Slow Light Propagation in Photonic Crystal-Based Meandering Delay Lines Using the PTS Material

Abstract

In this paper, rectangular and triangular photonic crystal (PC) delay lines are designed using PTS (p-toluene sulfonate) at $1550\,nm$. PTS possesses a high nonlinear refractive index; consequently, when it interacts with an incident light, it provides slow light propagation in a PTS-based device due to the Kerr effect. First, a PC waveguide (PCW) is designed by introducing a line defect made of PTS bars. Such a defect, by using PTS, provides two significant advantages; these include slow group velocity and extremely high optical confinement for a propagating wave through the PCW. Then, two similar PCWs are placed next to each other to investigate the crosstalk phenomenon between them. By choosing an appropriate distance between them, the rectangular and triangular PC reflective meandering delay lines are realized. The rectangular lattice PC reflective meandering delay line exhibits lower propagation losses because this lattice shows a higher transmission coefficient at the corners in comparison to the triangular one. On the other hand, the triangular lattice PC reflective meandering delay line provides very low group velocity for a propagating light-wave at the wavelength of $1550\,nm$; as a consequence, a higher slowing factor is achieved for the triangular lattice PC reflective meandering delay line due to the stronger light-PTS interactions. Simulations are performed using LUMERICAL FDTD SOLITION v8.15

Keywords

Slow light; Meandering; Delay line; PTS; Nonlinear.

1 Introduction

Slow light phenomenon provides ultra compact, low loss, and highly sensitive devices [1-3]. The field of slow light has received significant attention in recent years as it is important for emerging areas in integrated photonics [4–6]. Excitation of slow light has been used for many applications such as Electromagnetically induced transparency [6], stimulated Brillouin scattering [7], stimulated Raman scattering [8], waveguides [2], photonic beamformer circuits [5], etc. However, the mentioned applications usually need complex systems and the operation under certain conditions [9–11]; further, some of them require a complicated nanofabrication process. In contrast, photonic crystal (PC) is a suitable platform for realizing slow light in a waveguide configuration exhibiting striking advantages in comparison to the mentioned applications, such as room-temperature operation, on-chip integration, and so on [12-15].

PC is a medium wherein the refractive index changes periodically; consequently, it possesses a position-dependent refractive index. Hence, photons in a PC experience a periodic behavior when they pass through such a medium. Similarly, in a semiconductor, electrons experience a periodic potential because of the crystalline structure. This periodic potential allows electrons to occupy particular energies, leading to the formation of an electronic bandgap in the band diagram of a semiconductor. Accordingly, the periodic refractive index in a PC creates a photonic bandgap (PBG) forbiding the propagation of certain photons, depending on their wavelength. A PC waveguide (PCW) is formed via the creation of a linear defect in its structure; an incident wave can be propagated through this PCW only when the associated wavelength falls into the PBG of the original PC. Under these circumstances, some extremely high optical confinement can be achieved for a PCW, as compared to other waveguides; furthermore, a PCW can provide light propagation through sub-wavelength scales; so, such a platform offers promising opportunities for the implementation of nanophotonic devices.

PC, due to its unique PBG, has attracted great attention as a new platform for optical communications [16,1,8]. The mentioned fascinating feature of PCs results from their geometrical structures, rather than atomic characteristics [13,17,18]. By properly designing a PC, the group velocity of a propagating light-wave can be considerably reduced; for instance, this phenomenon can be observed close to the Brillouin zone's edge [19–21]. Recently, some works have been done to optimize the performance of PCWs for the excitation of slow waves. Kurt et al. [21] proposed a new PCW in which the slow light propagation was enhanced by modifying the hole size of PCs. Liang et al. [22] also modified the slow light propagation in a

PCW via adjusting the hole position. Additionally, it is possible to optimize the slow light properties in a PCW through the hole shape [14]. In addition, a rectangular lattice PC meandering delay line was designed at the wavelength of $1.55\mu m$ in [23]. Finally, in [15], this goal was achieved by changing the holes' refractive index in a PCW.

Although the mentioned techniques have enhanced the wave propagation in a PCW, they can not provide high delays for a constant length. In other words, in order to achieve high delays in the order of few picoseconds by using the mentioned works in the literature, the PCW length must be increased; however, this requires providing large sizes for PCWs. Moreover, to achieve a compact size for realizing a delay line, it is necessary to employ a meandering path for connecting PCWs. However, for such a structure, some extremely high optical confinement must be achieved to minimize the coupling between the adjacent PCWs. One solution to achieve both the exceedingly high optical confinement and the slow light propagation is the use of nonlinear materials for constructing a PCW. PTS exhibits a controllable nonlinear refractive index tuned via the power of an incident light-wave which can interact with light, providing the slow light propagation in a PCW.

In this paper, rectangular and triangular lattices PC reflective meandering delay lines are designed using PTS; this provides two significant advantages: the exceptionally high optical confinement and the great slow light factor. The delay lines are made of a number of cascaded PCWs achieved by introducing a liner defect using PTS in PCs. Moreover, during these designs, two optimization processes are implemented in order to minimize the scattering losses in the corners of the delay lines; additionally, crosstalk between the adjacent PCWs is maintained as low as possible. Eventually, the designed delay lines are evaluated by some figures of merit such as the slowing factor and the insertion loss. The slowing factor represents the extent to which the group velocity of a propagating light has been reduced; the insertion loss stems from light scattering, especially at the corners. It should be noted that simulations are performed using LUMERICAL FDTD SOLITION v8.15.

This paper is organized as follows: In Section 2, materials and methods are provided for designing the reflective meandering delay lines. In Section 3, simulation results are presented to analyze the delay lines. Finally, the conclusion is drawn in Section 4.

2 Materials and Methods

In order to utilize PTS for designing a PCW supporting the slow light propagation, it is necessary to analyze this material to reveal how it interacts with a propagating light. Although a meandering path provides higher delays, it exhibits greater propagation loss, especially at corners; furthermore, the crosstalk occurs in such a delay line, resulting from the coupling between the neighbourhood PCWs. Here, two different configurations are considered for PCs, i.e. rectangular and triangular lattices. For the rectangular lattice PCs, silicon bars are suspended in free space, while for the triangular lattice, air holes are drilled into a silicon substrate. It is well-known that the rectangular lattice PCs only support transverse electric (TE) propagation modes, whereas the triangular lattice PCs are capable of supporting both TE and transverse magnetic (TM) propagation modes.

2.1 Kerr effect

In this Section, the Kerr effect is employed to control the refractive index of PTS by the intensity of the incident wave. Polarizability is the ability to create instantaneous dipoles in a dielectric medium in response to an applied electric field. This property determines the dynamic response of a bound system to the applied fields. Dielectric polarizability is defined as the dipole moment per unit volume of the crystal cell. The Kerr effect is caused due to a nonlinear process in materials; the polarizability of materials is nonlinearly related to the applied electric field $E(t)$, as follows [24]:

$$\vec{P}(t)=\varepsilon_0(\chi\text{¿¿}(1)+\chi^{(3)}\left|\vec{E}(t)\right|^2)\vec{E}(t)\text{¿} \quad (1)$$

, where ε_0, $\chi^{(1)}$ and $\chi^{(3)}$ represent the permittivity of free space, the first order and the third order of the electric susceptibility, respectively. Electric flux density $D(t)$ is related to the applied electric field and the induced polarizability $P(t)$ [24]:

$$\vec{D}(t)=\varepsilon_0\vec{E}(t)+\vec{P}(t) \quad (2)$$

By inserting (1) into (2), the following relationship is obtained:

$$\vec{D}(t)=\varepsilon_0(\varepsilon_r+\chi^{(3)}\left|\vec{E}(t)\right|^2)\vec{E}(t) \quad \textbf{(3)}$$

, where ε_r represents the relative permittivity, which is defined as $\frac{\varepsilon}{\varepsilon_0}$. The nonlinear dependence in (3) can be simplified by using the following approximation:

$$\chi^{(3)}\left|\vec{E}(t)\right|^2 \ll \varepsilon_r = 1 + \chi^{(1)} = n_1^2 \tag{4}$$

Therefore, the nonlinear refractive index is obtained by applying this assumption as

$$n = \left(\varepsilon_r + \chi^{(3)}\left|\vec{E}(t)\right|^2\right)^{1/2} \cong n_1\left(1 + \frac{\chi^{(3)}\left|\vec{E}(t)\right|^2}{2n_1^2}\right) = n_1 + n_2 I \tag{5}$$

, where n_1, n_2 and I describe the linear refractive index, the nonlinear refractive index and the electric field intensity of the incident wave, respectively. If the relationship between the intensity and amplitude of the electric is considered similar to that in a plane wave, then

$$I = \frac{c\,\varepsilon_0 n_1}{2}\left|\vec{E}(t)\right|^2 \tag{6}$$

, where c refers to the speed of light in vacuum. Finally, it is a straightforward task to show that the nonlinear refractive index can be expressed in terms of the nonlinear susceptibility as follows:

$$n_2 = \frac{\chi^{(3)}}{n_1^2}\eta_0 \tag{7}$$

, where $\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$ denotes the intrinsic impedance of vacuum. The presented equations can be used for interpreting the experimental results because such datasets are usually measured based on the refractive index. Moreover, these relationships offer useful transformations for converting the experimental materials constituting parameters to a desired format which can be readily imported into solvers.

2.2 PTS material

PTS is a single crystal material for all-optical applications at the $1.32\,\mu m$ communications wavelength; its nonlinearities and electronic properties have been measured by picosecond pulses [25]. For ultra-fast switching applications, materials must satisfy some figures of merit. First of all, they must exhibit a large and nonresonant nonlinear refractive index necessary to satisfy the condition of $n_2 > 10^{-12} cm^2/W$ [26]. Secondly, they must provide a π phase shift over $1/e$ attenuation distances when the device throughput is reasonable. These requirements have been implicitly embodied in two figures of merit, i.e., $w = n_2 I_{sw}/(\alpha_1 \lambda) > 1$and $T = \alpha_2 \lambda / n_2 < 1$, where α_1, α_2, I_{sw} and λ refer to the one, two absorption coefficients, the required intensity for obtaining a phase shift of 2π, and the wavelength of the incident light, respectively [25]. Finally, they must exhibit an acceptable thermo-optic coefficient at the operating wavelength.

PTS satisfies all the required conditions mentioned above, because it exhibits$T < 1/27$, $n_2 = 2.2 \times 10^{-12} cm^2/W$ at $1.6 \mu m$ [25]. It will be shown later that this material plays an important role in designing reflective meandering delay lines, because it confines the propagating light in a PCW; furthermore, it provides the slow light propagation. These two features are vital for achieving a high performance reflective meandering delay line.

2.3 Slow light in PCs

The coupling phenomenon in the meandering delay lines is also known as the crosstalk; it should be maintained as low as possible. As a result, some strategies should be employed in order to mitigate this problem; otherwise, the crosstalk between the adjacent PCWs disturbs the operation of such delay lines. Increasing the distance between the adjacent PCWs is the simplest way to tackle this problem, but this increases the size of the meandering delay lines. Another strategy is the use of materials with a high nonlinear refractive index along the meandering path to confine the propagating light. If appropriate materials are chosen for this purpose, in addition to the confinement of light, the slow light propagation may also be achieved. These features are desirable for designing a meandering delay line. The slow light propagation is caused due to the Kerr effect and plays an important role in the evaluation of the delay lines performance. In this paper, PTS is utilized to create a linear defect in PCs, resulting in a PCW supporting the slow light propagation.

As mentioned in Section 2.1, due to the Kerr effect, the nonlinear refractive can be controlled through the incident power. If this feature is properly employed in a PC, very small group velocities are achievable in a PCW. To illustrate this, let's consider a x-directed plane wave propagating in a PCW whose dispersion relation is $\omega(k)$. Moreover, the phase difference $\delta\varphi$, due to the variation of the refractive index δn (the primary refractive index of this structure is n_1), is $\delta\varphi = L.\delta k$ and can be expressed as follows [27]:

$$\delta\varphi \approx L.\delta\omega / \left(\frac{\partial\omega}{\partial k}\right) = \left(\frac{L}{v_g}\right)\left[-\omega_0\left(\frac{\delta n}{n_1}\right)\right] \qquad \textbf{(8)}$$

, where ω_0, k and $v_g$stand for the radian frequency, the wave vector and the group velocity, respectively. Since for PTS, we have$\delta n = n_2 I$, athe phase difference in terms of the free space wavelength λ_0 is expresses as follows:

$$\delta\varphi = -\left(\frac{2\pi}{\lambda_0}\right).L.\left(\frac{c}{v_g}\right)\left(\frac{n_2}{n_1}\right).I \qquad \textbf{(9)}$$

, where λ_0 describes the wavelength in the free space. Eq. (9) states two important points about PCs. First of all, in order to achieve higher delays in PCs, three approaches are available: the utilizing materials with large nonlinear refractive indices, increasing the applied laser power, and decreasing the group velocity of light. Secondly, some applications such as a PC-based Mach Zehnder interferometer need the phase difference π; according to (9), it is clear that this goal can be achieved by increasing the group velocity of the propagating light. Consequently, for such applications, by employing this technique, the required length for providing this phase difference is decreased, which is suitable for integrated optical circuits.

Slowing (miniaturization) factor is defined as the ratio of phase velocity, V_φ, to group velocity, V_g, as follows:

$$SF = V_\varphi / V_g \qquad (10)$$

This factor represents the ability of a structure to decrease the group velocity based on a propagating light-wave. If the bandwidth and dispersion characteristics of a system are also included, it can be found that the slowing factor depends on the refractive index difference in the structure [28]. Therefore, by increasing the refractive index difference in PCs, the associated slowing factor will be enhanced.

3 Design and Simulation

Two of the most commonly used configurations for PCs are rectangular and triangular lattices, as depicted in Fig. 1. As shown in Fig. 1(a), the rectangular lattice PCs consist of suspended Si rods in air which can only support TE propagation modes (for these modes, the electric field is polarized along the rods). In contrast, the triangular lattice PCs are made of air holes drilled in the Si substrate, as depicted in Fig. 1(b), which can support both TE and TM propagation modes. It will be shown that a rectangular lattice PCW exhibits a better performance at corners because it provides a higher transmission coefficient at corners.

The finite difference time domain (FDTD) method is a papular method used for simulating complex structures like PCs. This method possesses simple formulism for analyzing a structure which can be applied to nonlinear media. However, the well-known plane wave expansion method can only be used for simulating PCs containing the linear media. The FDTD method uses perfect matched layer (PML) boundary conditions (BCs) to truncate the simulation domains; additionally, in the case of periodic structures, it employs Bloch BCs to speed up the simulation process. Moreover, the FDTD method offers various excitation sources; here, a gaussian pulse is used to excite the PCs shown in Fig. 1, which can be modulated by a sinusoidal carrier as follows:

$$p(t) = \exp ¿ \tag{11}$$

, where τ and λ represent the pulse width and the wavelength of the gaussian pulse, respectively. Simulations are performed using LUMERICAL FDTD SOLITION v8.15. This electromagnetic solver is a 3D solver computing electromagnetic fields based on the FDTD method.

3.1 Rectangular lattice PCs

In order to compute the band diagram related to the PCs, some considerations should be noted. First, the selection of the unit cell observed in Fig. 1 should be taken into account. Second, it is necessary to excite the unit cells by appropriate sources; in this study, some dipole sources are placed in the unit cells. However, the location of dipole sources should be chosen so that all possible modes could be excited.

Fig. 1

Let's compute the band diagram for the rectangular lattice PCs shown in Fig. 1(a). Since the FDTD boundaries are rectangular, only one unit cell is required for the simulation of the rectangular lattice PCs, as shown in Fig. 1(a). Although PML BCs can be employed to simulate the rectangular lattice PCs, they require a larger simulation area to accurately model the wave propagation in the PCs; consequently, the computation time is exceedingly increased. To resolve this issue, the Bloch BCs are used instead in this situation, such that only one unit cell of the rectangular lattice PCs is sufficient for computing the associated band diagram. To achieve the widest bandgap, an optimization process is performed for calculating the lattice parameters shown in Fig. 1(a). For $r/a_x=0.179$, the widest PBG is achieved; its center is located at $a_x/\lambda=0.37$. To achieve the largest bandwidth for this lattice, the working wavelength of $1.55\,\mu m$ is selected at the center of the calculated PBG. Therefore, the lattice constant and the rods radius are obtained as $a_x=a_y=574\,nm$ and $r=103\,nm$, indicating that a square lattice is employed for realizing a delay line.

Although Bloch BCs are used to extract the band diagram of the PCs, in this situation, the speed of the simulation process is significantly enhanced; they can not be used when introducing some defects in the PCs. Hence, PML BCs are utilized instead, especially when a linear defect is introduced for constructing PCWs. In this situation, the simulation boundaries are placed far away from PCWs to ensure that evanescent waves are properly absorbed; this is because PML BCs are impedance matched to the simulation region and its materials in order to minimize reflections [29,30]. Furthermore, some frequency monitors are employed to record fields using the Fourier transform to convert the time-dependent signals into frequency-dependent ones. For these monitors, apodization is utilized to exclude effects which occur near the start and/or end of the simulation from the monitors.

Fig. 2

By keeping these considerations in mind, a PCW with the rectangular lattice is designed by introducing a linear defect; three different configurations are considered for this purpose. One of these configurations is obtained by removing a row of the Si rods and the other configuration is realized when a row of the Si rods is replaced by a row of Si rods with a smaller radius. The last one is the same as the second configuration; however, in this configuration, the smaller rods are made of PTS. By investigating the wave propagation in the mentioned configurations, it can be concluded that the latter configuration exhibits the best performance because it provides high optical confinement and the slow light propagation, simultaneously. This configuration can be observed in Fig. 2(a),. The PTS radius is chosen such that a more uniform dispersion characteristic is achieved for the PCW whose value is $0.15\,a_x$.

Fig. 3

Fig. 4

Afterward, the crosstalk phenomenon is investigated, which is a major drawback of meandering delay lines. To this end, the distance between the two parallel PCWs is changed. Obviously, a trade-off exists between the crosstalk and the packing density of waveguide channels. An appropriate schematic for this purpose is shown in Fig. 3(a), where the radius of the PTS rods is $0.15\,a_x$. In Fig. 4, the electric field contour map is computed for the two parallel PCWs, where D is $3\,a_x$. One can observe that in this situation, the incident wave launched at the port P_i is completely coupled to the bottom PCW after travelling the coupling length. This phenomenon is undesirable for a reflective meandering delay line and must be avoided under any condition; this is because it disturbs the operation of the delay lines. To find an appropriate distance between the two adjacent PCWs, the distance between the two PCWs is varied and transmittance (T_C) and coupling (C_C) coefficients are calculated as follows:

$$T_c = \frac{\int P_o(t)\,dt}{\int P_i(t)\,dt} \qquad \textbf{(12)}$$

and

$$C_c = \frac{\int P_c(t)\,dt}{\int P_i(t)\,dt} \qquad (13)$$

, where P_i, P_c and P_o denote the power of the incident, coupling and output ports, respectively, as depicted in Fig. 3.

Fig. 5

Fig. 5 shows the coupling coefficients of the structures shown in Fig. 3 as functions of the distance between the two parallel PCWs. Apparently, the crosstalk between the two parallel PCWs shown in Fig. 3(a) has a negligible influence on $D=6a_x$. It is worth noting that for this selection, the assumption of neglecting the crosstalk is only valid when the length of the PCWs is $20a_{x;}$ clearly, if this length is increased, D must be increased too. As a result, for this length, the two adjacent PCWs can provide a meandering path for the propagation of an incident light-wave in which the coupling phenomenon does not take place throughout their lengths.

Fig. 6

To connect the adjacent PCWs, it is necessary to use bent PCWs which introduce several sharp bends in a PC-based meandering delay line. Most of propagation losses in a PC-based meandering delay line are caused due to multiple reflections and scattering losses at the associated bent PCWs. Consequently, some modifications should be applied at all corners to reduce propagation losses as much as possible. Fig. 6 depicts the proposed configuration for modifying all corners of the rectangular lattice PC reflective meandering delay line. In this configuration, some PTS rods are added to mitigate the transmission characteristic of the corners; for this geometry, the transmission coefficient of 99.1% is achieved, whereas for the unmodified corners, the transmission coefficient of 93% is obtained. In Fig. 6, the primary reflective meandering delay line can be observed and the associated electric field profile is shown in Fig. 7. One can see that the incident wave is properly confined along the PTS rods; furthermore, the crosstalk between the PCWs does not occur in this structure. By using this procedure, it is possible to design the final meandering delay line constructed by adding more PCWs. These PCWs are in series connected via the bent PCWs. In Fig. 8, the field contour map for the final reflective delay line is drawn. In Fig. 9, the electric field's envelop of the propagating wave can be observed; one can see that the delay of $8.785\,ps$ and the loss of $0.71\,dB$ are obtained for this delay line.

Fig. 7

Fig. 8

Here, for computing the slowing factor, c is assumed to be the speed of light in free space. Moreover, v_g is calculated according to the obtained delay; as a result, the slowing factor is obtained as follows:

$$SF = c/v_g = c/(L_t/Delay) \quad \textbf{(14)}$$

The rectangular lattice PC meandering delay line consists of 184 PTS rods, meaning that the total length of this structure becomes $L_t = 184 \times a_x$. Hence, by considering the delay of 8.785 ps according to Fig. 9, the slowing factor for the rectangular lattice PC reflective meandering delay line is 24.95.

Fig. 9

3.2 Triangular lattice PCs

In Fig. 1(b), triangular lattice PCs are shown to consist of air holes drilled into the Si substrate. It possesses the lattice constant of a; additionally, the two adjacent rows are separated by the distance of $b/2$, where b is equal to $\sqrt{3}a$. It is worth mentioning that the triangular lattice PCs can also support TM propagation modes if the materials of the rods and the substrate are interchanged. In addition, the calculation of the related band diagram is the same as that of the rectangular lattice; however, in this case, as shown in Fig. 1(b), we must choose two unit cells; this is because in the FDTD method, rectangular boundaries are usually considered for the simulation region. Both the existence and width of the PBG in PCs depend on the ratio of r/a. Simulation results reveal that in this structure, there exists a PBG located in the range of $0.2\,a/\lambda$ and $\frac{0.28\,a}{\lambda}$; additionally, for $r/a = 0.278$, the widest PBG is achieved. By setting the working wavelength of $1550\,nm$ at the center of the PBG, the lattice constant and the rods' radius are obtained to be $360\,nm$ and $100\,nm$, respectively.

Afterward, a linear defect in the triangular lattice PCs is created, as shown in Fig. 1(b). Similar to the rectangular lattice, it is found that to achieve a better dispersion characteristic for the PCW, a row of air holes should be replaced by a row of PTS rods, such as a PCW depicted in Fig. 2(b); the radius of the PTS rods is $0.15a$. In other words, in this case, the PCW is capable of supporting the slow light propagation due to the Kerr effect. Then, according to Fig. 3(b), an appropriate distance should be selected for the parallel PCWs; as mentioned before, two important notes should be taken into account. In this regard, the crosstalk between the parallel PCWs throughout their lengths must be minimized; at the same time, the size of the delay line should be maintained as small as possible. Fig. 5 depicts the coupling coefficient as a function of D/b. It is found that the proper distance is $3b, such$ that the corresponding coupling coefficient is $-21.1\,dB$.

Fig. 10

Now, we are in a position to construct a triangular lattice PC reflective meandering delay line; however, before that, its corners should be modified to enhance their transmission characteristic. Therefore, a new structure coincident with the triangular lattice is proposed. This structure is named drop hole; its structural parameters are depicted in Fig. 10. This idea arises from a configuration consisting of some rods with a decreasing radius along an arbitrary straight line. Fig. 11 shows a primary triangular lattice PC delay line; its corners are modified by using three drop holes. In Fig. 11, the related parameters for the middle drop hole are $\theta=0, L=2a$ and $r_2=0.325a;$ for the upper one, they are $\theta=30, L=1.85a$ and $r_2=0.33a$. Finally, for the lower drop hole, they are $\theta=30, L=1.85a$ and $r_2=0.33a$. The transmittance coefficient for the middle drop hole is 97.5%, whereas for the other drop holes, it is 96.9%.In contrast to the primary rectangular lattice PC reflective meandering delay line, which possesses two sharp corners, the triangular lattice PC delay line has three sharp corners; as a result, more propagation losses are obtained for the latter case.

Fig. 11

Fig. 12

In Fig. 12, the distribution of the electric field of the final triangular lattice PC reflective meandering delay line can be observed. Obviously, for this delay, more propagation losses are obtained in comparison to the rectangular lattice PC delay line because the former case has more sharp bends; further, the latter case exhibits a better performance at corners. In Fig. 13, the electric field envelop of the triangular lattice PC reflective meandering delay line versus time is shown. It is apparent that the propagation losses of $3.45\,dB$ and the delay of $7.45\,ps$ are achieved for this delay line. This delay line consists of 216 PTS rods, indicating that the total length of this structure is $L_t = 216 \times a$. As a result, the slowing factor for this delay line is 28.74, approximately twice more than that for the rectangular lattice PC delay line. This is due to a number of reasons. The first reason is that these lattices possess two different band diagrams; additionally, when a similar defect is introduced in these lattices, it is clear that two different dispersion relations are obtained for the resulting PCWs. At the operating wavelength of $1.55\,\mu m$, the dispersion relation of the triangular lattice PCW is closer to the Brillouin zone's edge; as a consequence, it can supportmodes possessing lower group velocities. The second reason is that the number of sharp bends in the triangular lattice PC delay line is greater; therefore, propagating waves have more interaction with the PTS rods; this results in higher refractive indices for these modes. However, the rectangular lattice PC reflective meandering delay line exhibits lower propagation losses.

Fakharzadeh et al. [23] proposed a square lattice PC meandering delay in which the achieved delay and the slowing factor were $1.99\,ps$ and22.2, respectively. In contrast, our designed rectangular lattice PC reflective meandering delay line provided the delay of $8.785\,ps$ and the slowing factor of 24.95; moreover, the triangular lattice PC reflective meandering delay line exhibited the delay of $7.45\,ps$ and the slowing factor of 28.74.

Fig. 13

Conclusion

Here, rectangular and triangular lattices PC reflective meandering delay lines were designed. PTS was employed to create a linear defect in the rectangular and triangular lattices PCs, such that the propagating light was confined along the PCWs; also, the slow light propagation was achieved due to the Kerr effect. To avoid the crosstalk between the adjacent PCWs, the distance between them was sufficiently increased, so that an incident light could be properly propagated in the meandering pathes. In order to enhance the transmission coefficient of corners regarded as sharp bends in the delay lines, two configurations were proposed for this purpose. High slowing factors were achieved for these delay lines in comparison to delay lines in the literature. In Table 1, these delay lines are compared to highlight their properties. Obviously, the triangular lattice PC delay line provides a greater slowing factor, whereas the rectangular lattice PC delay line exhibits a better performance at corners.