Modeling and simulation of optimized photonic crystal waveguide for slow-light enhancement

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Abstract. We present a novel type of slow-light photonic crystal waveguide prepared by changing only the position of the second rows of holes in the direction of light propagation of a line-defect photonic crystal waveguide. A nearly constant group index is achieved of 30, 31 and 32 over wavelength ranges of 10.4 nm, 13.5 nm and 14.5 nm, respectively. In addition, a large normalized-delay-bandwidth product ranging from 0.201 to 0.300 is obtained at the operation wavelength of 1550 nm.

1. Introduction

Slow light has recently attracted considerable interest for its promising properties in enhancing light-matter interactions allowing the design of highly sensitive and miniaturized devices [1-4]. The photonic crystal (PhC) line-defect waveguide is one of the most suitable and attractive structures for realizing a slow-light effect, and also offers various functionalities based on the photonic bandgap (PBG) [5]. The low group-velocity will be applicable to a delay-line or buffers [6-7]. However, a large group index in waveguides is only obtained in an extremely narrow bandwidth, while large group-velocity dispersion (GVD) effects accompany the slow light regime, which causes large signal distortion in the time domain [8]. An optimized PCW should have the following optical properties: first, a moderate group index when considering the equilibrium of slow-light properties and disorder-induced propagation loss; second, low chromatic dispersion, when considering the signal distortion; third, large operating bandwidth; and fourth, high normalized delay-bandwidth product (NDBP), when considering the equilibrium of group index and bandwidth [9]. Furthermore, modifications to the conventional PCWs have been proposed to decrease the GVD and higher-order dispersion [10]; the lattice modifications introduced with this purpose include modifying the hole size [11], altering the air-holes radius in the first two rows adjacent to the line defect [12], changing the hole shape [13]. Among these methods, shifting the air holes is considered to be the simplest one that can be controlled much more accurately [14].

In this paper we present a novel, simpler, and more flexible way of adjusting the PC waveguide geometry by shifting only the second rows adjacent to the line defect of the PCW in the direction of light propagation. A large bandwidth and a high NDBP can be achieved at high group index and low group-velocity dispersion.

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2. Design

Design and simulation are very important steps prior to fabrication[15]; the design proposed here is a photonic silicon-on-insulator (SOI) crystal slab with a thickness of 220 nm; the refractive index of silicon is $n_{si} = 3.48$. The slab is placed over a silica cladding, the top cladding being air, as shown in figure 1. The PhC is with a triangular lattice, where the lattice constant is $a = 392$ nm and the radius of the air holes is $r = 0.27a$ nm. The PCS has photonic band gaps in the x-y plane only; the index difference is used to confine the optical field in the z direction. The effective-index method (EIM) has been widely used to reduce the actual 3-D problem to a 2-D one [13]. Therefore, the effective index of the guided mode for the fundamental mode is 2.87 [14]. We obtained a photonic band gap for TE polarization in the normalized frequency range of $0.2436 – 0.2918$ ($\omega a/2\pi c$), as shown in figure 2 (a). Figure 2 (b) shows a selected supercell with one row of air holes in the X direction and 10 rows of air holes in the Y direction. To calculate the dispersion diagram which exhibits two guided modes (even and odd), only vertically even (solid blue and red curve), transverse electric-like modes are discussed in this paper. Utilizing triangular PhCs is of practical importance, since they have a large transverse electric bandgap and are expected to serve as a good platform for photonic integrated circuits and ultra-compact optical sensors [16-19]. We used the plane-wave expansion (PWE) method to analyze the properties of the proposed structure.

3. Simulation and results

The group velocity of the guided mode can be calculated from the slope of the dispersion curve $v_g = d\omega/dk = c/n_g$ where $k$ and $\omega$ are the wavenumber and the angular frequency, respectively; $n_g$ is the group index; and $c$ is the speed of light in vacuum. The group velocity dispersion GVD is defined as the derivative of the inverse group velocity $d(v_g^{-1}) = d^2k/d\omega^2$.

In order to modify the dispersion curve, we changed the position of the second rows of holes. Figure 1 illustrates the displacement of the rows of holes in the direction of light propagation used to modify the dispersion. The parameter $s$ (shift) describes the deviation of each row from the ideal lattice.
As shown in figure 3 (a), the dispersion curves shift to the higher frequencies as $s$ increases; it is seen that the dispersion curves contain flat bands over a large range of wavelengths, which generates regimes of wideband slow light with a high group index ranging from 30 to 33. As seen in figure 3 (b), the group index is almost constant in a ±10% range; nearly constant group indices of 30, 31 and 33 are obtained over wavelength ranges of 10.5 nm, 13.5 nm and 16.1 nm, respectively.

![Figure 3](image-url)

**Figure 3.** (a) Calculated dispersion curves of the PCW (b) the corresponding group indices for the fundamental mode of the PCW for different values of the parameter $s$.

The GVD parameters ($\beta_2 = d^2k/d\omega^2$) of our structures are shown in figure 4. One can see that the GVD values of the flat slow-light regions are in the order of $10^4$ ps$^2$/km over the bandwidths with a constant group-index values. Considering that an ESPCW is a nanostructure, acceptable GVD values are in the order of $10^5 - 10^6$ ps$^2$/km [20].

In the compromise between a wide bandwidth and a high group-index for slow light, an essential factor is the normalized delay-bandwidth product (NDBP, see table 1); it can be calculated by using the formula [21]:

$$NDBP = n_g \times \frac{\Delta \lambda}{\lambda_c},$$

where $\Delta \lambda$ is the bandwidth, $\lambda_c$ is the central wavelength.

![Figure 4](image-url)

**Figure 4.** Group velocity dispersion curves of three optimized PCW with varying $s$.

| Shifts | $n_g$ | $\Delta \lambda$ (nm) | NDBP ($\times 10^4$) |
|--------|-------|------------------------|---------------------|
| Current work | $s = 0.204a$ | 30 | 10.4 | 0.201 |
| | $s = 0.229a$ | 31 | 13.5 | 0.270 |
| | $s = 0.240a$ | 32 | 14.5 | 0.300 |
| [20] Shift of two rows | | | | 0.293 |
| [22] Two-hole diameter variations | | | | 0.240 |
| [24] Liquid infiltration in a slotted PCW | | | | 0.207 |

**Table 1.** Group index, bandwidth (central wavelength of 1550 nm), and NDBP factor in the current work and in previous works.
4. Conclusions
By only changing the position of the second rows of holes of a line-defect photonic crystal waveguide in the direction of light propagation, we could easily achieve a wideband and a low-dispersion slow-light PC waveguide. The simulation results showed that propagation of slow light with nearly constant group indices of 30, 31 and 32 is possible over wavelengths ranges of 10.4 nm, 13.5 nm, and 14.5 nm, respectively, the corresponding NDBPs being 0.201, 0.270 and 0.300. Thus, the design proposed offers strong potential for use of integrated circuits.

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