An ultrafast all-optical switch based on a nonlinear photonic crystal waveguide using single crystal p-toluene sulfonate

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Abstract: A novel design of an all-optical switch is proposed based on a nonlinear photonic crystal Mach–Zehnder interferometer (PC-MZI) to get the maximum switching speed and the minimum consuming power. As far as we know, this is the first study using a nonlinear polymer in one of the PC-MZI arms for realizing the switching phenomenon. All used components, such as bends, waveguides, and splitters, were individually optimized. Finite difference time domain and plane wave expansion methods were also utilized for the simulation of light propagation in the proposed structures.

Key words: Optical switch, p-toluene sulfonate, photonic crystals, extinction ratio, insertion loss

1. Introduction
Nowadays, the vital need for storing and communicating information has encouraged researchers to take great steps toward improving optical fiber telecommunication networks [1]. The main purpose of designing optical devices is to effectively utilize the high bandwidth of optical fibers [2]. One of the main and important ways to achieve this goal is the use of ultrafast optical switches [3]. Recently, photonic crystal switches have been of great interest due to specific characteristics of photonic crystals in controlling and conducting light [4]. These structures are small and can work with low power in comparison with dielectric plane surface switches [5]. Optical switches are inherently nonlinear devices and the nonlinearity behavior of each switch can be a good factor determining its quality and performance [6]. All-optical switches can be designed using the nonlinear Kerr effect [7]. When high intensity light passes through an environment built from a Kerr nonlinear material, the phase of input light can be changed in accordance with the light intensity. The phase difference occurring between linear and nonlinear cases is the basis of all-optical switching [8]. Crystalline minerals with high Kerr nonlinear effect have been commonly used in optical gates [9–11], slow light waveguide, and all optical switches [12–14]. Meanwhile, the organic materials with high nonlinearities, in comparison with mineral counterparts, can be used for designing optical switches. In [15], a 2 × 2 MMI-MZI polymer thermo-optic switch was proposed and in this structure an extinction ratio of 28.6 dB was achieved and measured switching time was 0.7 ms. In [16], Sugimoto et al. experimentally demonstrated 2D PC waveguides such as straight, bent, Y-branch, directional coupler, and quantum dot based nonlinear optical waveguides, using a GaAs air-bridge membrane with a triangular lattice. In [17], Lin et al. proposed a dual-path heterodyne Mach–Zehnder interferometer; high measurement resolution and stability are the advantages of this structure. In [18], Djavid et al. proposed

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coupled-mode analysis of a two-dimensional photonic crystal add–drop filter based on ring resonators. In [19], Li et al. proposed a novel photonic crystal waveguide based symmetric-Mach–Zehnder-type ultrafast all-optical switch using a quantum dot semiconductor optical amplifier.

Suitable materials for ultrafast all-optical switching must satisfy a series of figures-of-merit. First, they must have a sufficiently large, nonresonant, optical Kerr effect for the intensity-dependent refractive index, such that they can operate at watt peak powers in centimeter long devices, and second these materials must exhibit a nonlinear phase shift of at least $\pi$ over 1/e attenuation distances [20]. According to the figure-of-merits defined and computed by [20] for p-toluene sulfonate (PTS), this material satisfactorily operates for ultrafast all-optical switching at $\lambda = 1.6 \mu m$.

To create all optical switching with low power consumption, it is necessary to use suitable material to satisfy these requirements. Moreover, the dimension of the structures must be miniaturized in order to be compatible with other devices. Therefore, in this paper we make use of PTS as a nonlinear material. In this paper, for the first time, single crystal PTS has been employed as the constitutive material of the PC-MZI-based all-optical switches. MZI-based structures have been proposed for $1 \times 1$, $1 \times 2$, and $2 \times 2$ all-optical switches. The optimized structures have been simulated after a complete optimization process including the enhancement of bends, waveguides, and splitters. The designed switches have the integration capability in optical integrated circuit and also wide applications in WDM networks. The calculations of photonic band gap and the analysis of photonic crystal ring mode have been done by plane wave expansion method. Finite difference time domain has been used for achieving the power-time switching curves.

The theoretical background of photonic crystal structures is presented in section 2. Section 3 includes the proposed structures for $1 \times 1$, $1 \times 2$, and $2 \times 2$ all-optical switches where the optimization process and simulation results of the proposed switches are investigated. Finally, the effect of some parameters on the performance of the proposed switches are discussed and the comparison of the designed structures in terms of extinction ratio, insertion loss, intensity, switching speed, and dimensions is given in section 4.

2. Theoretical background
The identification of parameters in band structure is important for the optimization of photonic crystal designs. This can be achieved through the gap map shown for SiGe in Figure 1. As can be seen, the evaluation of frequency bandwidth corresponding to each radius leads to achievement of the optimum radius. The gap map shows that the optimized radius occurs in the maximum region of the photonic band gap. This graph also shows that bigger gaps occur in the higher frequencies. It is obvious that the selection of suitable crystal geometry is necessary to achieve the maximum refraction. The used material is SiGe with the refractive index of $n_0 = 3.6$ [14].

In Figure 1, the normalized frequency value $(a/\lambda)$ is drawn with respect to the radiuses of rods for TE band gap. This figure also shows that the maximum band gap is achieved at $r/a = 0.155$ and TE band gap width exists in $0.311 \leq a/\lambda \leq 0.463$. To find the optimized value for lattice constant $a$, the center of this band gap is considered as the designed frequency $(\lambda = 1.5 \mu m) a = 0.6 \mu m$.

As can be observed from Figure 1, the maximum band gap was at $r/a = 0.155$ and by substituting the value of $a$ from the above equation, $r$ could be achieved as $r = 0.155 \times a = 0.093 \mu m$. Now we have all the necessary parameters for the optimum design.

A dispersion diagram could be obtained by PWE in order to analyze wave behavior. Figure 2 shows the structure of the band achieved from the PWE method for SiGe waveguide. The photonic band gap in the band structure corresponding to the wavelength range is from 1.3 $\mu$m to 1.93 $\mu$m.
3. All-optical photonic crystal switch

3.1. 1 × 1 all-optical switch

The refractive index of nonlinear materials can be increased by increasing the incident light intensity. The total refractive index of materials can be calculated as follows [7]:

\[ n = n_0 + \Delta n = n_0 + n_2 I \] (1)

where \( n_0 \) denotes the linear refractive index, \( \Delta n \) is the refractive index change, \( n_2 \) is the coefficient of nonlinear refractive index, and \( I \) is the light intensity. The propagation constant of material can be defined as \( k = n\omega/c \).

Thus, the changes in propagation constant can be written as [7]

\[ k = \frac{n\omega}{c} = \frac{n_0\omega}{c} + \frac{n_2 I\omega}{c} = k_0 + \Delta k \] (2)

where \( k_0 = n_0\omega/c \) is the propagation constant in low intensity conditions and \( \Delta k = n_2 I\omega/c \) refers to the changes of propagation constant in high intensity light [8,10,11]. The phase change, which is accompanied by the propagation of light through the length of \( L \), can be calculated as [7]

\[ \Delta\varphi = \Delta kL = \frac{2\pi n_2 I}{\lambda_0}L \] (3)

Such dependency of phase on light intensity is called self-phase modulation [21]. These nonlinear characteristics can be used in MZI structure. Figure 3 shows the schematic of a PC-based MZI structure. The upper arm is substituted with a nonlinear material.

The nonlinearity in the upper arm of MZI has been produced by utilizing a nonlinear polymeric material referred to as PTS with Kerr nonlinearity coefficient of \( n_2 = 3 \times 10^{-16} \text{ m}^2/\text{W} \) [7]. Some other advantages of these polymeric materials are the high potential for easy fabrication and integration. PTS rods were placed in the middle of the waveguide, as can be seen in Figure 3. The radius of these nonlinear rods was equal to \( r = 0.077a \). A material with the same linear refractive index as PTS was used in the lower arm in order to have a symmetric MZI in the linear region. The material used for the lower arm was LiF with the low nonlinearity of \( n_2 = 9 \times 10^{-20} \text{ m}^2/\text{W} \) [7]. It should be noted that this material has much lower nonlinear refractive index.

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**Figure 1.** The TE gap map of SiGe with the refractive index of \( n_0 = 3.6 \).

**Figure 2.** Frequency band for rectangular photonic crystal with SiGe rods \( \varepsilon_r = 12.96, r = 0.155 \times a \).
in comparison with polymeric material used in the upper arm. Therefore, the high intensity light did not show any nonlinear effects in the lower arm.

An optical switch based on MZI is composed of direct waveguides, waveguide splitters, and waveguide bends. The main purpose in the design of bends and splitters is to achieve maximum power transition and the minimum size of the designed device. The radius of bends can be changed by displacing the rods of the bend corner. The transmitted power of some bend designs with different radiiuses is compared in Figure 4. As can be seen, the structure in Figure 4b has higher output transmission power in comparison with the other structures. Moreover, the normalized output power for a T-shaped splitter with and without two extra rods is shown in Figure 5. It is obvious that the input light can be identically split by inserting two additional rods, as shown in Figure 5b. Two extra output rods have the half radius of other rods in the lattice structure.

The ON and OFF switching states in the proposed switch could be obtained with low and high intensity input light, respectively. The analysis of guided modes in nonlinear waveguide is necessary for determining the length of arms and switching power. The dispersion curve for the two arms of the structure is shown in Figure 6.

As can be seen from Figure 6, propagation constant difference was equal to $\Delta k = 0.078$ at the normalized frequency of $\frac{a}{\lambda} = 0.378$. According to Eq. (3), the length of nonlinear region at $\pi$ phase difference can be obtained to be equal to 40.3 $\mu$m. In addition, the input light intensity for introducing $\pi$ phase difference can be achievable from Eq. (3). By setting up monitors in three positions of entrance, middle, and end of the switch, ON and OFF states of the switch can be determined, as shown in Figure 7.

With respect to the designed $1 \times 1$ MZI switch, switching occurs at the input light intensity of $I = 17$ W/$(\mu$m)$^2$.

3.2. $1 \times 2$ all optical switch

The waveguide splitters used in the proposed $1 \times 1$ switch cause the light of each arm to propagate in another arm, creating unwanted ring modes. In order to eliminate unwanted ring modes and also increase the performance of switch, we used a directional coupler (DC) instead of an output Y-splitter. A DC is composed of two waveguides that can be separated with rows of rods or cavities. For the optimum design, we have changed the radius of rods in the middle of waveguide and achieved the best choice of $r/a = 0.115$, such that it can give the maximum difference of propagation constant. By considering the previously mentioned propagation constant $\Delta k = 0.0456$, which has been obtained at $a/\lambda = 0.378$, the length of DC can be obtained to be $L_C = 6.6$ $\mu$m.

Here a new structure of directional coupler is designed by substituting the T-shaped splitter instead of
Figure 4. Normalized transient response for different bend types with the radiiuses of a) $L = 0.33\sqrt{2} a$, b) $L = 1.33\sqrt{2} a$, c) $L = 2.33\sqrt{2} a$, d) $L = 3.33\sqrt{2} a$.

Figure 5. a) Structure of a simple T-shaped splitter; b) structure of the T-shaped splitter with extra rods; c) the normalized power spectrum for the two structures, blue curve for the simple structure, and the green curve for the splitter with extra rods.

the Y-shaped one (Figure 8). Figures 8a and 8c show the final design of directional couplers with Y- and T-shaped splitters, respectively. Port A is considered as the input port in order to analyze the performance of
Figure 6. Dispersion TE gap map for the two arms of structure. The green dotted line shows the dispersion curve for guided mode in waveguide.

Figure 7. Oscillations measured by time monitors placed at entrance (red), middle (blue) and end (green) of switch for: a) ON state, and b) OFF state for the given structure in Figure 4b. The value given in the x-axis is proportional to the amount of time required for light to propagate in free space as much as the distance given in the x-axis where the proportionality constant (c) is the speed of light in free space.

the designed directional coupler and port B is monitored to show cross talking with port A. Figures 8b and 8d present the normalized transmission spectrum curve of outputs for the mentioned directional couplers.

As can be seen in Figure 8, the proposed coupler with the T-shaped splitter shows higher performance in comparison with the one with the Y-shaped splitter. In addition to the identical splitting of the input light in the T-shaped structure, this structure shows lower unwanted crosstalk light in port B. The outputs of the proposed 3 dB directional coupler can be changed due to the phase difference of input electromagnetic waves. If the inputs had the same phase or phase difference of $\pi$, the intensity of input electromagnetic waves would be divided into two outputs of coupler and both outputs could have the same distribution. If the input phase difference becomes $\pm \pi/2$, the total power of inputs will appear in one of the outputs. A $1 \times 2$ all-optical switch was proposed by utilizing the T-shaped directional coupler. The proposed structure is shown in Figure 9.

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It is obvious that the light that passes through identical arms of the MZI shows zero phase difference. Therefore, in order to solve this problem, we proposed an asymmetric structure of MZI by decreasing the number of rods in the lower arm. This structure introduces the phase shift of $\pi/2$ before reaching the directional coupler. As previously discussed, such phase difference between the inputs of 3 dB directional coupler would result in the total light seen in one of the outputs. Another switching state can occur by inserting high intensity input light and changing the refractive index of structure. Thus, the desired output port for receiving light can be
Figure 8. a) and c) Directional coupler schematics, and b) and d) normalized power spectrum, for Y- (a) and T-shaped (c) structures, respectively.

Figure 9. The proposed MZI-based all-optical $1 \times 2$ switch.

selected by changing the state of switch from a linear to nonlinear one. Simulation results of light propagation in the proposed $1 \times 2$ all-optical switch are presented in Figure 10.

As can be seen, the modified directional coupler prevents unwanted light in the zero output ports of linear and nonlinear states. This behavior shows the high performance of the proposed switch.
3.3. 2 × 2 all optical switch

In this section, a 2 × 2 all-optical switch is designed that could act as a frequency selective channel in WDM circuits. This structure is designed by utilizing two 3-dB directional couplers in order to achieve a 2 × 2 all-optical switch based on a complete MZI. The proposed structure, which comprises two 3-dB couplers as splitters and two straight waveguides as arms of the MZI, is shown in Figure 11.

Increasing the intensity of input light resulted in the nonlinear effect and a change in the achievable output port. Figure 12 shows the curve of the normalized output power as a function of the input light intensity at $a/\lambda = 0.387$.

As can be seen, the switching phenomenon occurs when the input intensity of light exceeds 4.7 W/($\mu$m)$^2$ and the essential phase difference for switching could be obtained when the intensity of input light reached 6.5 W/($\mu$m)$^2$. Simulation results of the proposed 2 × 2 all-optical switch are shown in Figure 13.
4. Discussion

The most essential parameters that should be considered in optical switching are extinction ratio ($Ex. R.$) and insertion loss ($I. L.$). The values of these parameters show the performance of the structure.

Extinction ratio and insertion loss can be calculated as follows:

\[
I. L. (dB) = 10 \log\left( \frac{P_{out}}{P_{in}} \right)
\]  

\[
Ex. R. = \frac{P_{out}}{P_{in}}
\]  

Figure 12. The normalized power of output ports based on the variations of input light intensity.

Figure 13. Light propagation simulations of: a) and c) linear and b) and d) nonlinear switching states for the upper and lower input ports, respectively.
Ex. R. (dB) = 10 \log \left( \frac{P_{\text{low}}}{P_{\text{high}}} \right) \quad (5)

where $P_{\text{out}}$ and $P_{\text{in}}$ are the output and input power, respectively. In addition, $P_{\text{low}}$ and $P_{\text{high}}$ show the lower and higher levels in the output for both ON and OFF states, respectively [22,23]. The values of extinction ratio and insertion loss for the proposed $1 \times 1$, $1 \times 2$, and $2 \times 2$ all-optical switches are given in Table 1.

Table 1. The values of extinction ratio and insertion loss for $1 \times 1$, $1 \times 2$, and $2 \times 2$ all-optical switch.

<table>
<thead>
<tr>
<th>Switch type</th>
<th>Output port</th>
<th>Linear</th>
<th>Nonlinear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Port B</td>
<td>Port C</td>
</tr>
<tr>
<td>Insertion loss (dB)</td>
<td>$1 \times 1$ all-optical switch</td>
<td>-0.17</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$1 \times 2$ all-optical switch</td>
<td>-16.9</td>
<td>-0.7</td>
</tr>
<tr>
<td></td>
<td>$2 \times 2$ all-optical switch</td>
<td>-0.09</td>
<td>-23</td>
</tr>
<tr>
<td>Extinction ratio (dB)</td>
<td>$1 \times 1$ all-optical switch</td>
<td>-19.8</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$1 \times 2$ all-optical switch</td>
<td>-16.3</td>
<td>-16.3</td>
</tr>
<tr>
<td></td>
<td>$2 \times 2$ all-optical switch</td>
<td>-22.9</td>
<td>-22.9</td>
</tr>
</tbody>
</table>

As can be seen, high extinction ratio and low insertion loss were obtained for the designed switches. The observed values for the proposed $2 \times 2$ switch presented a considerable enhancement in comparison with two other switches. The other parameters, such as switching light intensity, switching speed, and dimensions of switches, were also considered for the design of structures. Different values of these parameters for the designed structures are given in Table 2.

Table 2. The comparative results.

<table>
<thead>
<tr>
<th>Switches</th>
<th>$1 \times 1$ proposed switch</th>
<th>$1 \times 2$ proposed switch</th>
<th>$2 \times 2$ proposed switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (Ps)</td>
<td>$\approx 1$</td>
<td>$\leq 2$</td>
<td>$\leq 4$</td>
</tr>
<tr>
<td>$I$ (W/\mu m)</td>
<td>17</td>
<td>11</td>
<td>6.5</td>
</tr>
<tr>
<td>Dim. ($\mu m^2$)</td>
<td>$62 \times 21$</td>
<td>$67 \times 21$</td>
<td>$72 \times 21$</td>
</tr>
<tr>
<td>Er (dB)</td>
<td>-19.8</td>
<td>-14.24</td>
<td>-17.53</td>
</tr>
<tr>
<td>Loss (dB)</td>
<td>-0.17</td>
<td>-0.9</td>
<td>-0.45</td>
</tr>
</tbody>
</table>

In terms of switching speed, PTS crystalline-based switches outperform the other samples [12–14] up to several picoseconds. It is worth mentioning that lower light intensity was required for switching due to the use of PTS with high nonlinearity characteristics. As can be observed from Table 2, minimum size ($72 \times 21 \mu m^2$) is achieved for the designed switches. Moreover, these designed switches are found to have integration capability in the integrated optical switch and WDM networks with respect to the very small size and the ultrahigh speed.

5. Conclusion
In this paper, we have designed three optimized all-optical switches based on photonic crystals to achieve high switching speed and low consuming power. Minimum switching loss is considered in the design of a photonic crystal to obtain the optimized structure. Therefore, all components of the switch such as bends, splitters, and waveguides are designed in such a way to achieve the maximum output power and minimum loss. First, we have designed $1 \times 1$ all optical switch based on MZI. One polymeric material with high nonlinearity Kerr effect
is used in one arm of the MZI to make a nonlinear structure. In order to achieve a high performance $1 \times 2$ switch, a directional coupler is designed with vertical bends to eliminate ring mode loss in the outputs of MZI. Finally, we have designed one $2 \times 2$ switch with various applications in WDM with respect to the designed switch dimensions. These structures are found to have high switching speed (less than 4 picoseconds), the low insertion loss of about $-0.09 \text{ dB}$ and the high extinction ratio of $-22.9 \text{ dB}$ for the $2 \times 2$ switch. These switches also have potential to provide good performance in integrated photonic crystal circuits.

References


