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Research paper

Performance evaluation of GaAs photonic crystal based directional coupler all optical switch

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Abstract

In future, the telecommunication systems will be totally based upon the photonic integrated circuits and components for the transmission of optical signals. Since optical signals offer high speed, less delay and higher efficiency. This introduces a new research area for photonic crystal based optical components like optical switch, multiplexer, optical filters etc. Among these devices, the optical switch draws more attention due to its primary switching operation. Hence, this paper deals with the modified design structure of GaAs photonic crystal based directional coupler all optical switch which operates at the wavelength of 1300nm. Further the switching performance evaluation of this device is made for both electro optic effect and non-linear optical effect. The design and simulation of the optical switch is done through Comsol Multiphysics software.

Keywords: *Directional Coupler; Linear State; Non-Linear State; Electro-Optic Effect; Non-Linear Optical Effect.*

1. Introduction

Photonic Crystals (PCs) are the new frontier in modern optics. For the past few decades, Photonic Crystal (PC) based optical switches are being analyzed and studied owing to its reduced size, delay and losses. Due to these pros, many applications demands optical components based on photonic crystal than that of the electronic components. Photonic Crystals (PCs) are attractive artificial optical materials with periodic variation of dielectric constant. PC can be constructed either in micro or nano scale structure to interact with microwave or optical frequencies respectively. It controls and manipulates the propagation of light wave defined by Photonic Band Gaps (PBG) of the structure [1]. PC structure can either allow or block a specific wavelength of light depending on the frequency of their dielectric constant. The structure can be made periodic in one, two or three dimensions. Fig. 1 represents the schematic view of the two dimensional (2D) PC structure formed by triangular lattice with dielectric rods placed in air. Depending upon the dielectric variation of the PC structure, only particular wavelengths are permitted through the structure i.e. the wavelengths which are allowed to pass through these structures are named as modes and the set of modes are termed as bands. Wavelengths that are not able to pass through the structure are called band gaps. If that band gap falls under the range of optical frequency, then they are known as PBG. Based on these characteristics, PC structure finds application in various photonic integrated devices and circuits such as waveguides, filters, power splitters, switches etc., by introducing some defects in the structure.

Among various applications of Photonic Integrated Circuits (PIC), Directional Coupler (DC) plays a vital role as switch and its basic requirement is size; hence the larger length couplers are not appropriate to implement. Therefore, in order to reduce the coupling length and to improve the coupling characteristics, a new modified structure of DC based PC is proposed in this paper by introducing certain changes in the existing structure [2]. Also the insertion loss and the directivity of the coupler for various switching mechanism is analysed for the proposed structure using COMSOL software.

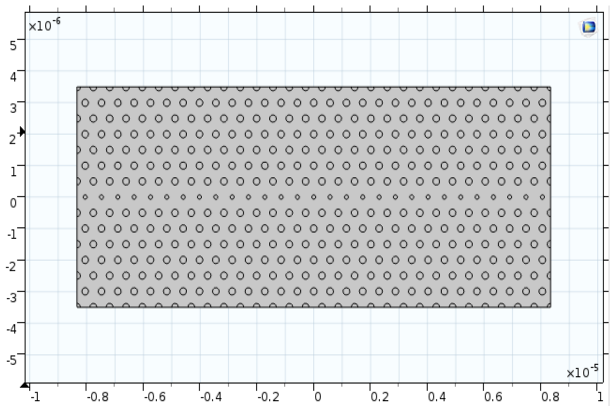

Fig. 1: Schematic View of 2D PC Structure.

The rest of the paper is structured as follows. Section II provides an overview of related works. Section III describes the basic working principle of DC all optical switch and its various switching mechanisms used for nonlinear switching operation. Section IV explains the design of proposed structure geometry and the corresponding simulation results. Section V, finally concludes the paper.

2. Related works

Several researches had been made so far on designing the all optical switch based on photonic crystal structure. Andrea Locatelli et. al proposed an ultra-short photonic crystal optical coupler [3]. The author mainly concentrated in decoupling the waveguides without increasing the switch length. In this structure the waveguides are separated by five lattice constants. Though the switch length is reduced but the input power required for introducing Kerr nonlinearity is quite large for this structure. Then, A. Eshaghi et. al proposed a new all optical switch structure based on photonic crystal directional coupler by introducing some parameter changes in the coupling region [4]. Five design parameters such as central rods radius and two adjacent rod radii of waveguides and their corresponding positions are mainly considered. These parameter values are adjusted to obtain the increased difference between the wavenumbers of linear and non-linear regions which results in reduced coupling length of 18a, where a = 627.75 nm. Further the extinction ratio is increased by applying modified 60o bends in the switch structure. Though the coupling length is reduced, it fails to satisfy the necessity of small size switch.

A. Taher Rahmati et. al proposed a non-linear photonic crystal optical switch with refractive index variation of 0.132 and 1.55W input power required for switching [5]. The switch operates in non-linear state by changing the refractive index of the central row rods by applying the required input signal power. In order to obtain the better coupling efficiency and less input power, the switch length is taken as 24a, where a=573nm. In continuation with this work, the same author's proposed an ultra-compact Kerr nonlinear optical switch [6]. They proposed three different switch structures and analyzed their respective input pump power required for switching operation. Finally, concluded that the structure with 4 rows of rods between the waveguide input and output ports, and the structure with increased number of central row rods perform better than the normal structure.

In related to PBG, Abdenacer Assali et. al presented the study of photonic band gap in Si/air based 2D PC [7]. From the band diagrams, they concluded that PBG of the material is mainly dependent on the radius or size of the dielectric rods. Babak Vakili et. al proposed a new structure of all optical switch with switching length of about 94µm and extinction ratio of 67dB [8]. The switch is designed to operate at wavelength of 1.55µm. Unlike the other switch structures, the waveguides are formed by reduced rod radius instead of removing the entire row of rods. With this structure, good isolation between control signals and the probe signal are obtained but size of the switch is quite large. Meisam Rezapanah et. al proposed the new optical switch structure based upon the slow light in coupled cavity waveguides [9]. By slow light wave propagation, the switching length of 13.6µm for 1.55µm wavelength is obtained for refractive index change of 0.02. In addition, 80% output efficiency is achieved for both bar and cross state operation. But author fails to justify the required input power for switching operation.

Though many research articles has proposed various design structures to build an efficient directional coupler optical switch, still the shorter coupling length, switching speed, output power, insertion loss and coupling efficiency of DC optical switch in any one aspect needs to be improved for making compatible with the future photonic integrated devices and circuits.

3. All optical switch – working principle and switching mechanisms

Directional Coupler (DC) based on non-linear Photonic Crystal (PC) can be used as an all optical switch in Telecommunication networks and various applications. Conventional DC consists of two waveguides placed close to each other. In order to construct PC based DC, some defects needs to be introduced in the PC structure shown in the Fig. 1. The waveguides of DC are formed by introducing linear defects in the structure. The linear defects are nothing but the removal of row of rods in PC structure which creates the path for transmission of the optical signal.

Directional coupler based on PC structure is shown in Fig.2 which consist of three regions namely input region, coupling region and output region. Input region contains two input ports (Port1, Port2) and output region contains two output ports (Port3, Port4). Since the waveguides are located very close to each other, the input light wave applied to one waveguide will be coupled to another waveguide periodically under suitable conditions. The coupling of the light wave takes place in the coupling region with coupling length (Lc). The coupling length (Lc) of the optical switch is given by the following relation[10]:

$$L_c = \frac{\pi}{\beta_e - \beta_o} \quad (1)$$

Where βe and βo are the even & odd mode propagation constants,

$\Delta\beta = \beta_e - \beta_o$.

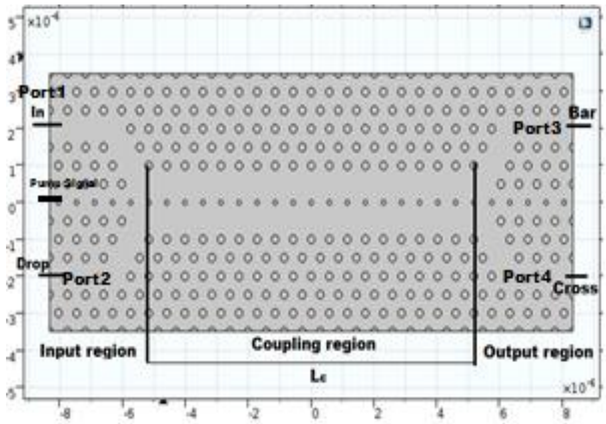

Fig. 2: Schematic View of PC Based DC All Optical Switch.

DC can be operated in two states namely bar state and cross state. It operates either in bar state under linear condition or in cross state due to the presence of non-linearity in PC structure. In bar state, the light wave applied to Port1 will be present at Port3, whereas in cross state, the light wave will be coupled to Port4 due to the change in refractive index of the central dielectric rods which results in switching operation.

The condition for DC to operate in cross state is inferred from [11], i.e., the change in refractive index (Δn) of the central dielectric rods will cause the change in wavenumber of even and odd modes (Δβ) accordingly. So, it will have direct effect on coupling length which is evident from the relation 1. The resulting change in coupling length will make the light wave to transfer to Port4. Since the switch length is inversely proportional to Δβ which is function of Δn, the relationship between Δβ and Δn is dependent to the geometry structure.

From the above discussion, it is obvious that small variation in refractive index is required to reduce the coupling length. There are several mechanisms present to introduce optical non linearity in rods of PC structure. Some of the basic effects generally used in all optical integrated waveguide switches are electro-optic, acousto-optic effect, magneto-optic effect, thermo-optic and non-linear optical Kerr effect.

Among these mechanisms, two types of effects namely electro-optic effect and non-linear optic effect are considered in this paper for analysis of switching performance of the proposed structure. The electro-optic effect can be classified as linear electro-optic effect (Pockels effect) and non-linear electro-optic effect (Kerr effect). These effects introduce refractive index change of the waveguide by applying an external electric field. This results in phase shift which can be used for switching applications. The other effect considered here is non-linear optical effect (Optical Kerr effect). Using optical Kerr effect, the refractive index of the nonlinear dielectric material can be altered by applying high intensity optical pump signal. The refractive index change introduced by this effect is given by the relation,

$$\Delta n = n_0 + n_2 I \quad (2)$$

where n0 is the refractive index of rods in the linear state, I is the optical input pump signal intensity and n2 is the nonlinear Kerr coefficient of dielectric rods.

4. Design and evaluation of all optical switch

Recently, the design of all optical switch based on PC attracts many researchers' attention due to its future application in telecommunication industry. The basic requirement of directional coupler based all optical switch is its size and efficiency. This work mainly concentrates to design the switch with small size which makes it suitable to implement in photonic integrated circuits. Further the design of the switch is made to emphasis on providing high output power ratio, less insertion loss and improved directivity. Therefore, a modified two dimensional (2D) design structure of DC all optical switch based on GaAs PC is proposed in this paper.

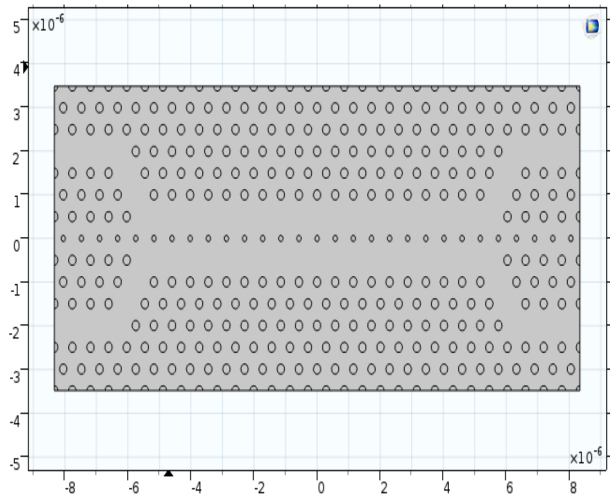

Fig. 3: Geometry of Proposed DC Structure with Gaas Dielectric Rods Placed in Air.

Fig. 3 portrays the schematic view of the switch design structure, designed with the help of COMSOL Multiphysics software. Initially, the PC nanoscale structure is formed by placing Gallium Arsenide (GaAs) dielectric rods in air with hexagonal or triangular lattice of array size (30 x 15). The dielectric material GaAs is chosen for its higher refractive index of 3.6 which makes it suitable for nonlinear operation of the switch. The PC switch structure is designed with dielectric rods radii of 0.2a, and the central dielectric rods with radii of 0.12a, where a is the lattice constant and the value of a is taken as 575nm to guide the wavelength of 1300nm. The structure has a TM band gap in a range of $0.27 \leq a/\lambda \leq 0.38$, where λ is the free space wavelength. In the above shown PC design structure, the two waveguides of DC are formed by removing some row of GaAs dielectric rods to guide the range of frequencies within the specified TM band gap mentioned above. The constructed geometry of the proposed directional coupler all optical switch is analysed by using Finite Element Method (FEM). Fig. 4 shows the finite mesh applied to the switch structure for the study of light wave propagation along the waveguides.

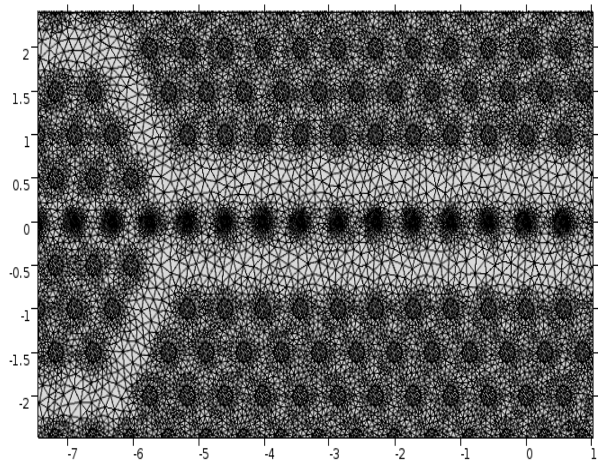

Fig. 4: Finite Free Triangular Mesh Structure Applied in DC Structure

After finishing the geometry design procedure, the switch is subjected to make the study analysis for both linear and nonlinear condition. First the optical switch is made to operate in linear condition or bar state without applying any change in the refractive index of the central dielectric rods. Once the input signal is applied at the input port Port1, the switch starts to work in linear state which makes the input light wave signal to appear at output port Port3 as shown in Fig.5.

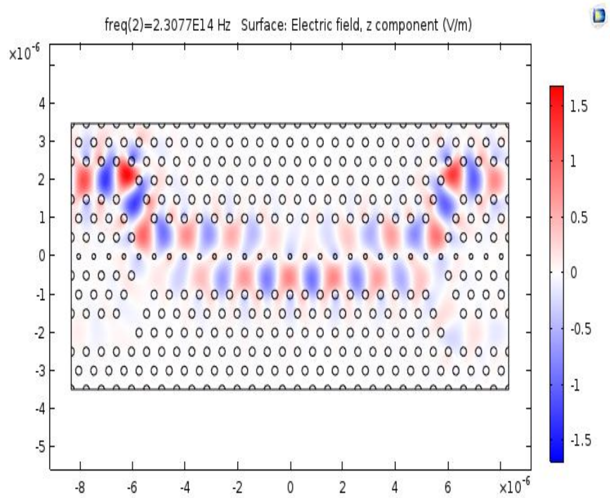

Fig. 5: DC All-Optical Switch in Linear State.

Fig. 6 illustrates the time average of power flow across all the ports of the switch while it operates in linear state. From the figure, it is inferred that power flow across Port3 is maximum when compared to that of port4 as it operates in linear state. In case of Port2 and Port4, still it shows a negligible power flow from which the insertion loss and directivity are calculated as shown in Table I.

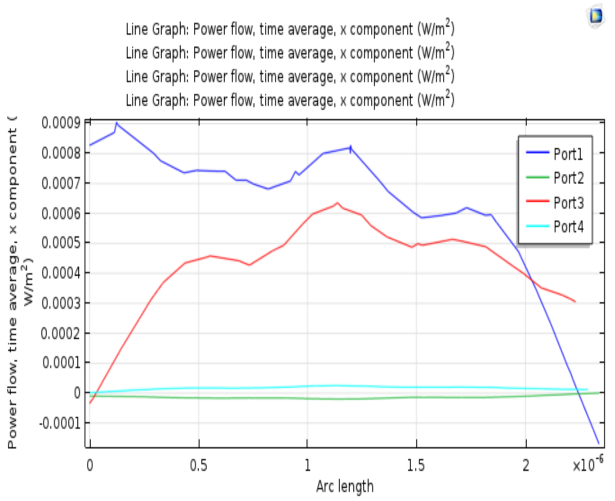

Fig. 6: Power Flow across All the Ports of DC All-Optical Switch in Linear State.

Then the optical switch is made to operate in non-liner condition by applying an external input to introduce refractive index change in the central row rods as discussed above in section III. Here, the switching performance analysis is done for two types of mechanisms namely, electro-optic effect and non-linear optical effect.

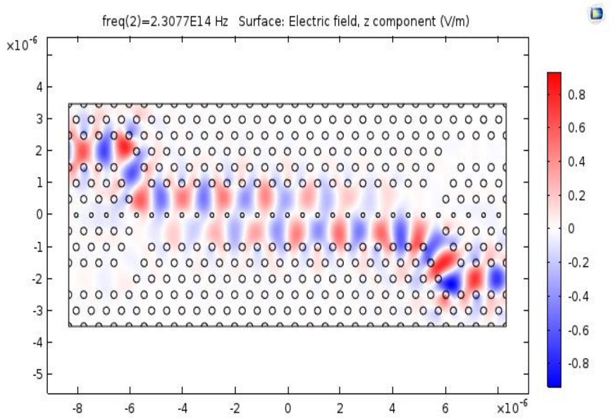

Fig. 7: Dc All-Optical Switch in Non-Linear State with High Input Pump Control Signal.

First, the electro optic effect is considered for evaluation. In this switching mechanism, the external electric field of 1V/m is applied to all central row rods of the structure to induce refractive index change. Due to the application of external electric field, the switch operates in cross state and makes the input signal to appear at Port4 as shown in Fig. 7. The corresponding time average of power flow across all the ports of the switch is shown in Fig.8.

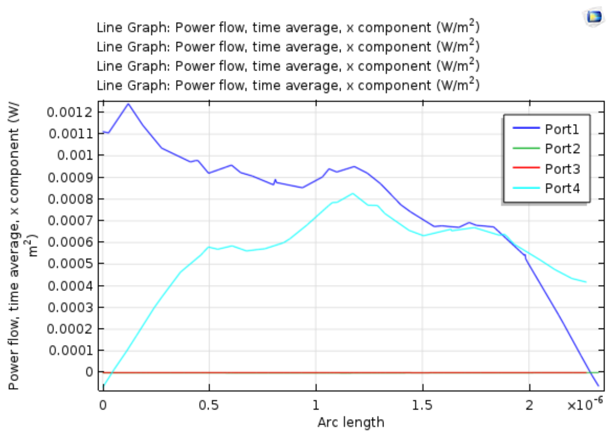

Fig. 8: Power Flow across All the Ports of DC All-Optical Switch with High Input Pump Control Signal.

Next, the non-linear optical Kerr effect is used to provide the required refractive index change in the central row rods. In this mechanism, the high intensity input pump signal with 1W power is applied externally to all the central row rods. Due to this, there will be change in coupling length, which makes the light wave to appear at Port4 as shown in the Fig.9. The corresponding time average of power flow across all the ports of the switch is plotted in Fig.10.

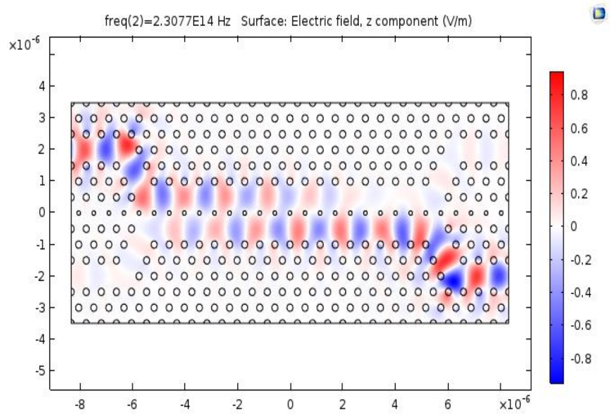

Fig. 9: Dc All-Optical Switch in Non-Linear State with External Electric Field Control Input.

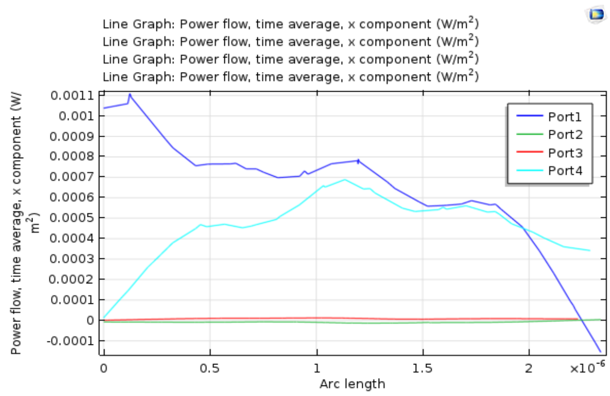

Fig. 10: Power Flow across All the Ports of DC All-Optical Switch with External Electric Field Control Input.

From the results obtained, the performance evaluation of the proposed modified design structure of the switch is done by the following parameters. The important practical parameters considered for analysis are insertion loss and directivity. The insertion loss of the directional coupler optical switch is the fraction of signal power lost and it is calculated using the relation,

$$\text{Insertion Loss (dB)} = 10\log\left(\frac{P_1}{P_{3,4}}\right) \tag{3}$$

Where, P1 is the input signal power and P3 is the bar state output power, P4 is coupled output power at cross state.
The directivity of the coupler is the ability of the coupler to differentiate between forward and reflected signals. It is given by the relation,

$$\text{Directivity(dB)} = 10\log\left(\frac{P_2}{P_1}\right) \tag{4}$$

Where, P1 is the input signal power and P2 is the reversed signal power. The parameters calculated from the above obtained results are given in Table I.

Table 1: Performance Parameters of Proposed DC All Optical Switch

Mode of operation		Insertion Loss (dB)	Directivity (dB)
Bar or Linear state		0.902	-16.53
Non-linear state	Electro optic effect	0.525	-20.41
	Optical Kerr effect	0.586	Better than –40dB

5. Conclusion

In order to meet the basic requirements of DC optical switch such as shorter coupling length, high output power ratio, switching speed, less insertion loss and high directivity, an efficient switch structure needs to be designed. In this paper, a modified new design switch structure which operates at the wavelength of 1300nm is proposed which results in reduced coupling length of 19a better than other conventional designs. Further the parameters such as insertion loss and directivity of the proposed structure is calculated for linear state and non-linear state with two types of switching mechanisms. Also the reported values given in the Table I lie in the operational range of the coupler. The total length of the proposed switch structure is approximately 16µm. Since, the proposed design has more bend loss as portrayed in the results; the modified bends can be introduced in this structure as a future work.

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