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Chapter 6

# The Dawn of Photonic Crystals: An Avenue for Optical Computing

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http://dx.doi.org/10.5772/intechopen.71253

**Abstract**

In this chapter, a new paradigm is developed for optical computation using photonic crystals. As photonic crystals are the most sophisticated optical materials to date, information processing using this structure is one of the most sought-after technologies in photonics. While the semiconductor industry is striving hard to increase the microprocessors' processing power, it is certain that the trend would not last forever as against Moore's prediction. At this juncture, photonics technologies have to compete with the upcoming quantum computing technology to emerge as a promising successor for semiconductor microprocessors. This chapter is devoted to the introduction of photonic crystals as the workhorse for an all-optical computational system with a myriad of logic gates, memory units, and networks which can be constructed using these structures.

**Keywords:** optical computing, optical logic gates, optical memory, nanocavity, optical Kerr effect

## 1. Introduction

Modern computers evolved out of the semiconductor technology which began with the invention of transistor in 1948 [1]. Compared to previous generation of computers which used vacuum tubes, transistors were smaller, reliable, and efficient. In a subsequent development, integrated circuit which incorporates several transistors into a single chip was invented in 1958 [2]. This was a real revolution for the semiconductor technology which has enabled scalability of the processing power with an increase in the number of transistors that are inducted into the chip. In addition, these chips consume less power, run faster, and are smaller than their transistor counterparts. With an ever-increasing demand for processing power, there is a corresponding increase in demand for fabricating chips with more and more transistors in them. This has resulted in miniaturization of the individual transistor components in the chip,

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which has now crossed into the nano regime [3]. This trend is supposed to end somewhere in the near future, due to the size of individual components reaching the size of individual atoms. This roadblock in semiconductor technology can be solved by embracing alternative technologies such as optical computing.

Ever since the advent of lasers, there have been deliberate efforts to develop an optical analog for computation. Optical computation was initially envisaged as a hybrid system consisting of electronic and optical components. This venture turned out to be unsuccessful due to the unfeasible conversion time required from one system to another [4]. Even today, this is a daunting task, provided the communication networks are all made of optical fibers. However, the processing part is currently done by semiconductor microprocessors. With the introduction of photonic crystals, there is again a renewed interest in an otherwise dropped plan of optical computation. Photonic crystals have got the potential to create an all-optical information processing system. This will have an overwhelming influence on the information processing capacity of the communication system as a whole. In this chapter, an overview of such an optical computational system which can be implemented using a photonic crystal is outlined. An introduction to computer architecture is given in Section 2. The basics of planar photonic crystals are described in Section 3. The implementation of logic gates using photonic crystals is discussed in Section 4. An optical memory unit which can be implemented using photonic crystals is delineated in Section 5. The chapter is concluded in Section 6.

## 2. Computer architecture

Computer architecture deals with the design which stipulates the working of a computer with its components such as microprocessor, memory, and input/output devices [5]. Ever since the introduction of von Neumann architecture in 1945 for the computer called EDVAC, it has been the de facto architecture for electronic computers for the subsequent generations to date [6]. Although the discussion in this section centers on this architecture, one cannot be sure if the future optical computers would continue to lean on this architecture. For the first time, the von Neumann architecture embarked on the concept of stored program for realizing a general purpose computer. This enabled the computer to perform different computational tasks based on the program stored in its memory. Other salient features of this architecture include the usage of binary digits and sequential execution of instructions from a given program. Major components of von Neumann architecture consist of central processing unit (CPU), memory unit, and input/output units. The general outline of von Neumann architecture is shown in **Figure 1**.

In a modern computer, microprocessor occupies the position of central processing unit by handling data processing and system control [7]. The data processing part is done by arithmetic/logic unit and register array of the microprocessor, whereas the system control is done by the control unit. Primitive computers had these units separately, but with the advancement in circuit integration technology, it is possible to incorporate them onto a single chip. A microprocessor takes data from input devices such as keyboard and mouse, processes those data

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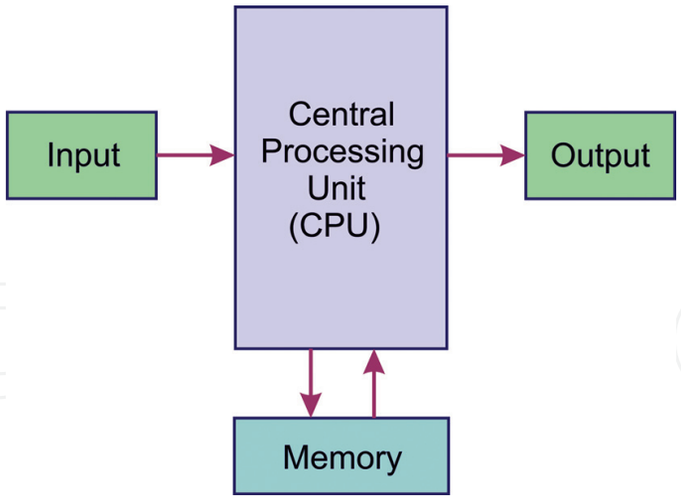



**Figure 1.** Outline of von Neumann architecture for computer.

according to the instructions stored in the memory, and sends the processed data into an output device such as monitor [8]. In this process, the data and control signals are transferred between microprocessor, memory, and input/output devices through a communication network known as the system bus. A typical microprocessor operation consists of fetch-execute cycles. A microprocessor fetches an instruction from the memory and executes that instruction on the input data. Afterward, it goes to the next instruction in the memory, fetches, and executes it. This process goes on until the last instruction before finishing a given task according to the program stored in the memory.

## 3. Planar photonic crystals

Photonic crystals (PhCs) are artificial periodic structures made of dielectric materials [9]. They are generally classified into three categories based on the dimensionality of the structure—1D, 2D, and 3D. Two dimensional structures such as planar photonic crystals, which are useful in integrated photonic circuits, are considered here for discussion. In these structures, air holes are arranged periodically across the plane of the structure such that the spacing between them is less than the wavelength of light propagating through them [10]. This causes light to reflect away from the air hole structure when trying to pass through them. On the other hand, light can propagate through a channel made within this structure with width more than the wavelength of light [11]. In some ways, this is analogous to cutting a road for transportation. This type of light localization feasible within these structures has made them suitable for integrated photonics circuits. Similar to optical fibers used in communication, these structures also exhibit very low loss for the passage of light as against the case of their electronic counterparts [12]. In this way, this technology is an energy efficient alternative for integrated circuits with minimal heat loss. A schematic representation of PhC slab with channel for light passage is shown in **Figure 2**.

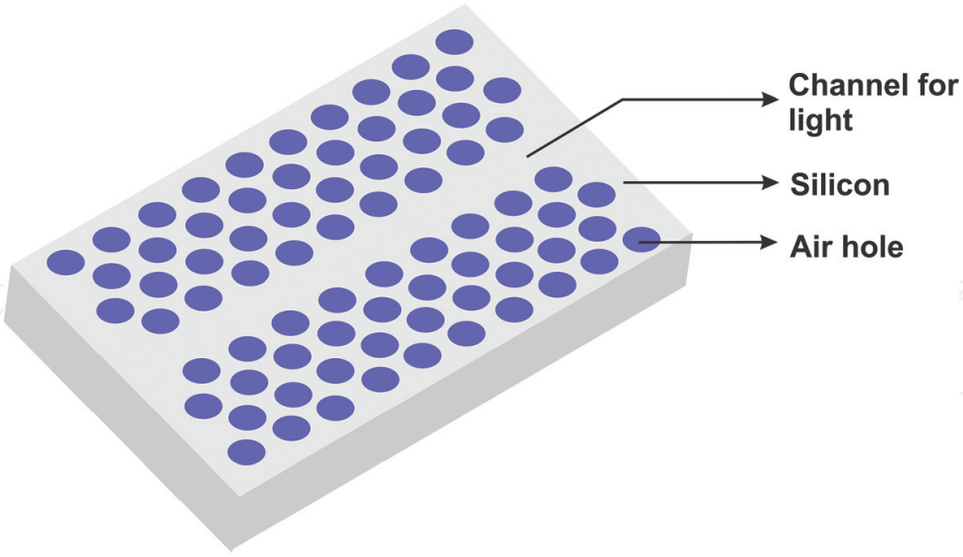



**Figure 2.** Schematic representation of photonic crystal slab with channel for light passage.

### 3.1. Structure of photonic crystal slabs

Photonic crystal slab is a planar structure made of silicon or other compound semiconductor material with periodically varying refractive index [13]. Toward this goal, air holes are etched in these structures such that a photonic band gap (PBG) is formed for certain wavelengths at which light cannot propagate through this structure. For these wavelengths, when some defects are created within the structure by disturbing the periodicity, light can be channelized through them with little propagation loss [14]. This is the working principle of a PhC slab. The PBG formation in a periodically varying refractive index structure is analogous to band gap formation for electrons in a crystal structure with Bragg diffraction from multiple ion lattice sites [15]. In planar photonic crystals, the Bragg diffraction is due to the periodic variation in refractive index by air holes. The PBG formed in a planar photonic crystal is not three dimensional. Rather, the band formed in it is two dimensional. In this way, there is light confinement for a defect in the horizontal plane of the PhC slab, whereas the vertical directions remain unconfined [16]. This can give rise to loss along the vertical directions. To do away with this loss, total internal reflection with the underlying silica or air layer is sought such that the light is confined within the structure [17]. Accordingly, for a silicon PhC slab, two types of structures are possible, one with silica and another with air as the underlying medium, as shown in **Figure 3**.

### 3.2. Nanocavities in photonic crystal slabs

Similar to a line defect which creates a channel waveguide, a point defect can create a nanocavity in the PhC slab structure [18]. Due to the requirement of tight light confinement in the vertical directions, an air-cladding photonic crystal structure having high refractive index contrast with the slab is preferred to a silica cladding for realizing a nanocavity [19]. A nanocavity can be created in a PhC slab by various means. It can be realized by creating a point defect, a line defect, or a width-modulated line defect in a photonic crystal [20]. A fourth method is also in practice wherein a double heterostructure results in a nanocavity. Each one of these

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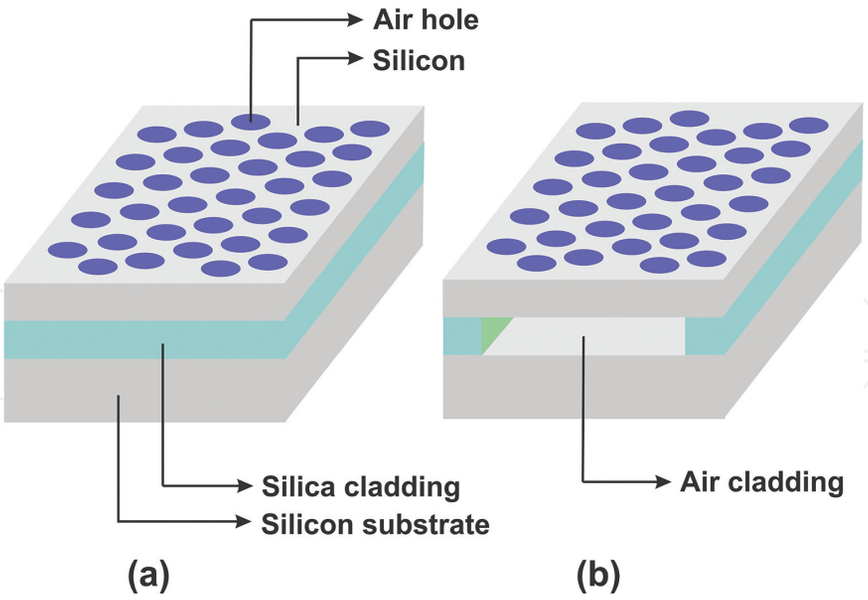



**Figure 3.** Schematic diagrams of two classes of photonic crystal slab structures, (a) with silica as the cladding layer and (b) with air as the cladding layer.

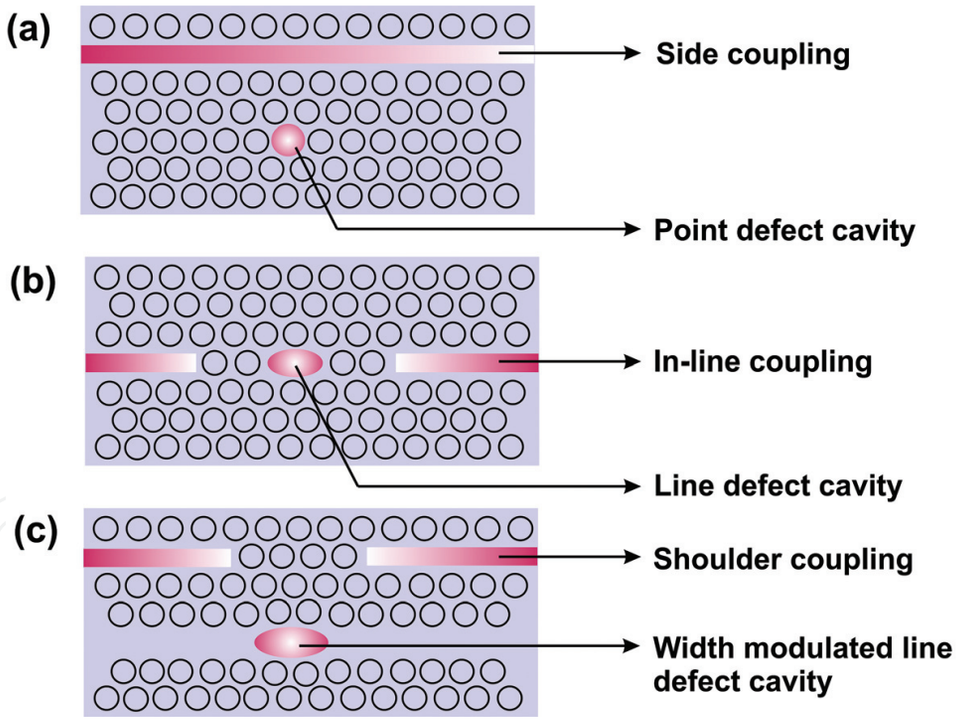



**Figure 4.** Schematic representation of nanocavities along with various coupling schemes: (a) a point-defect nanocavity with side coupling with the waveguide, (b) a line-defect nanocavity with in-line coupling with the waveguide, and (c) a width-modulated line defect nanocavity with shoulder coupling with the waveguide.

nanocavities is illustrated in **Figure 4**. For a point-defect nanocavity, a slight shift of the air holes from their regular positions away from the cavity region is found to produce significant increase in the Q factor of the cavity. Similarly, for a line defect cavity, a shift in the end holes

away from the cavity region offers an appreciable increase in the Q factor. Among these configurations, width-modulated line defect cavity and double-heterostructure cavity offer the highest Q factors and are the preferred configurations for nanocavity-based applications. There are various coupling schemes for coupling a nanocavity with a channel waveguide. Of these, side coupling, in-line coupling, and shoulder coupling schemes which are commonly in use are represented in **Figure 4**.

### 3.3. Fabrication of photonic crystal slabs

PhC slabs can be fabricated using electron beam lithography or UV lithography technique [21]. While electron beam (e-beam) lithography is suitable for fabrication on a laboratory scale, UV lithography suits to the requirements for mass production. In both schemes, there are a series of steps to be followed for realizing a PhC slab with an air cladding. For silicon PhC slabs, the readily available SOI (silicon-on-insulator) wafer used in semiconductor industry is used as a substrate for realizing PhC slabs [22, 23]. On the other hand, for compound semiconductors, the substrates have to be custom-made in the laboratory [24]. The process steps involved in the fabrication of silicon PhC slabs are considered here. Initially, the SOI wafer is coated with an e-beam resist such as polymethyl methacrylate (PMMA). The pattern that has to be imprinted is transferred from a CAD onto the surface of the resist using an e-beam. The resist is sensitive to e-beam, and the exposed parts of the resist are subsequently removed using chemicals in the development stage. This process is analogous to photographic film development in analog photography. The resulting resist which contains holes at lattice points serves as a template for the subsequent etching process on SOI. After etching is done in the silicon layer, the resist and the underneath silica layer are removed to form the air-cladding PhC slab. These process steps involved in the fabrication of silicon PhC slabs are illustrated in **Figure 5**.

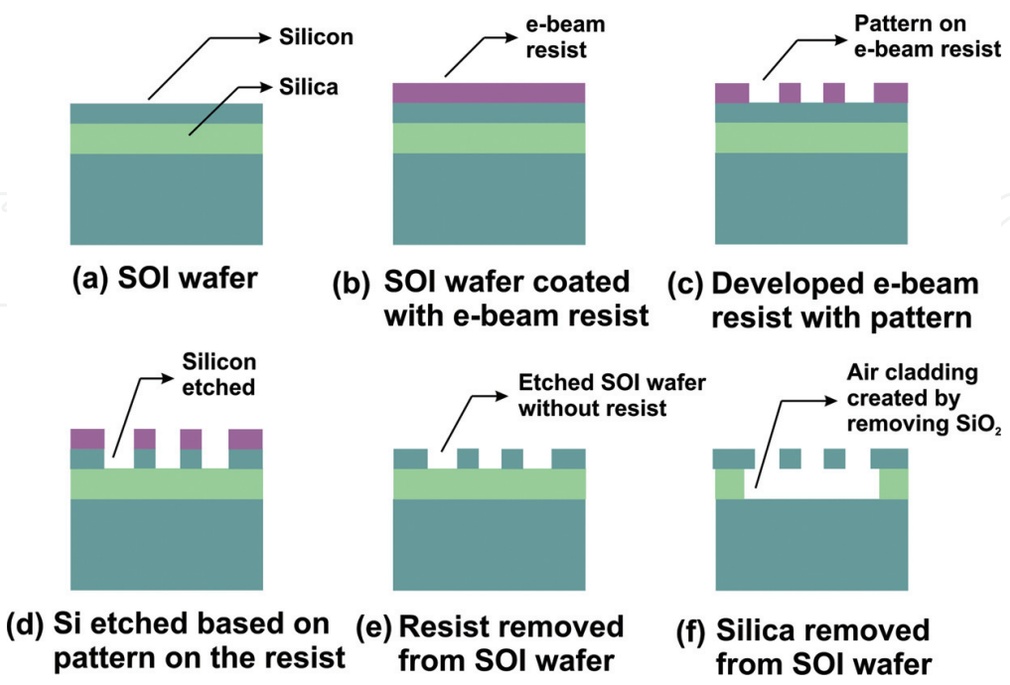



**Figure 5.** Series of process involved in the fabrication of silicon photonic crystal slabs.

## 4. Logic gates using photonic crystals

Many of the phenomena in optics can very well be described within the framework of wave theory of light based on Maxwell's equations, without resorting to the complexity of quantum mechanics. Even today, this is the preeminent theory which stands out against the test of time [25]. Nonlinear optics which is an offshoot of classical electrodynamics is also a branch of optics. Even though nonlinearity is routine in electronic devices such as diodes and transistors, it was not so in optics until the invention of laser. Laser, due to its high intensity, can have electric field strength comparable to bond strength between atoms, resulting in nonlinear response from the optical materials through which it propagates [26]. The nonlinear response from the medium can be modeled by taking into account of the Taylor series expansion of the electric field of the laser light. This can be explicitly represented in terms of polarization of the medium, wherein higher order terms in series describe the nonlinear polarization [27],

$$P(E) = \varepsilon_0\left(\chi_1 E + \chi_2 E^2 + \chi_3 E^3 + \cdots\right), \tag{1}$$

where first term denotes linear polarization, and higher order terms represent nonlinear polarization. Here, $E$ is electric field strength, $\varepsilon_0$ is permittivity in free space, and $\chi_1, \chi_2, \chi_3, \ldots$ denote first-order, second-order, and third-order electric susceptibilities, and so on. Eq. (1) can be used for describing various nonlinear optical processes which can occur in a system. Accordingly, first-order term in Eq. (1) is responsible for linear polarization, second-order term is responsible for second harmonic generation, and third-order term is responsible for third harmonic generation, optical Kerr effect, and so on. Optical Kerr effect is responsible for change in refractive index corresponding to intensity of the light source [28]. Intensity dependent refractive index is expressed as,

$$n(I) = n_0 + n_2 I, \tag{2}$$

where $n_0$ is the linear refractive index and $n_2$ is the nonlinear refractive index coefficient. The value of $n_2$ can be positive or negative depending on the type of material. Thus, for a material with positive $n_2$, the overall refractive index increases and vice versa. The intensity dependent variation in refractive index can be used for making optical logic gates. But, in this approach, the nonlinearity of the medium turns out to be crucial as it relates to the operation of the logic gates. Hence, materials with high nonlinearity are preferred to those with weak nonlinearities. Since nonlinearity of silicon is very low when compared to other compound semiconductors, it may not be the suitable candidate for realizing such all-optical logic gates [29]. Further, with the materials of high nonlinearity, deploying ultrashort pulses down to femtosecond range results in faster switching [30]. In this way, nonlinear response of the medium can be put to good use for realizing logic gates in PhC slabs.

### 4.1. NOT gate in a photonic crystal

Logic gates are fundamental building blocks of a digital computer [31]. Basic logic operations such as NOT, AND, OR, as well as their derivatives can be generated using these digital circuits. Truth table of a logic circuit represents the output of the circuit under various conditions of input. The truth table and circuit symbol of a NOT gate are shown in **Figure 6(a)**. It is possible to carry

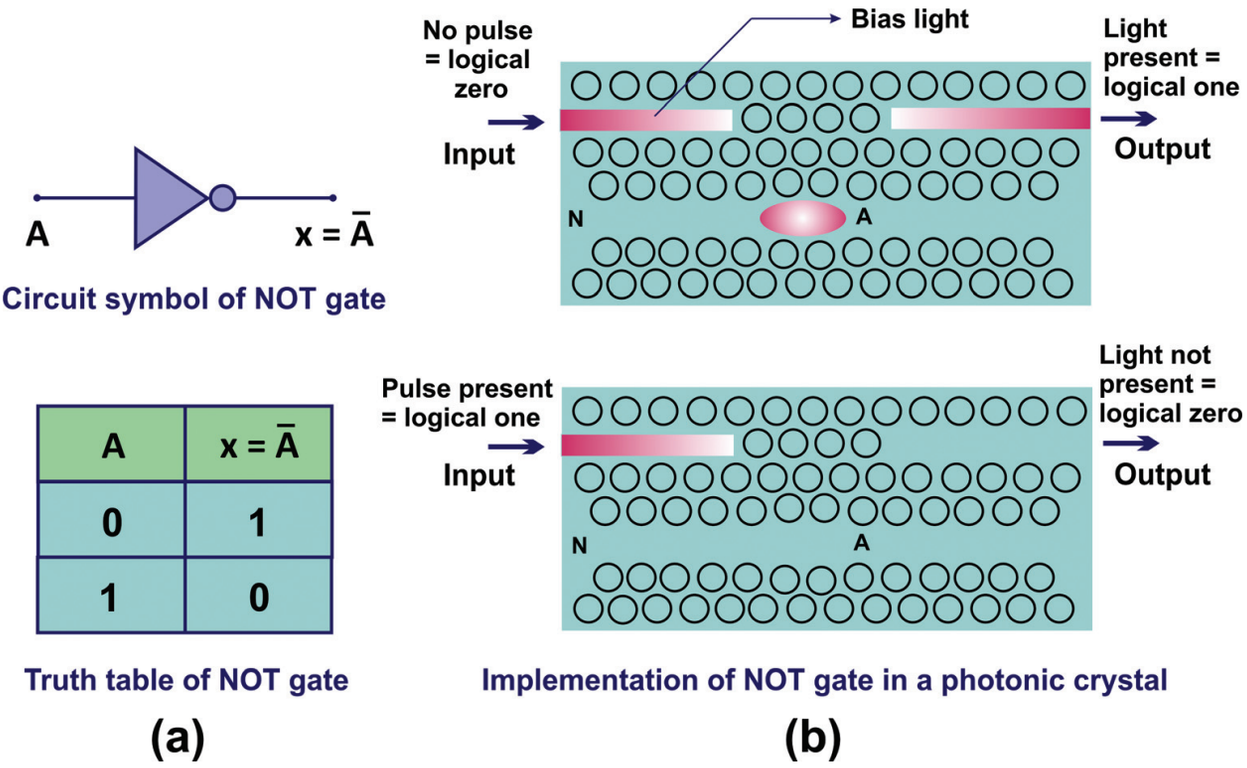



**Figure 6.** (a) Circuit symbol and truth table of a NOT gate and (b) implementation of NOT operation using a photonic crystal slab.

out the inverting operation done by the NOT gate using a PhC slab by exploiting the optical nonlinearity. A nonlinear medium with negative value for $n_2$ can be used for achieving this goal as shown in **Figure 6(b)**. Here, the coupling between the waveguide and nanocavity is such that when there is no optical pulse at the input waveguide, the bias light would emerge at the output waveguide. On the other hand, when an optical pulse is passed through the input waveguide, refractive index of the medium gets reduced due to negative nonlinearity of the medium. As a result, the resonant wavelength of the resonator differs considerably from the input wavelength of the bias light, resulting in decoupling of the bias light from the nanocavity and the output waveguide. In this way, the requirement of a NOT gate can be satisfied using this design, wherein the presence of an optical pulse at the input end gives no light at the output, and the absence of an optical pulse gives light at the output end of the waveguide. Here, the presence of a pulse at the input waveguide denotes a logic one, and the absence of a pulse denotes a logical zero. The same can also be implemented using materials with positive value for $n_2$.

It would be useful to adopt some naming conventions before dwelling further into the topic. In this regard, it is useful to note that there are two types of nonlinear media, one with positive Kerr nonlinearity ($n_2$ is positive) and the other with negative Kerr nonlinearity ($n_2$ is negative). Here, these two nonlinearities are represented in the sketch of PhC slab by **P** and **N**, respectively. In the sketches, a lighter shade is used to represent a material with positive Kerr nonlinearity, whereas the one with a darker shade represents negative Kerr nonlinearity. Moreover, based on the resonance wavelength of the nanocavity, three types of cavities are possible. A cavity having resonance at the same wavelength as that of the input light is denoted by **A** in the sketch, whereas a cavity with resonance wavelength lower than the input

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light is denoted by **L,** and a cavity whose resonance wavelength is set higher than the input light is denoted by **H** in the sketch. When an incoming radiation satisfies the resonance condition of the cavity [32],

$$2nd = p\lambda, \tag{3}$$

it is allowed to pass through the cavity. In other cases, the cavity would block the passage of light through it. In Eq. (3), $d$ is cavity length, $\lambda$ is wavelength of light, $p$ is an integer, and $n$ is the refractive index of the medium within the cavity given by Eq. (2). From this equation, it is clear that the resonance wavelength of the cavity is decided by the cavity length and refractive index of the medium. A cavity can be designed such that a slight deviation from the resonance cavity length can be compensated by the variation in refractive index due to the optical Kerr effect. In this way, when the refractive index of the medium gets altered by the input pulse, the resonance condition of the cavity sets in, allowing the passage of light through the cavity. When there is no input light pulse, resonance condition of the cavity is disturbed, resulting in blockage of the light. This is the working principle of a cavity-based optical switching circuit. In total, two types of nonlinearities along with three types of cavity configurations result in six possible combinations. Of these, four can be put to good use for creating logic gates.

### 4.2. OR gate in a photonic crystal

For an OR gate, the output is a logical one even if either of the inputs is a logical one. It gives a logical zero only when all of the inputs are at logical zero. For two inputs A and B, the OR logical operation is expressed by A + B. The circuit symbol and truth table of an OR gate are given in **Figure 7(a)**. This logical operation can be implemented in a PhC slab by using a combination of three nanocavities as shown in **Figure 7(b)**. Here, the PhC slab is made of

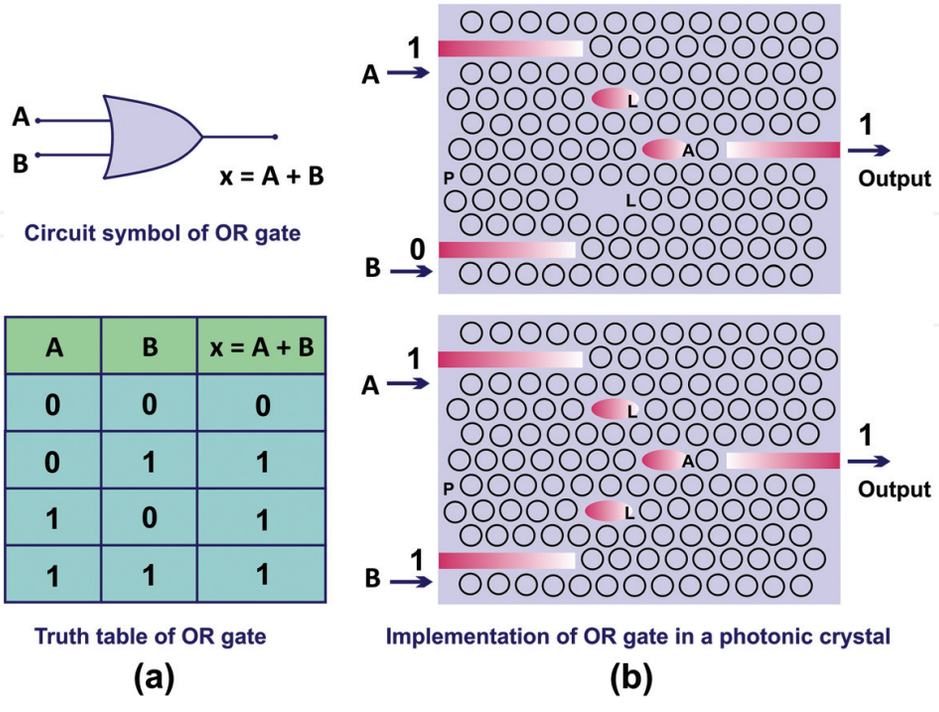
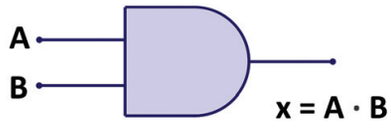



**Figure 7.** (a) Circuit symbol and truth table of OR gate and (b) implementation of OR gate operation in a photonic crystal slab.

material with positive Kerr nonlinearity. But, it can also be implemented using a material with negative Kerr nonlinearity too. The nanocavities adjacent to the input waveguides are set to have resonance at wavelengths below the input wavelength of light. In this way, they are opaque when there is no input pulse. On the other hand, when a pulse is sent through the input waveguide, there is an increase in local refractive index due to optical Kerr effect, and as a result, the **L** cavities are set to resonance such that the light reaches the output waveguide through the **A** cavity. This can occur when a pulse is sent through both or either of the input waveguides. Thus, the arrangement of nanocavities in this manner helps mimic the operation of an OR gate in a PhC slab.

### 4.3. AND gate in a photonic crystal

For an AND gate, the output can go to logical one only, when all the inputs are at logical one. For the rest of the cases, the output of an AND gate turns out to be logical zero. The circuit symbol and truth table of an AND gate are shown in **Figure 8(a)**. For two inputs A and B, AND logical operation is expressed by $A \cdot B$. It is possible to achieve AND operation with a proper combination of NOT and OR gates. This is the usual practice in digital circuits wherein the universal gates such as NOR and NAND are used for creating other gates. This insight stems from De Morgan's theorem in Boolean algebra which is at the very basis of digital circuitry. Accordingly, the implementation of an AND gate using NOR gates is shown in **Figure 8(b)** [31]. An optical logic circuit can also be constructed along the same lines using nanocavities in a PhC slab.

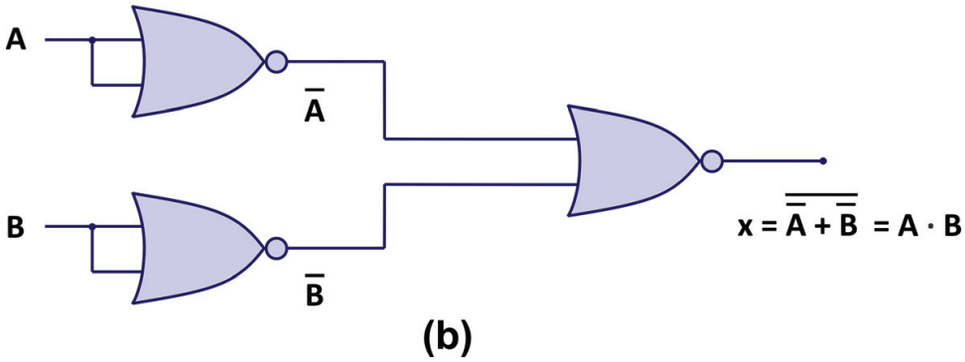



Circuit symbol of AND gate

| A | B | x = A · B |
|---|---|---|
| 0 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 1 |

Truth table of AND gate

(a)




(b)

**Figure 8.** (a) Circuit symbol and truth table of AND gate and (b) implementation of AND operation using NOR gates.

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## 5. Optical memory using photonic crystals

Memory unit in a computer stores data and instructions required by a microprocessor for execution. For a modern digital computer, there are two types of memories, namely, a main memory which communicates directly with the microprocessor and an auxiliary memory which serves as a secondary storage [33]. Data and programs in auxiliary memory are brought into the main memory before being executed by the microprocessor. An efficient memory unit is required for increasing the performance of a computer. A microprocessor can locate memory addresses of a main memory using the address bus and transfer data through the data bus. Usually, the main memory which stores the data as electric charge in capacitors are volatile and cannot store data for more than few milliseconds due to the discharge of capacitor within this period. So, they need to be refreshed regularly to store data continuously. An optical analog of capacitors for storing data can be created in a PhC slab by using nanocavities [34, 35]. The scheme is similar to implementation of NOT gate discussed in the previous section. Here, the memory device is capable of achieving optical bistability as a result of optical Kerr nonlinearity-induced switching process [36]. The nanocavity can be set to resonance by the input pulse denoting a logical one, whereas the withdrawal of the pulse distorts the resonance which resets the cavity back to the logical zero state. Whenever the cavity is set to resonance, there is light at the output waveguide, denoting the logical one state of the cavity and vice versa. Light at the output waveguide can be used for identifying the instantaneous state of the cavity. In this way, nanocavities in a PhC slab can be used for storing digital data. The working of nanocavity-based memory device is illustrated in **Figure 9**.

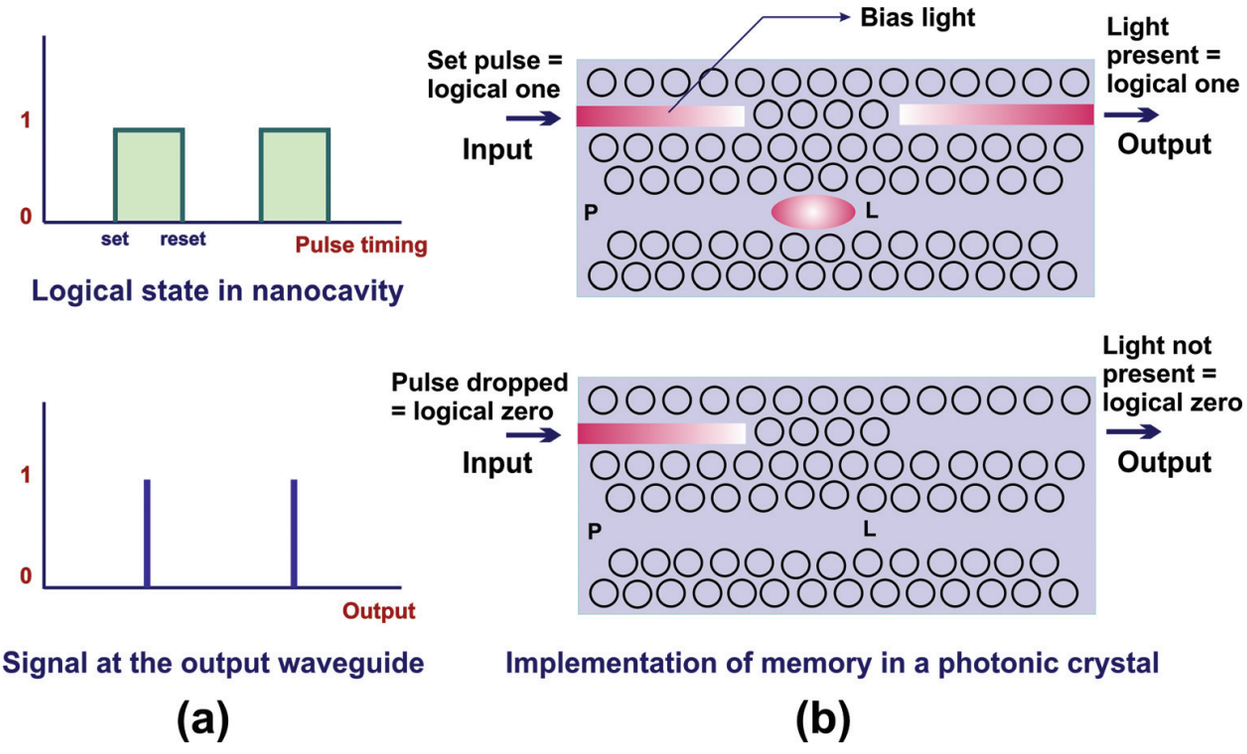



**Figure 9.** (a) Logical state of nanocavity and its indication in the output waveguide, and (b) implementation of memory in photonic crystal.

## 6. Conclusion

In this chapter, the implementation of an all-optical computational system has been delineated using photonic crystal slabs. Following the introduction to the computer architecture which comprises of microprocessor, memory, and input/output devices, the implementation of the same using photonic crystal slabs has also been discussed. Further, we have demonstrated optical logic operations in photonic crystals using optical nanocavities which can be created in these structures. The key feature which decides the working of photonic crystal slab-based logic gates is the change in refractive index which arises due to the optical Kerr effect upon the passage of laser pulses. An attempt has also been made for creating optical memory in photonic crystals, wherein resonance condition decides the logical state inside the cavity. Photonic crystal slabs with nanocavity-enabled logic gates and memory units can be used for constructing an all-optical information processor analogous to semiconductor microprocessors.

## Acknowledgements

This work was inspired by the video "Photonic crystal optical bit memory" by NTT Basic Research Laboratories, Japan.

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