Optik 168 (2018) 237–243

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

All-optical logic gates based on coupled heterostructure waveguides in two dimensional photonic crystals

W. Belhadj[a,b,*], N. Saidani[b], F. Abdelmalek[b]

[a] *Faculty of Applied Sciences, Department of Physics, Umm Al-Qura University, Makkah, Saudi Arabia*
[b] *Laboratoire de Physique Quantique et Photonique, Faculté des Sciences de Tunis, Université Tunis El – Manar, BP 1060, Tunis, Tunisia*

ARTICLE INFO

Article history:
Received 22 August 2014
Received in revised form 17 February 2018
Accepted 11 April 2018

Keywords:
All-optical logic gates
Finite-difference time domain FDTD
Coupled photonic crystal waveguides (CPCWs)
Optical information processing (OIP)

ABSTRACT

In this study, all-optical logic gate with multifunctional performance have been designed in two-dimensional coupled photonic crystal waveguides (CPCWs) employing modulation of the refractive index in the coupling region. A two dimensional finite-difference time domain (2D-FDTD) was employed in our numerical simulations. It is shown that by switching the optical signal to different input waveguide ports, the proposed device can function as AND, OR, NOR and NOT gates operating at many or single wavelength. Our simulation results show that the optimized devices have very good transmission efficiencies, a broad frequency range and the contrast ratios between the output ports reveal a satisfactory level. Our results not only provide a simple on chip platform for next generation logic optical circuits, but also open up the possibility for the realization of ultrahigh speed signal processing, and future photonic crystal based all-optical integrated circuits.

1. Introduction

Recently, optical information processing (OIP) has attracted intensive attention due to its unique benefits such as high speed, low energy consumption, potentially improved security, and parallel processing [1–4]. Compared with electrical information processing, OIP is a most hopeful scheme at large amounts of data in real time domain. Actually, several achievements have been obtained in OIP, and diversified fundamental OIP devices have been achieved [5–7]. Since, any complex OIP device can be attributed to optical logic operations. Therefore, all-optical logic gates appear to be key elements in OIP systems. They have many applications such as adders, subtractor, header recognizers, parity checkers, and encryption devices. In practice, it is desirable to implement all-optical logic gates having small size, low power consumption and high-speed [8].

There are many existing approaches for realizing optical logic gates. Many materials and devices have been suggested for use in optical logic. Previous developments have focused on two routes to construct optical logic gates: the first one is based on linear optical effects, such as interferometry [9], semiconductor optical amplifier (SOA), Mach–Zehnder interferometer (MZI) [10,11] and cascaded microring resonators [12]. This type of optical logic devices is based on mature techniques of optical fibers but it requires large space and is impossible for micro- or nano-integration. In micro-structures linear effect all-optical logic functions, such as optical interference effect [13], were demonstrated, which preliminarily solves the integration problem. But the disadvantage of this type of optical logic devices is the lack of polarization and phase tolerance, indicating it requires precise initial conditions that are very hard to implement. The interference plasmonic networks [14,15] were

* Corresponding author at: Faculty of Applied Sciences, Department of Physics, Umm Al-Qura University, Makkah, Saudi Arabia.
E-mail address: wbbelhadj@uqu.edu.sa (W. Belhadj).

https://doi.org/10.1016/j.ijleo.2018.04.051
0030-4026/

utilized to implement optical logic functions but the plasmonic loss problem limits its further application in cascaded logic gates.

In this context, Photonic crystals (PCs) which are artificially fabricated periodic dielectric structures [15,16], are promising candidate to construct devices with dimensions of a few wavelengths of light for future photonic integrated circuits. As a consequence of recent advantages in nano photonic construction, the amount of compactness and low loss of PCs structure make them one of the best candidates for building ultra-fast optical integrated circuits. So far, several schemes have been investigated to realize various all-optical logic functions such as AND, NOT, NOR, XOR, NAND gates. However, most of them were based on nonlinear optics [17–22] which suffered from certain fundamental limitations like power consumption and narrow operating frequency range. In addition, all-optical logic gates, based on multimode interference (MMI) in two dimensional (2D) PC, have been also studied [23–27]. These researches have generated multifunctional logic gates like: OR, NAND, NOR and NOT gates.

In this paper, we have proposed novel all optical AND, NOT, OR and NOR gates based on two-dimensional coupled photonic crystal waveguides (CPCWs) employing modulation of the refractive index in the coupling region. The prominent features of these gates are their very good transmission characteristics and structure compactness (it has the dimensions in the order of several wavelengths of light). In addition, since the same structure has the compatibility to be used as AND, NOT, OR and NOR gates it offers good candidates for all-optical integrated circuits in contrast to previously designed gates.

2. Structure design

The two-dimensional photonic structure considered in this work is formed by a square lattice of dielectric pillars with a dielectric constant $\varepsilon = 11.56$ in air. The ratio of the dielectric pillars radius r to the lattice constant a is set to be r/a=0.18. This structure exhibits photonic band gaps only for TM modes appearing from the normalized frequency of $a/\lambda = 0.303$ to 0.445, where λ being the optical wavelength in free space [28]. Therefore, only Transverse Magnetic (TM) polarization will be discussed in the following study. Two dimensional finite difference time-domain (FDTD) [29] method was employed to simulate the light propagation in the designed structures.

Two parallel photonic crystal coupled waveguides (PCWs) are created by removing two rows of dielectric pillars in ΓX direction. The two PCWs are separated by two rows of pillars. Meanwhile, low-loss bends are introduced to minimize the interference of the ports [30]. In the most basic form, a coupler is consisted of two parallel identical waveguides running together over some distance L. When placed closely together, the modes in each guide interact to produce super-modes in the coupled wave guide system. If a signal is injected into one of the coupled waveguides it couples after a propagation distance L. When the entire signal in one guide is totally transferred to the other, the propagation distance is labeled L_c. Here, we construct a heterostructure coupled waveguides by changing the refractive index of the pillars in the interaction region to be n' (represented in red color) as shown in Fig. 1.a. The light coming from the input port is totally transferred to the lower waveguide and exit from port B. For a fixed normalized frequency, by modulating n' values, different coupling lengths are obtained. Fig. 1.b. shows the coupling length variations versus normalized frequencies. For three pairs of normalized frequency a/λ and refractive index n' ($a/\lambda = 0.345$; $n' = 3.2$), ($a/\lambda = 0.350$; $n' = 3.1$) and ($a/\lambda = 0.355$; $n' = 3.02$) the coupling length is always $L_c = 12a$. But, for ($a/\lambda = 0.355$; $n' = 3.4$), the coupling length increases to become $L'_c = 24a$. By setting $a = 0.550\ \mu m$, the three operating normalized frequencies cited above correspond respectively to wavelengths of $\lambda = 1595$; 1572 and 1550 nm, which are in the communication window.

3. Results and discussions

First, we are interested in constructing an all-optical device operating for three different wavelengths. The proposed heterostructure coupled waveguides based all-optical logic device shown in Fig. 2, is formed by three input ports labeled A, B and C and an interaction zone created by two coupling regions with a refractive index n' and three output ports called D, E and F. By modulating the refractive index of the interaction region, the device can operate for the several wavelengths. The length of the upper input is less than the length of the lower one by one lattice constant; which creates a phase difference equal to π. According to Wave Optics Theory, if the phase difference between tow signals is $2k\pi$ (where k = 0, 1, 2. . ..), the constructive interference will occur and the outputted signal will have higher power. But, if the phase difference between two signals is $(2k + 1)\ \pi$, (where k = 0, 1, 2. . ..), the destructive interference will occur and the outputted signal will have approximately zero power [31]. Thus, a destructive interference is obtained when two signals are launched simultaneously in the upper and lower inputs. The steady electric field distributions represented in Fig. 3 at the three operating wavelengths show that two kinds of basic logic functions (NOR and AND) exist. It should be noted that if the output power is higher than $0.35P_0$, it is considered corresponding to logic operation "1" contrarily representing logic operation "0"; where P_0 is the initial inputted power. The two logic functions, cited above, are summarized as follows:

(1) NOR gate: When an optical signal is launched in input port **A** without control signals there is always an output signal in port **F** as shown in Fig. 3.a. When control signals are launched in **B** or/and **C** there is no output signal in port **F** as shown in Fig. 3.c, e, f. Therefore, the device can really function as NOR gate, i.e. $\mathbf{F} = \overline{\mathbf{B+C}}$, as summarized in Table 1.

(2) AND gate: When an optical signal is launched in input port **B** without control signals there is no output signal in port **D** as shown in Fig. 3.b. When control signals are lunched in **A** or **C**, there is also no output signal in port **D** as shown in Fig. 3.c,