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A review on the techniques for building all-optical photonic crystal logic gates

Hussein M.E. Hussein [a,*], Tamer A. Ali [a,b], Nadia H. Rafat [a]

[a] *Department of Engineering Mathematics and Physics, Faculty of Engineering, Cairo University, 12613 Giza, Egypt*
[b] *Communications and Information Engineering, University of Science and Technology, Zewail City of Science and Technology, 12578 Giza, Egypt*

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ABSTRACT

Recently, photonic crystals have emerged to contribute in building all-optical computers and optical communication systems. This is due to the urgent need for faster computers and mobiles with high speed processing of data and with higher data transmission rates. In this paper we review the operation of photonic crystal logic gates and depict the different design techniques that produce a wide range of structures realizing the logic functions. We investigate several techniques such as self-collimated beam, multi-mode interference, interference based defect method and nonlinear Kerr materials based gates. As a summary, we compare the various key features of each design and illustrate the advantages and disadvantages of each design technique.

Contents

1. Introduction

Since the first introduction of Photonic Crystals (PhCs) by Yablonovitch and John [1,2], they have attracted much attention from research teams due to their unique properties in controlling the propagation of light signals. PhCs allow full control of the propagation of light in all directions. However, the complexity of the design increases as the number of dimensions to control propagation increases. Logic gates are the basic elements of building central processing units (CPU). Photonic crystals logic gates have played a great role in this field due to their high rate of data transmission and low power consumption. Different design techniques were reported to control light propagation inside PhC logic gates structures such as the self-collimated beam [3–8], Multi-Mode Interference (MMI) [9–13], interference based gates [14–31], Mach-Zehnder Interferometer (MZI) [32–34], and nonlinear effects [35–38].

In this review, we summarize these design techniques shedding light on their theories of operation. We start by the self-collimated beam method in Section 2 that realizes all the logic gates using a simple structure with a line defect, then we discuss the Multi-Mode Interference (MMI) method in Section 3 and show how the directional coupler can be optimized to achieve the logic functions. In Section 4 we present the interference based defect method that shows a wide range of flexible designs for different gates, while in Section 5 we cover the nonlinear based gates and illustrate how the signal intensity can change the properties of the structure to

* Corresponding author.
E-mail address: hessiun_mohamed@cu.edu.eg (H.M.E. Hussein).

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operate as desired in the logic function. Finally, we discuss the reviewed techniques in Sections 6, where we concentrate on the advantages and disadvantages of the presented structures; and provide two summarizing tables: Table 1 that summarizes the main features and drawbacks of different techniques; and Table 2 that compares the main design parameters of each technique; such as lattice type, area, contrast ratio, bit rate, signal polarization and operating wavelength.

2. Self-collimated beam

Self-collimation effect is a phenomenon where the incident light can propagate along specific directions through a structure without experiencing any diffraction. In general, building PhC logic gates using the self-collimated beams depends on the Total Internal Reflection (TIR) phenomena. Mainly, the TIR happens if the angle of incidence is greater than the critical angle according to $\theta > arcsin(n_L/n_H)$, where n_L is the low refractive index and n_H is the high refractive index. The structure shown in Fig. 1 clarifies the concept of the self-collimated beam, where it depicts a 2D PhC structure of square lattice built with dielectric rods in air background. To trigger the TIR, a transition between a higher refractive index medium to a lower refractive index medium should be introduced by creating a line defect that consists of dielectric rods of smaller radius. This is done instead of totally removing the rods because it is desired to have a weak TIR, where part of the beam will be reflected and the other part will continue to propagate through the PhC. Because of the creation of the transmitted and reflected beams for each input signal, a phase shift occurs between received signals at the output. Thus, the operations of the logic gates can be realized by introducing different phase shifts between the incident beams on the input faces of the PhC structure to create a constructive or destructive interference at the output faces [3].

The PhC structure of the self-collimated beams is defined by the lattice constant a, the rod radius r while the radius of the rods forming the line defect is r_d. Several papers have been published on building PhC logic gates using the self- collimated beams [3–8]. For example, the structure suggested by [3] to build an OR and XOR gates is shown in Fig. 1. The effective refractive index of the line defect is lower than that of the surrounding area due to its smaller rod radius. Thus, the structure consists of two opposite prisms of high refractive indices with an interface between them of low refractive index. Also, the line defect is aligned along the direction of $\Gamma - X$ to create a symmetric structure on both the sides of the line.

Due to the spatial symmetry introduced by the two prisms and the line defect and the lossless medium (the refractive index has real value only), a phase shift occurs between the transmitted and the reflected beams. The reflected beam has a $\pi/2$ phase lag relative to the transmitted beam when the defect rods are smaller than the surrounding rods [39,40]. Furthermore, the line defect can be designed to split the beams by 3 dB as in the structure proposed by [41], which means that the amplitudes of the transmitted and the reflected beams are equal. However, the ratio of the transmitted beam and the reflected beam can be controlled by changing the radius of the defect rods.

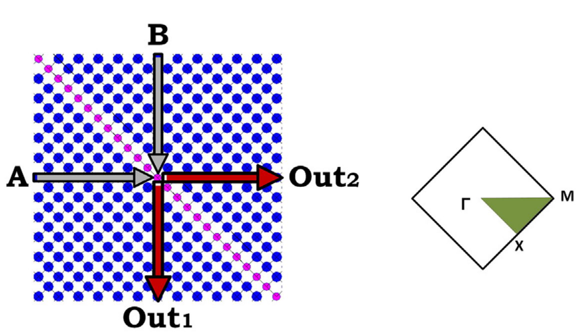
The structure proposed by [3] shown in Fig. 1 has four faces, where the faces A and B are the input faces whereas the faces Out_1 and Out_2 are the output faces. When an input wave is launched at input face A, the transmitted beam will propagate through the output face Out_2 while the reflected beam will propagate through the output face Out_1 with phase lag $\pi/2$. Similarly, when an input wave is launched at input face B, the transmitted beam will propagate through the output face Out_1 while the reflected beam will propagate through the output face Out_2.

To realize the complete functionality of the logic gates, simultaneous beams are launched at the input faces A and B with different phase combinations. Assume that the input signals have initial phases ϕ_1 and ϕ_2. The values of the intensities at the output faces can be controlled by adjusting the phases of the input signals at A and B. For the case of phase difference $\phi_1 - \phi_2 = 2m\pi + \pi/2$, where m is an integer value, an output intensity is detected at Out_1 whereas no output value is obtained at Out_2 as shown in Fig. 2 (b). Similarly, in case of phase difference $\phi_1 - \phi_2 = 2m\pi - \pi/2$ an output intensity is detected at Out_2 whereas no output value is obtained at Out_1 as shown in Fig. 2(c). Thus, the functionality of the logic gates with two inputs can be realized by introducing a phase shifter between the input beams A and B as shown in Fig. 2(a).

It can be noticed that if the phase difference $\phi_1 - \phi_2 = 2m\pi + \pi/2$, the faces Out_1 and Out_2 will realize the functions of OR and XOR gates, respectively. On the other hand, if the phase difference $\phi_1 - \phi_2 = 2m\pi - \pi/2$ then the faces Out_1 and Out_2 will operate as XOR and OR gates, respectively [3].

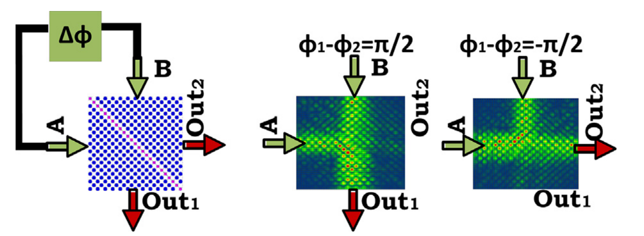
Another structure proposed by [4] is introduced as shown in Fig. 3 that can realize the AND, NAND, NOR and XNOR gates. The line defect 1 is facing the input signals A and B, whereas the line defect 2 is facing an input reference signal *Ref*. All the input signals have the same operating wavelength. The interaction between the reflected beams due to the input signals A and B with the transmitted beam due to the input reference signal *Ref* produces the output logic at the output face. This interaction causes a constructive or a destructive interference depending on the phase difference at the line defect 2, hence the corresponding output logic of the device is observed at face 2.

For the AND gate operation, the inputs A and B are set to $2I_o$ while the reference signal *Ref* is set to $0.5I_o$, where I_o is the signal intensity. In the absence of A and B signals, only the *Ref* interacts with the line defect 2 and its beam will be equally divide which



(a) (b)

Fig. 1. (a) The 2D square lattice PhC structure consisting of dielectric rods in air background with input faces A and B and output faces Out_1 and Out_2 (b) The directions in the lattice, similar to Fig. 2 in [3].



(a) (b) (c)

Fig. 2. (a) Schematic of the structure with the phase shifter. (b) and (c) The field distribution of a TE mode signal for phase difference $\phi_1 - \phi_2 = \pi/2$ and $\phi_1 - \phi_2 = -\pi/2$ respectively, similar to Fig. 4 in [3].