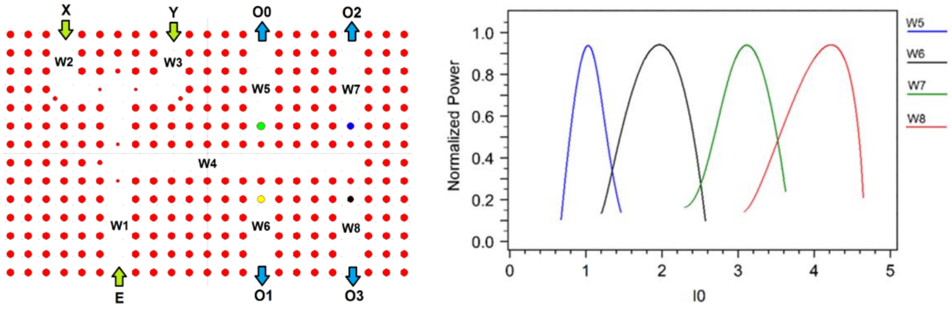
To simulate photonic crystal-based decoders, the finite difference time domain method is commonly used due to its effectiveness in solving Maxwell's equations. This method calculates the components of electric and magnetic fields in both space and time domains. It is essential to discretize the spatial grid with a cell size (Δu) smaller than $\lambda/10$, where λ represents the wavelength, in order to achieve convergence. Additionally, the Courant condition should be satisfied, determining the time step (Δt) based on the inequality $c\Delta t \leq \Delta u/\sqrt{2}$ for two-dimensional simulations. Here, c represents the speed of light in free space. The perfectly matched layer is another consideration that helps to eliminate external effects during simulations.

In this section, optical decoders based on photonic crystals are categorized into two groups: cavity resonator-based and ring resonator-based decoders. The following ideas and design structures for decoding operations are explored.

4.1. Resonant cavity for decoding operation

In cavity-based structures, the presence of at least one cavity allows for constructive resonance at a specific wavelength while suppressing others. This effect is achieved with the assistance of defects made from various linear and nonlinear materials. Nonlinear materials, such as doped glass, are used to leverage the optical Kerr effect within the cavities. In recent times, nonlinear cavities have served as the foundation for the design of several optical decoders.

One such example is a 2-to-4 decoder comprised of eight waveguides that connect two input ports, X and Y, to four output ports, O0, O1, O2, and O3 (refer to Figure 2a) [10]. A bias signal originating from port E influences the waveguide W1, where it interacts with the two signals arriving from the input ports through waveguides W2 and W3. The waveguide W4 serves to transmit the resulting waves towards the nonlinear cavities. Within waveguides W5, W6, W7, and W8, four nonlinear rods consisting of doped glass material are positioned.

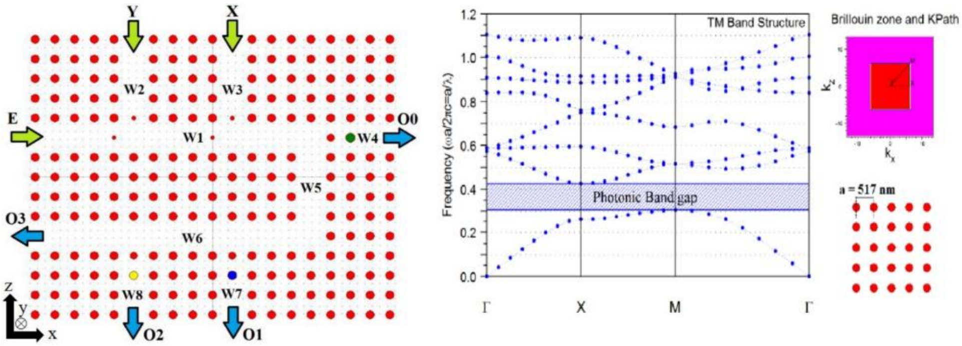


(a) (b)

Fig. 2. **(a)** A view of the structure with four resonant cavities in waveguides W5, W6, W7, and W8 **(b)** dropping efficiency of the cavities versus the incoming intensity into W4 [10]. The filled circles represent the rods at a top view.

The refractive index of a dielectric material is influenced by the applied optical intensity, thanks to the optical Kerr effect. Utilizing different radii within the cavities, along with the optical Kerr effect, enables the selective dropping of various intensities while they pass through the cavities. By adjusting the radii values of the nonlinear rods in increments of 1 nm and evaluating the power at the output ports, the following radii were assigned: 118 nm for the green rod in waveguide W5, 111 nm for the yellow rod in W6, 104 nm for the blue rod in W7, and 97 nm for the black rod in W8. Consequently, different optical intensities in waveguide W4, corresponding to the different states of the input ports, will be dropped through waveguides W5, W6, W7, and W8 to achieve the decoding operation (refer to Figure 2b). To enhance the transmission of optical waves at the bends, rods with radii of 64 nm were positioned at the corners of waveguides W2 and W3. Additionally, four rods with radii of 74 nm and one rod with a radius of 70 nm were included in waveguides W1, W2, and W3 to facilitate the desired interferences at the cross-connections of the waveguides. This enables the dropping of different optical intensities in waveguide W4 in response to the various states of the input ports for successful decoding. The power consumption of the proposed structure is 10 mW/μm^2. The delay time of the structure was measured to be approximately 220 fs within an area of 90 μm2. Furthermore, the difference in the margins between logic 0 and 1 was calculated to be around 83%.

In another research [11], a photonic crystal-based design has been put forward as an all-optical 2-to-4 decoder. The structure comprises an array of chalcogenide rods arranged in a square lattice. It consists of two input ports (X and Y), one bias signal (E), and eight waveguides (W1, W2, W3, W4, W5, W6, W7, and W8) responsible for transmitting input waves towards the output ports (O0, O1, O2, and O3) as shown in Figure 3a. To achieve constructive interferences, a bias signal and two input signals are guided through three waveguides towards the cross-connections. The resulting signal then passes through a waveguide connected to three nonlinear cavities. In order to leverage the optical Kerr effect, each cavity contains a rod made of doped glass. Depending on the optical intensity, the maximum normalized powers at ports O0, O1, and O2 are observed at approximately I0, 2I0, and 3I0 respectively. The waves are dropped and directed towards the desired output ports accordingly. The device occupies an area of 76 μm2. Additionally, the proposed structure exhibits a delay time of around 210 fs. Furthermore, the contrast ratio of the output ports is measured at 13.52 dB. Figure 3b illustrates the photonic bandgap and the Brillouin zone of the structure for TM polarization.



(a) (b)

Fig. 3. **(a)** An optical decoder including three cavities **(b)** the photonic bandgap in along with the Brillouin zone at TM mode [11].

In contrast to the references [10,11], the subsequent decoder [12] introduces a triangular lattice of a two-dimensional photonic crystal in its all-optical decoder design utilizing cavities (refer to Figure 4). As depicted in Figure 4b, the proposed structure consists of two input ports (X, Y), and one bias port (Z) for applying the incoming optical signals. Four waveguides (W1, W2, W3, and W4) facilitate the transmission of optical waves towards the W5 waveguide. To prevent the occurrence of backward waves, four defects are positioned at the cross-connection of W4 with W2 and W3. Based on the optical intensity within W5, three nonlinear cavities drop the waves towards the output ports O0, O1, and O2 through the waveguides W6, W7, and W8, respectively. If the dropping operation is not performed by the mentioned cavities, the waves will reach the output port O3. The cavities incorporate three nonlinear rods made of doped glass. Time analysis of the device reveals a rise time of 200 fs. The device occupies an area of 110 μm^2 and exhibits margins of 4% and 88% for logics 0 and 1 respectively.

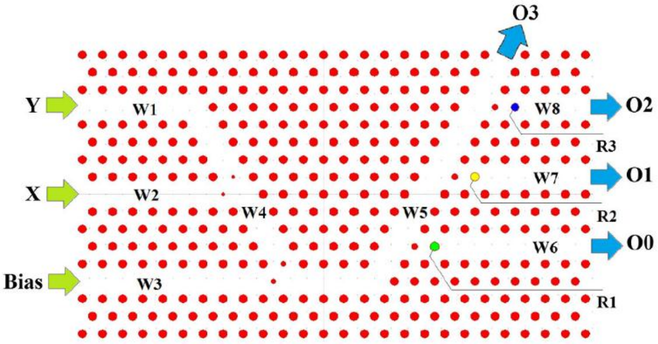
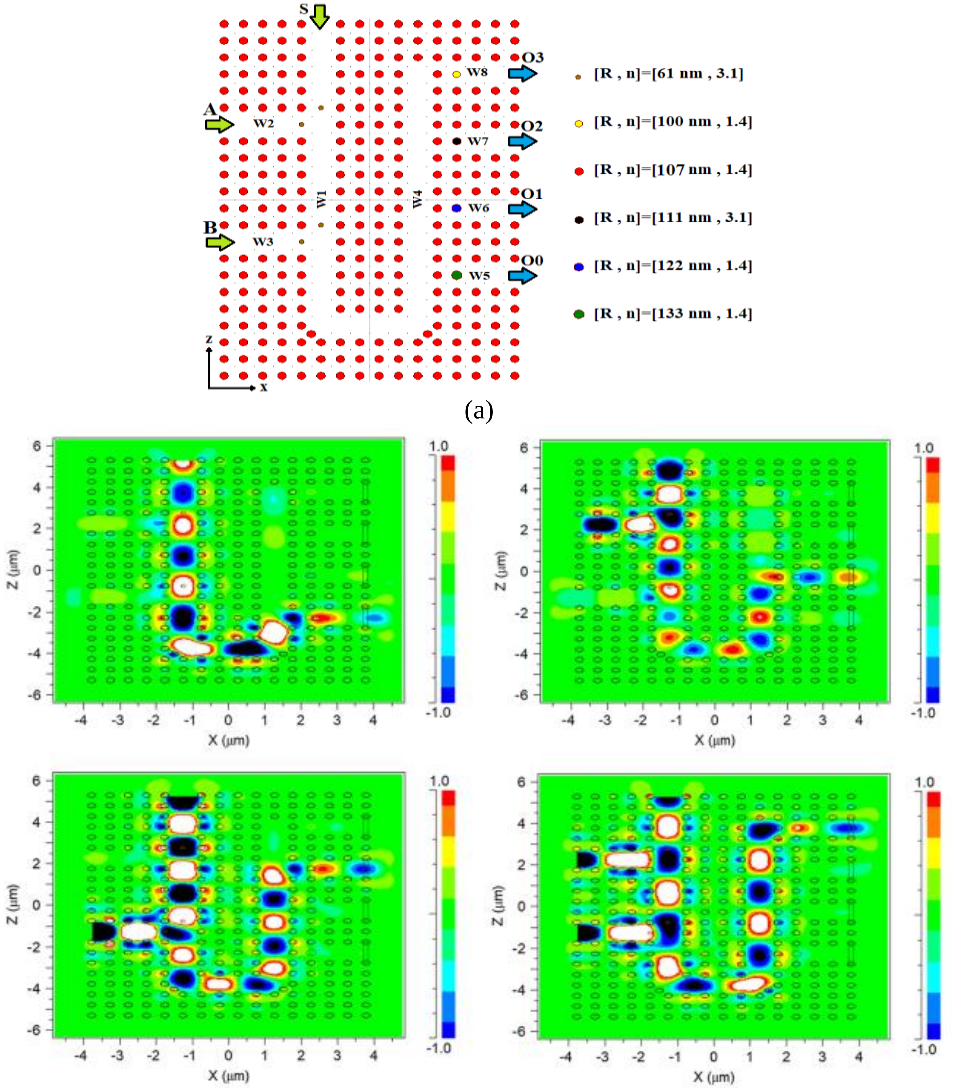


Fig. 4. Cavity connection to a main waveguide with nonlinear rods for decoding [12].

The most recent study [13] presents a decoding technique using photonic crystal resonant cavities, incorporating a structure of doped silicon rods with varying radii within the cavities to enable nonlinear decoding operations (refer to Figure 5a). The performance of the system is influenced by different power levels applied to the input ports, resulting in variations in operating conditions. Expanding on this observation, an all-optical 2-to-4 decoder is designed, occupying an area of 86 μm^2. The proposed structure consists of eight waveguides, named W1 to W8, formed by selectively removing a certain number of rods. With a lattice constant of 495 nm and a fundamental rod radius of 107 nm, the structure exhibits a photonic bandgap in the TM mode, covering wavelengths ranging from 1190 nm to 1661 nm. The proposed device demonstrates a response time of approximately 0.2 ps and a contrast ratio of 13.58 dB. Furthermore, the reported insertion loss in this study is -1.8 dB. Distribution of electric field has been shown for four possible states for inputs A and B (Figure 5b). It can be seen that the outputs O0, O1, O2, and O3 be turn ON corresponding to AB=00, 01, 10, and 11, respectively.



(a)

(b)

Fig. 5. **(a)** The proposed decoder with input ports S, A, and B, and dropping the incoming waves toward the outputs through the nonlinear cavities **(b)** transmission of light through waveguides and cavities for AB=00, 01, 10, and 11 [13].

4.2. Resonant ring for decoding operation

An approach to designing all-optical decoders using photonic crystals involves utilizing ring resonators. These rings play a critical role in directing or filtering incoming light towards the desired output ports by employing nonlinear defects. Within this section, six structures are examined, all of which are based on rings. In reference [14], a 2-to-4 decoder consisting of six resonant rings is introduced (as depicted in Figure 6). A single bias signal is utilized to activate the device. Two input ports, labeled A and B, and four output ports, named O1, O2, O3, and O4, are present. The six rings are emphasized and denoted as ring #1 to ring #6. Depending on the input intensity through ports A and B, incoming signals are guided through the resonators. The compact size, measuring 512 μm^2, makes this structure suitable for implementation in optical circuits. Transmission analysis of the structure reveals a normalized power of 10% and 37% for logic 0 and 1, respectively. With an achieved response time of 6 ps, the decoder operates at a speed of 160 GHz, making it proper for high-speed applications. The insertion loss of the decoder ranges from -2.76 dB to -20 dB, while cross-talk varies between -15.6 dB and -38 dB.

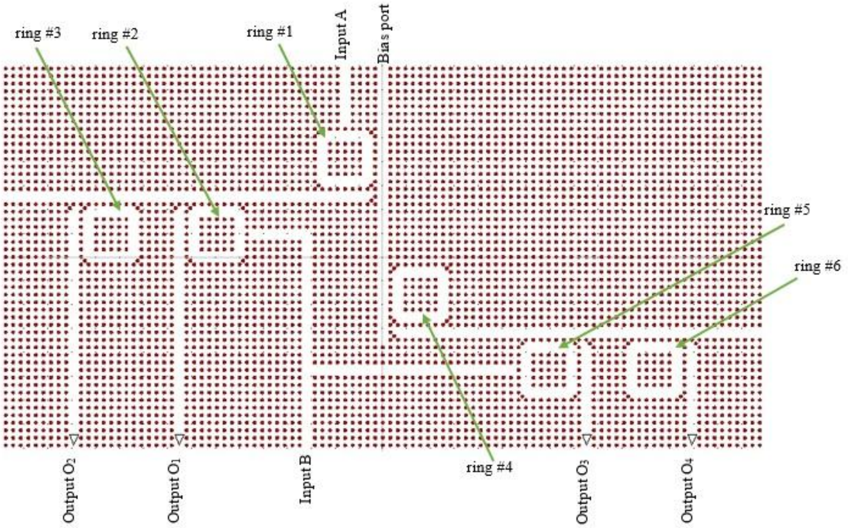


Fig. 6. Using six resonators to guide the incoming waves from the Bias toward the outputs with the help of inputs A and B [14].

It can be inferred that the input intensity required to activate the rings is contingent upon the nonlinear coefficient of the ring resonator. In the subsequent decoders [15,16], chalcogenide glass is employed instead of silicon due to its higher nonlinear refractive index. The primary advantage of using this ring lies in its nonlinear coefficient. In accordance with the Kerr effect, a higher nonlinear coefficient results in a lower input intensity requirement for switching applications.

Figure 7 depicts a decoder based on photonic crystal nonlinear ring resonators, featuring a single enable port (port E) to govern the decoding operation [15]. Additionally, the structure comprises four rings, two input ports X and Y, and four output ports O0, O1, O2, and O3. To minimize the input power intensity, nanocrystal rings with a high Kerr coefficient are positioned at the center of the rings. As a result, the threshold intensity for achieving dropping is reduced to 13 mW/µm^2. The logic 0 and 1 margins correspond to 10% and 63%, respectively. The maximum insertion loss is -4.31 dB, and the maximum cross-talk value measures approximately -17.53 dB. Compared to the reference [14], the size of the device is reduced to 368 µm^2.

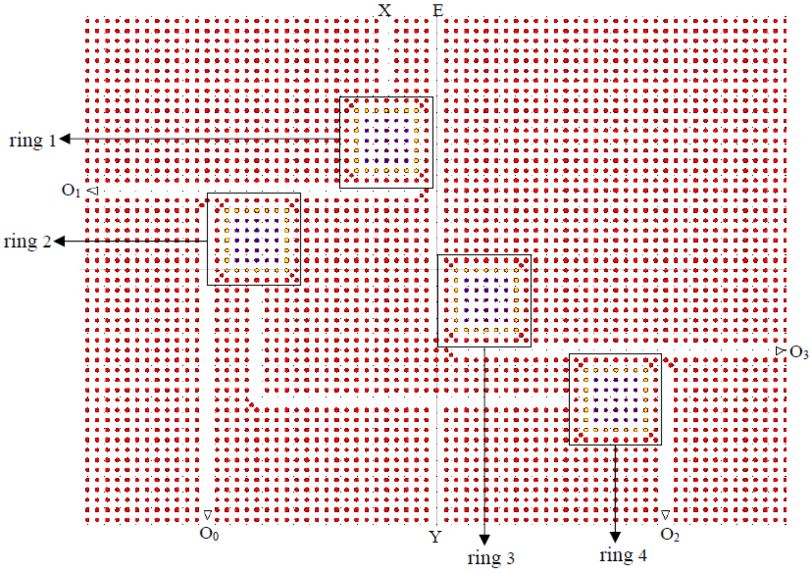


Fig. 7. A structure with four nonlinear rings for decoding two inputs X and Y [15].

Figure 8 illustrates a 2-to-4 decoder that employs three resonant rings [16]. This particular design has achieved decoding operation in a compact area of 360 µm^2, which is an improvement compared to references [14,15]. The maximum response time is 2 ps, while the switching speed reaches 500 GHz. The normalized margins for logic 0 and 1 are 14% and 49%, respectively.

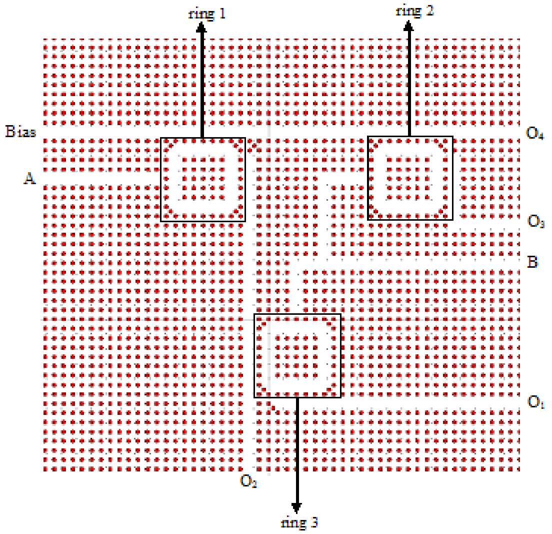


Fig. 8. A schematic of ring-based decoder with the help of three resonant rings [16].

In another study, a novel design of a decoder based on a photonic crystal is presented (Figure 9) [17]. This design incorporates an array of 57×37 silicon rods with air gaps. The dielectric rod radius is 120 nm, and the lattice constant is 600 nm. The proposed structure includes three inputs (one for enable and two for decoder inputs), three PhC X-shaped resonators, waveguides, and four outputs. Each resonator features silica rods with graphene shells. Numerical results indicate that normalized transmission values below 30% and above 50% correspond to logic 0 and 1, respectively. The decoder exhibits a maximum delay of 2.5 ps and a total footprint of 690 μm^2.

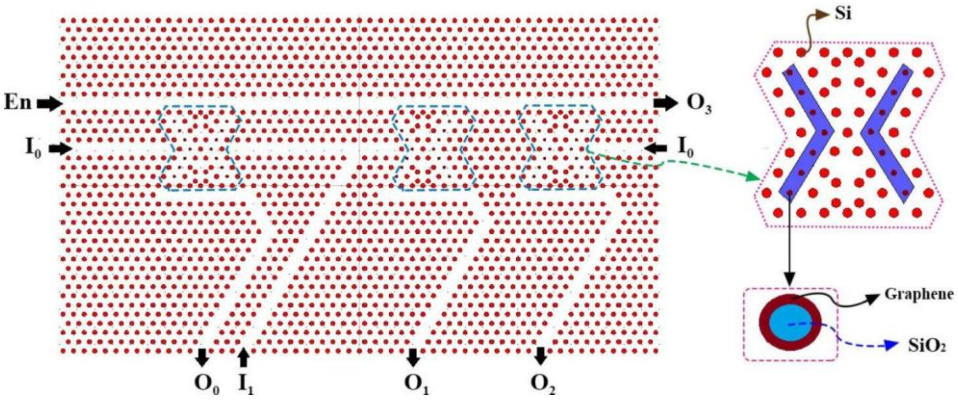


Fig. 9. The proposed structure of the 2-to-4 decoder [17].

In a recent study [18], a new design for a configurable 2-to-4 binary decoder is introduced. The design, shown in Figure 10, utilizes three photonic crystal ring resonators. These resonators consist of silicon rods surrounded by silica (SiO_2) rods coated with graphene nanoshells (GNSs). By manipulating the gate voltage to adjust the chemical potential of GNS, fine-tuning of the desired PhC resonant mode is achieved. Numerical analysis reveals that the structure exhibits a maximum rise time of 0.8 ps and a maximum fall time of 0.3 ps. The device size is measured at 850 μm^2. Additionally, the contrast ratio is approximately 13.5 dB.

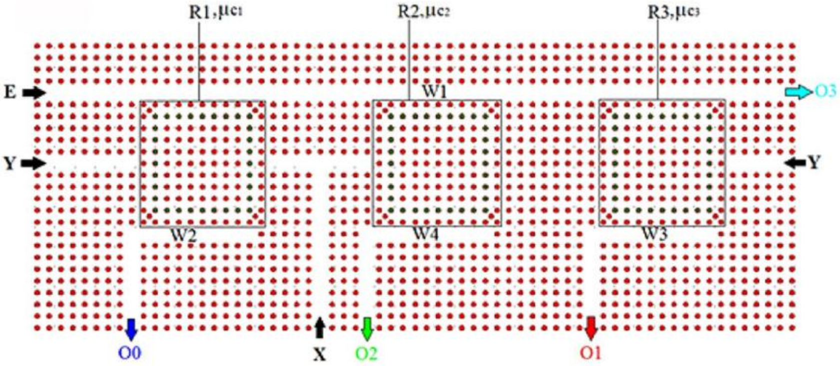


Fig. 10. The graphene nanoshell rods in rings to tune the dropping in decoder [18].

A design for a 2-to-4 decoder has been put forward by implementing two distinct types of resonators [19]. The design incorporates a nonlinear ring and three nonlinear cavities, specifically tailored for operating in a slow-light regime. This enables improved interaction between light and the material, along with enhanced coupling efficiency through the waveguides (refer to Figure 11). Notably, the proposed design achieves a significant increase in the high-level margin for output ports, raising it from 82% to 99%, surpassing previous works [10-18]. Additionally, the device size is remarkably as compact as 228 μm^2, compared to earlier implementations [15-18].

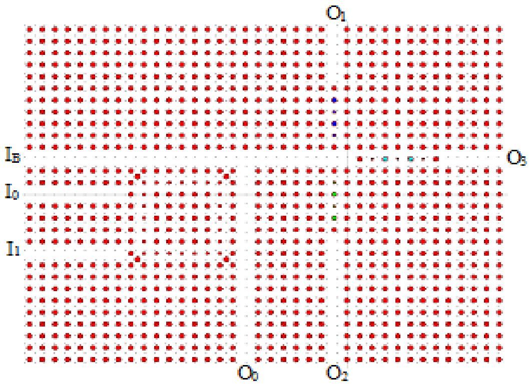


Fig. 11. Realizing a decoder with nonlinear ring and cavity [19].

Generally, cavity-based structures tend to have smaller sizes compared to ring-based structures. Table II provides a summary of the important parameters from various works. It is notable that references [9-13], which utilize cavities, exhibit smaller sizes in comparison to references [14-19] that employ resonant rings. Based on the published works and the data presented in Table II, it is recommended to adopt a lattice form and utilize cavity-based resonators when designing photonic crystal decoders that prioritize fast response and compact area. However, if transmission efficiency is the primary consideration for the photonic crystal, then ring-based decoders would be the preferable choice.

TABLE II

COMPARISON OF THE IMPORTANT PARAMETERS OF ALL-OPTICAL PHOTONIC CRYSTAL DECODERS [9-19].

Ref.	Resonator	Lattice	Material	Contrast ratio (dB)	Size (μm^2)	Response time (ps)
[9]	Cavity	Square	Chalcogenide	13.37	90	0.22
[10]	Cavity	Square	Chalcogenide	13.52	76	0.21
[11]	Cavity	Triangular	Silicon	8.4	91.75	0.1
[12]	Cavity	Triangular	Chalcogenide	13.42	110	0.2
[13]	Cavity	Square	Doped silicon	13.58	86	0.2
[14]	Ring	Square	Chalcogenide	4.3	184	3.1
[15]	Ring	Square	Silicon	9	368	5.9
[16]	Ring	Square	Chalcogenide	5.78	380	2
[17]	Ring	Triangular	Silicon	5.4	690	2.5
[18]	Ring	Square	Silicon	13.5	850	0.28
[19]	Ring&cavity	Square	Silicon	13.12	228	3

5. MATERIAL SELECTION

When it comes to material selection in photonic crystal structures, several factors come into play:

Refractive index contrast: Photonic crystals rely on a significant contrast in refractive index between different materials within the structure. This difference enables the creation of bandgaps, which are ranges of wavelengths where light is strongly prohibited from propagating through the structure.

Optical properties: The optical properties of the materials are crucial considerations. Different materials have varying transparency, refractive indices, and dispersion characteristics. The desired optical properties will depend on the specific application and functionality required from the photonic crystal structure.

Fabrication compatibility: The materials should be compatible with the fabrication techniques used for constructing photonic crystal structures. This includes considerations like deposition methods, etching processes, and patterning techniques. The chosen materials should be capable of being processed and integrated into the desired structure effectively.

Bandgap engineering: The choice of materials in photonic crystal structures can influence the position and width of the photonic bandgap. The ability to engineer the bandgap allows for controlling the propagation and manipulation of light within the structure. Different materials may offer distinct opportunities for bandgap engineering.

Thermal stability: Photonic crystal structures may experience changes in temperature during operation or fabrication. Hence, it is necessary to select materials with high thermal stability to ensure the structure's performance remains consistent under varying temperature conditions.

6. FABRICATION METHODS

The fabrication process of photonic crystal structures involves creating periodic patterns or structures in a material to control the propagation of light. These structures are designed to manipulate the flow of light in a way that allows for the control or confinement of specific wavelengths or frequencies. Here are some commonly used fabrication processes for photonic crystal structures:

Lithography: Lithography is a technique used to transfer patterns onto a substrate. It involves creating a mask with the desired pattern and transferring it onto a photosensitive material through exposure and subsequent chemical processing.

Electron Beam Lithography (EBL): EBL is a high-resolution lithography technique that uses a focused beam of electrons to write patterns directly onto a substrate. It offers high precision but is a relatively slow process.

Nanoimprint Lithography (NIL): NIL is a technique that involves pressing a stamp or mold onto a substrate to create patterns. This process can be used for large-area pattern replication and has high resolution capabilities.

Reactive Ion Etching (RIE): RIE is a process used to etch away material from the surface of a substrate to create patterns. It involves bombarding the material with a reactive plasma, which selectively removes the material exposed through a mask.

Self-assembly Techniques: Self-assembly methods rely on natural or guided processes to form patterns or structures. These techniques utilize the inherent properties of materials to spontaneously arrange themselves into desired configurations.

Atomic Layer Deposition (ALD): ALD is a thin film deposition technique that allows precise control over the thickness and composition of deposited layers. It can be used to create multilayer structures in photonic crystals.

Due to the compatibility with the fabrication technologies, silicon and chalcogenide are the relevant materials in the design of the photonic crystal decoders. The possibility of high doping in chalcogenide and high optical Kerr coefficient makes it the excellent material for nonlinear rods into the resonators.

Some challenges in the fabrication of photonic crystal structures are as follows:

High-precision Patterning: Achieving precise and accurate patterning at nanoscale or sub-micron levels is essential for creating photonic crystal structures. The fabrication process must ensure high fidelity and uniformity in feature sizes and geometries.

Material Selection: Choosing the appropriate materials for fabricating photonic crystal structures can be challenging. The materials should possess suitable optical properties, compatibility with fabrication techniques, and structural stability at the desired operating conditions.

Fabrication Techniques: The selection and optimization of fabrication techniques play a crucial role. Techniques such as electron beam lithography, focused ion beam milling, nanoimprint lithography, or self-assembly must be chosen carefully to achieve the desired structure efficiently and cost-effectively.

Scalability: Scaling up the fabrication process to larger areas or three-dimensional structures can be difficult. Techniques that work well on a small scale may not be easily scalable or commercially viable for mass production.

Alignment and Registration: Precise alignment and registration of multiple layers or patterns are necessary to create complex photonic crystal structures.

Any misalignment or registration errors can degrade device performance or yield.

Fabrication Defects: Fabrication processes may introduce defects such as surface roughness, pattern irregularities, or material impurities. These defects can adversely affect the desired optical properties of photonic crystal structures.

Cost and Time: Some fabrication techniques can be time-consuming and expensive, especially when high-resolution and high-yield requirements are considered. Balancing cost, efficiency, and quality is an ongoing challenge.

CONCLUSION

In this article, decoders based on photonic crystals were investigated. Resonant cavities and rings are used to direct light from input ports to the desired output. Nonlinear optical Kerr effect is also used to provide the sensitivity to input power. The study of the designed structures shows that the use of a cavity resonator can reduce the size of the structure while for obtaining better transmission efficiency, it is preferable to use a ring resonator. Published reports indicate that photonic crystal-based optical decoders can be designed within an area of 76 μm^2. The response speed of these devices can be increased up to 100 femtoseconds. These features are favorable for decoder integration, and with technological advancements, it is expected to achieve even smaller sizes using scalability feature.

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