

A Novel Flat Band Slow Light in Photonic Crystal Waveguide with Elliptical Air Holes

Vali Varmazyari¹, Hassan Ghafoorifard^{1,2} and Hamidreza Habibiyan¹

¹ Photonics Engineering Group, Amirkabir University of Technology, Hafez Ave, Tehran, Iran

² Department of Electrical Engineering, Amirkabir University of Technology, Hafez Ave, Tehran, Iran
habibiyan@aut.ac.ir

Abstract: In this paper, a procedure for generating wideband and low dispersion slow light in photonic crystal waveguide (PCW) with elliptical air holes is presented. By optimization of major and minor radii of ellipse rods in the line defect waveguide, the maximum value of normalized delay-bandwidth product (NDBP) is obtained. The simulation results and numerical calculations are performed by plane wave expansion method. By adjusting the structural parameters, a slow light with nearly constant group index of 15.1 and a bandwidth over 26 nm is acquired for central wavelength of 1550 nm. For optimized structure, the maximum NDBP of 0.253 is achievable. Moreover, the buffer capability and signal transmission characters of the PCW, is discussed.

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1. Introduction

The growth of all-optical technologies is essential for developing future telecommunication networks, where tunable delay lines are required for the synchronization of optical signals and signal buffering. In recent years, extensive researches have focused on slow light and its properties, in which speed of optical pulse is dramatically reduced in comparison with the velocity of light in vacuum c . It can be used for the enhancement of light-matter interaction. Slow light has various applications such as magnetic Faraday rotation, nonlinear effects (higher harmonic generation, wave mixing, etc.), and also is used in the design of controllable optical delay lines, phase shifters, modulators, miniature and efficient optical amplifiers and lasers, biosensors, ultrasensitive optical switches, quantum all-optical data storage and data processing devices, etc.

The most important issue for a slow light device is the group velocity v_g , group index n_g and group velocity dispersion (GVD). The group index is the index which indicates the deceleration of propagating pulse in medium [1]. The group velocity of a propagating pulse is calculated as the derivative of the angular frequency over the wavevector [1].

$$v_g = \frac{d\omega}{dk} = \frac{c}{n_g} \quad (1)$$

$$n_g = n + \omega \frac{dn}{d\omega} \quad (2)$$

where ω is the light frequency, c is the velocity of light in vacuum and k is the propagation constant. Another important parameters in slow light devices is group velocity dispersion (GVD) which can cause

significant distortion in short optical pulses. GVD parameter β_2 is expressed by the second order derivative of the dispersion relation as [2]:

$$\begin{aligned} \beta_2 &= \frac{d^2k}{d\omega^2} = -\left(\frac{1}{v_g}\right)^3 \frac{d^2\omega}{dk^2} \\ &= \frac{1}{c} \frac{dn_g}{d\omega} \end{aligned} \quad (3)$$

In order to evaluate the capacity of slow light PCWs, the normalized delay bandwidth product (NDBP) is used to represent the trade-off between group velocity and slow light bandwidth. The NDBP is given as [3]:

$$NDBP = n_g \times \frac{\Delta\omega}{\omega_0} \quad (4)$$

where $\Delta\omega/\omega_0$ is the normalized bandwidth of a slow light region and n_g is the average group index.

The slow light experiment was demonstrated by Hau *et al* by using electromagnetically induced transparency (EIT) effect [4]. This experiment was performed in gas medium at the temperature of 450 nK where group velocity reached to 17 m/s. Several different approaches have been reported in order to create a slow light medium e.g. coherent population oscillation (CPO) [5-7], stimulated Raman scattering (SRS) [8, 9], stimulated Brillouin scattering (SBS) [10-12] and photonic crystals (PCs) [1-3], [13-35].

Photonic crystals, due to their capabilities of guiding and controlling light propagation on a wavelength scale, and compatibility with CMOS technologies, have attracted a great deal of interest.

These unique characteristics may lead to miniaturization and large scale integration of optical devices. Within the past years, many efforts have been reported in the context of photonic crystal-based slow light devices using various methods such as line defect waveguides and coupled cavity waveguides. Photonic crystal (PC) slow light devices have many advantages such as operating at room temperature and the ability to attain desired communication wavelength by engineering of the structural parameters. Also photonic crystal slow light waveguides are suitable for enhanced light-matter interactions.

Several novel methods have been used to design slow light PCWs; for example, Notomi *et al* reached the group velocity of $c/90$ by changing the width of the waveguide in a conventional PCW formed by removing one line of air holes [13]. Ma and Jiang designed an asymmetrical line-defect waveguide, which is formed by shifting the holes in the bottom PC cladding along the waveguide axis and reached the group velocity of $c/50$ and the bandwidth of 40 GHz [14]. Rawal *et al* reported the design of a SOI-based partially liquid-crystal infiltrated photonic crystal channel waveguide with rectangular air holes and achieved the average group index of 43 over a bandwidth of 1.02 THz [17]. Hou *et al*, in a symmetric line defect PCW, obtained high average group index of 74.4 with 2.3 nm bandwidth [21]. O'Brien and his colleagues, in a chain of 10 coupled photonic crystal heterostructure nanocavities which were fabricated using standard silicon processing technology, measured the group velocity of $c/140$ over a bandwidth of 1 nm [26]. Monat and his colleagues reported nonlinear measurements on 80 μm silicon photonic crystal waveguide that were designed to support dispersion-less slow light with group velocities between $c/20$ and $c/50$ [28].

This paper is structured as follows. In section 2, the proposed line defect PCW is introduced and we study the slow light property by adjusting the major and minor radii of the ellipse rods and also the optimization of NDBP is presented. Section 3 discusses the optical buffer applications of the PCW. Finally, the conclusions on the results of optimization of the slow light property in PCW are presented in Section 4.

2. Proposed structure and numerical simulation

A. Basic structure

Figure 1 is the suggested structure for producing slow light which consists of SOI platform perforated by triangular lattice of elliptical air holes with lattice constant $a = 404$ nm in a dielectric silicon background with refractive index of 3.46. The major and minor radii of ellipse holes are $L_a = a/2.5$ and $L_b =$

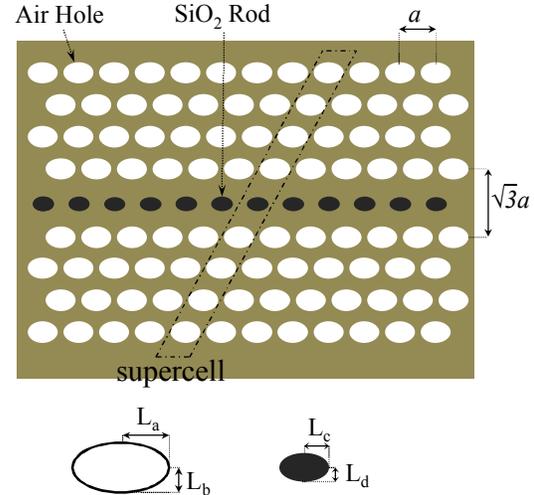


Figure 1. Schematic of the proposed slow light device. a , L_a and L_b , represent the lattice constant, major and minor radii of ellipse holes, Also L_c and L_d depict major and minor radii of line defect rods, respectively. The dashed line shows supercell used in computation of the designed SOI based structure.

$a/3.5$, respectively. The waveguide formed by filling one line of the holes by SiO_2 with refractive index of 1.44. Also the major and minor radii of ellipse rods in the proposed line defect PCW are L_c and L_d , respectively.

The dispersion relation of the proposed line defect PCW is calculated by the plane wave expansion (PWE) method. Figure 1, shows the selective supercell in numerical calculation for the presented structure.

Band structure of the above mentioned photonic crystal with the major radius of $L_a = a/2.5$ and the minor radius of $L_b = a/3.5$, are illustrated in Figure 2. As can be seen from the figure, the

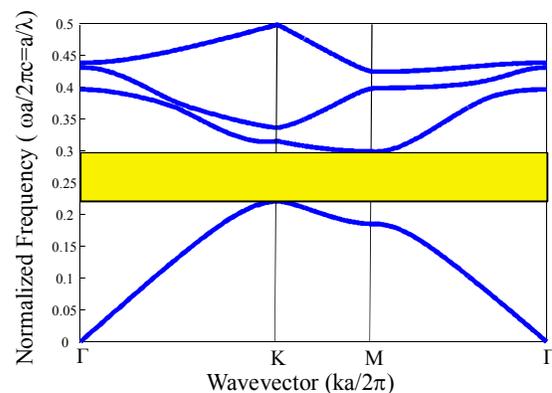


Figure 2. Typical band diagram for proposed triangular lattice of elliptical air holes in silicon background with major and minor ellipse holes radii of $L_a = a/2.5$ and $L_b = a/3.5$, respectively.

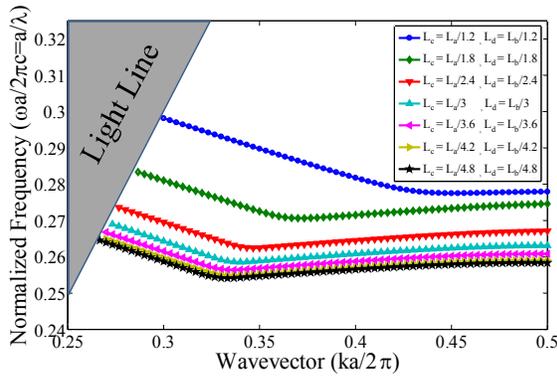


Figure 3. Projected band diagram of TE-like modes for various values of the major and minor radii of defects from $L_c = L_a/1.2$ to $L_c = L_a/4.8$ and $L_d = L_b/1.2$ to $L_b/4.8$, respectively. The grey zone shows the light line of clad.

presented structure has a bandgap for even modes (TE-like) ranging in the normalized frequency (a/λ) from 0.22 to 0.3. By making defects in one line of the holes, some modes will be created in PBG.

B. Optimization of NDBP

In this section, to study the effect of major and minor radii of ellipse rods on the slow light properties, the ratio of L_c/L_a and L_d/L_b are modified, while other structure parameters are the same as the basic structure. Also, L_c and L_d are optimized to achieve a maximum value of NDBP.

Figure 3 presents the dispersion curves of the main propagation modes of the line defect PC waveguides for TE-like modes. The linear photonic bands are below the light line in the PCW system, and this means a good light confinement in the vertical direction of the slab. As is clear, by decreasing radii of L_c ranging from $L_a/1.2$ to $L_a/4.8$ and L_d from $L_b/1.2$ to $L_b/4.8$, the bands will shift to lower frequencies. Also the slop of slow light region is increased.

Figure 4 shows the group index characteristics as a function of the normalized frequency. As is obvious from the figure, when L_c and L_d decreases, the group index values are decreased, but the slow light bandwidth are increased. For $L_c = L_a/3$ and $L_d = L_b/3$, the maximum bandwidth of 26 nm is obtained, but group index is relatively low, whereas the high n_g value of 59 can be obtained for $L_c = L_a/1.2$ and $L_d = L_b/1.2$ (with the bandwidth of 2 nm).

The normalized DBP dependencies on structure parameters are given in Figure 5. The values in the figure are extracted from the results of the group index and the bandwidth for various states. As

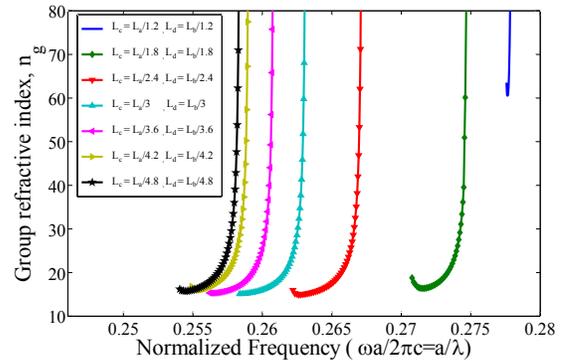


Figure 4. Group index variation as a function of normalized frequency for various values of the major and minor radii of line defects waveguide.

it can be seen, the NDBP is changed ranging from 0.081 to 0.253. In the proposed structure, the maximum NDBP of 0.253 with group index of 15.1 and slow light bandwidth of 26 nm at the centre wavelength of 1550 nm (for $L_c = L_a/3$ and $L_d = L_b/3$) is selected as the optimum result.

Figure 6 shows the GVD characteristics corresponding to the parameters in Figure 3. It is clearly shown that, there exists a bandwidth of “zero” dispersion in each situation, and by decreasing the major and minor radii of ellipse rods, the bandwidth of “zero” dispersion increases rapidly. These areas are corresponding to the areas with constant n_g as shown in Figure 4. The results show that the values of GVD parameter (β_2) of the presented structure for a different situation (with constant n_g) are in the order of 10^4 ps²/km and 10^5 ps²/km which is an acceptable GVD. Thus, the proposed structure in the different situation is suitable for pulse propagation with negligible dispersion in optical buffering applications.

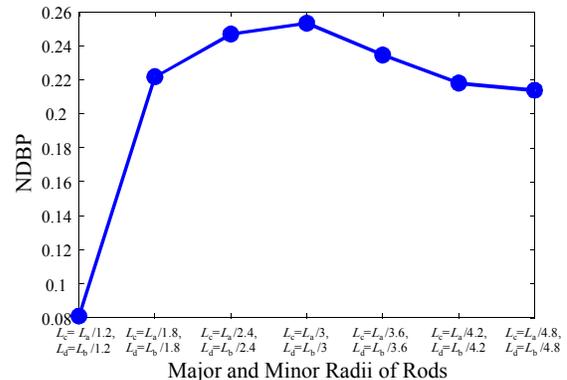


Figure 5. NDBP of the proposed structure as a function of L_c and L_d .

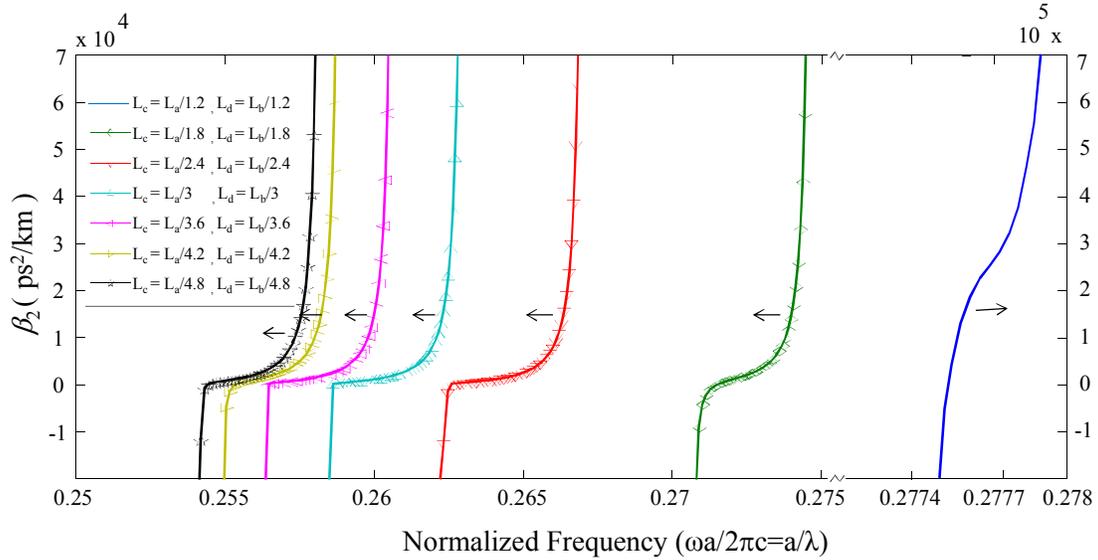


Figure. 6. Group velocity dispersion parameter (β_2) of the proposed structure as a function of normalized frequency for various values of the major and minor radii of line defects waveguide.

3. Optical buffer application

According to the previous section, the optimum NDBP of 0.253 was achieved for optimized value of the major and minor radii of ellipse rods ($L_a = 3 L_c$ and $L_b = 3 L_d$) in the proposed line defect PCW. In this section, we study the optical buffer capability of the PCW. There are some important parameters that characterize the overall performance of the buffer, for example, storage time T_s , buffer capacity C and physical size of the stored bit L_{bit} . If the length of delay line based on PCW is L , then the storage time is given by [35]:

$$T_s = L / v_g \quad (5)$$

Another important parameter is the buffer capacity. The capacity of the buffer is the maximum number of bits that the device can store, which is defined as [3]:

$$C = \frac{L}{2a} \times n_g \Delta \omega \quad (6)$$

The physical size of each stored bit, which affects the minimum size of buffer, is expressed by [2]:

$$L_{bit} = L / C \quad (7)$$

Table 1 summarizes the slow light parameters and buffer capabilities of the suggested PCW with different values of L_c and L_d . It can be seen that by changing the L_c and L_d in the range of $L_a/1.2$ to $L_a/4.8$ and $L_b/1.2$ to $L_b/4.8$, the slow light group index is varied from 59 to 14.8 over the bandwidth of 2 nm to 26 nm, respectively. Also central wavelength of propagating pulse is shifted from 1456 nm to 1581 nm. The important buffer parameters analyzed for a buffer length of 1 mm. When the major and minor

Table 1. Slow light parameters and buffer capability of the proposed PCW with different values of L_c and L_d

#	L_c	L_d	n_g	$\Delta\lambda$ (nm)	λ_0 (nm)	C (bit)	L_{bit} (μm)	T_s (ps)
1	$L_a/1.2$	$L_b/1.2$	59	2	1456	27	37	196
2	$L_a/1.8$	$L_b/1.8$	16.3	20.2	1485	74	13.6	54
3	$L_a/2.4$	$L_b/2.4$	14.8	25.5	1529	79	12.6	49
4	$L_a/3$	$L_b/3$	15.1	26	1550	81	12.3	50
5	$L_a/3.6$	$L_b/3.6$	15	24.5	1567	75	13.3	49.9
6	$L_a/4.2$	$L_b/4.2$	15.9	21.6	1575	72	13.8	53
7	$L_a/4.8$	$L_b/4.8$	15.6	21.6	1581	73	13.5	52

radii of rods modified, the buffer capacity and the physical size of each bit altered from 27 to 81 and 37 to 12.3, respectively whereas, the delay time of the propagating pulse varied from 196 ps to 49 ps.

4. Conclusion

In summary, we have discussed the slow light propagation in the line defects waveguide with a triangular lattice of elliptical holes. Different wavelength components can be slowed down along the propagation direction. In the proposed PC waveguide, by carefully choosing the major and minor radii of ellipse rods, a linear band structure appears from which the low group velocity and wideband slow light and ultralow GVD characteristics can be gained. Numerical calculations, by using PWE method, shows that in the proposed structure, the group index of 59 to 14.8, over the slow light bandwidth from 2 nm to 26 nm were achievable for central wavelength of 1456 nm to 1581 nm, respectively. Also, the NDBP value was achieved ranging from 0.081 to 0.253. Furthermore, the buffer parameters such as capacity and physical size of the stored bit and storage time of this structure were studied as well.

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Corresponding Author:

Vali Varmazyari

Photonics Engineering Group, Amirkabir University of Technology, Hafez Ave, Tehran, Iran

E-mail: habibiyan@aut.ac.ir

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9/12/2013