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Novel slow-light waveguide with large bandwidth and ultra low dispersion

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ABSTRACT

To tailor the bandwidth and the group-velocity dispersion, we demonstrate a novel waveguide based on a photonic crystal within a triangular array with crescent-like-shaped air holes. By changing the angle between the waveguide axis and symmetric axis of the air hole from 0 to $\pi/2$, we find that the available bandwidth with a nearly constant group index in excess of 22 increases from 7 nm to 13 nm, that the corresponding normalized delay-bandwidth product increases from 0.202 to 0.245, and that the absolute value of the group-velocity dispersion decreases from 13.500 ps^2/km to 10 ps^2/km. The origin of all the findings is related to the widening of the slow-light region with the increasing of the angle.

1. Introduction

Slow-light technology [1–5] is showing a promising future for applications in optical-delay lines [3,4], optical-integrated circuits [1,3], highly non-linear devices [6–15], all-optical buffers [4,2], etc. As one of the most practical methods [1,16–19] to realize slow-light effect, photonic-crystal waveguides (PCWs) have received more and more attention recently due to many merits, such as compatibility with on-chip integration, room-temperature operation [20], and propagation, with wide bandwidth and free dispersion [4,5]. Furthermore, the slow-light performance in PCWs is not predetermined by the natural material dispersion [21]. For example, the slow-light frequencies can be chosen by suitably designing the PCW. As a result of these merits, the propagation of slow light in planar PCWs has recently received significant attraction because of its promising platform for on-chip all-optical signal processing. Especially, "slow-light enhanced nonlinear optics" now is becoming a very active research area with hips of quite recent experimental demonstrations from several groups [6–8]. These groups have recently demonstrated that the mechanism of nonlinear effects is associated with self-phase modulation [7], two-photon [7] and three-photon absorption [8], and third-harmonic generation [7], and that the nonlinear effects can be strongly enhanced by slow light in PCWs made of III–V semiconductors [8] and silicon [7,9,10]. By means of the enhanced-nonlinear effects, we can realize all-optical signal processing, with wide bandwidth [11] and high bit rates [12], and enable to manufacture wanted short nonlinear devices less than 100 μm [13,14] with the expected performance [15].

However, the operating point of a PCW is typically on a near-parabolic dispersion curve near the edge of the Brillouin zone [3]. Therefore, slow light in PCWs tends to coincide with high group-velocity dispersion (GVD) which severely limits the bandwidth of slow light, deforms optical pulses [22], and disturbs practical applications.

To overcome these drawbacks, various approaches have been proposed. Some of them are based on the nearly zero GVD obtained by adjusting PCW geometries, such as the use of W2 waveguides [23], the modification of the hole radius [24], the introduction of annular holes for the whole lattice, [25] the change of the period [26] in the first one or two row(s) of holes next to the waveguide axis, the modulation of the position [27] of the first one or two row(s) of holes next to the waveguide channel, and the infilling of selective liquid infiltration in the first two rows of holes adjacent to the waveguide channel [11], this technique could be also applied for optical regeneration [13]. While the other approaches are based on the dispersion compensation realized by adding two opposite dispersion regions in a chirped waveguide [28,29]. Recently, Hao et al. succeeded in improving the delay-bandwidth product (DBP) from 0.150 to 0.350 at a constant group index of 90 by arranging the radius of holes and the lateral interval distance between two successive rows of holes [30]. Lately, in Ref. [31], the authors demonstrated an index-chirped photonic-crystal-coupled waveguide. As a result, they obtained an extremely large group index n_g. Very recently, Wu et al. investigated slow light and its GVD in a slotted photonic-crystal waveguide using microfluidic infiltration, and they discovered that the GVD has slight variation at different operating wavelengths when the refractive index of the infiltrated fluid changes [32]. However, most of the

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approaches in Ref [11,25–32] are based on the typical W1 waveguides with cylindrical inclusions, and the fine-tuning of the waveguide dispersion properties is realized by modifying the distribution of refractive index in the local region, such as the waveguide channel or its adjacent region. In reality, to realize any one of the expected modification is not easy.

To tailor the bandwidth and the GVD, in this paper, we employ a novel structure with crescent-like-shaped air holes. Due to an extra free parameter in the lattice design, for all the primitive cells in the typical W1 PCW, we can change the distribution of refractive index in each primitive cell by the shift of the angle between the guide axis and symmetric axis of the air hole to realize the fine-tuning of the waveguide dispersion properties. As a result of each change for the angle, the structure always keeps its typical W1-waveguide form. Thus, the structure is characterized by its non-modification of a typical W1-waveguide. Besides, numerical results show that the available bandwidth and the GVD can be effectively tailored when the angle is tuned suitably in the range between 0 and $\pi/2$.

2. The new waveguide geometry

The proposed structure shown in Fig. 1(a) is a typical W1 waveguide created by removing the central row of air holes along the $\Gamma-K$ direction in a triangular array with crescent-like-shaped air holes to drill in a silicon layer. For an arbitrary primitive cell, the crescent-like-shaped air hole is formed by the air-rod O1 and silicon-rod O2 which are always tangent as shown in Fig. 1(b). The radii of the air-rod O1 and that of the silicon-rod O2 are 0.38a and 0.24a, respectively, and the lattice constant a is 430 nm. Technically, the suggested PCW can be fabricated by the reference technology: standard silicon-on-insulator (SOI). The considered indices for air (top layer), silicon layer (middle layer) and silica (bottom layer) are 1.0, 3.45, and 1.45, respectively. The variable θ shown in Fig. 1(b) is defined as the angle between the waveguide axis and symmetric axis of the air hole.

3. Numerical results and analysis

Because the full three-dimensional calculation of the band frequency is very time consuming, a two-dimensional analysis with an effective refractive index is adopted [33], which is expected to be sufficiently accurate to estimate the group velocity in the slow-light regime. For a silicon slab with the thickness of 240 nm on the silica substrate, which supports only a single TE-like mode centered at 1550 nm, the effective refractive index of the background is then 2.84.

The plane-wave simulation gives the dispersion relation of a waveguide mode. By the slope of the dispersion–relation curve, one can obtain accurately the group velocity which is expressed as

$$v_g = \frac{d\omega}{dk} \tag{1}$$

Here ω is the frequency and k is the wave vector in the propagation direction, i.e. the propagation constant.

For slow-light devices, the performance of slow light is usually described by the concept of group index which is defined as the ratio of the speed of light in vacuum to the group velocity v_g, namely

$$n_g = \frac{c}{v_g} \tag{2}$$

where c denotes the speed of light in vacuum.

As a typical example, Fig. 2 shows the dispersion relation of the waveguide mode and group index n_g for the situation of

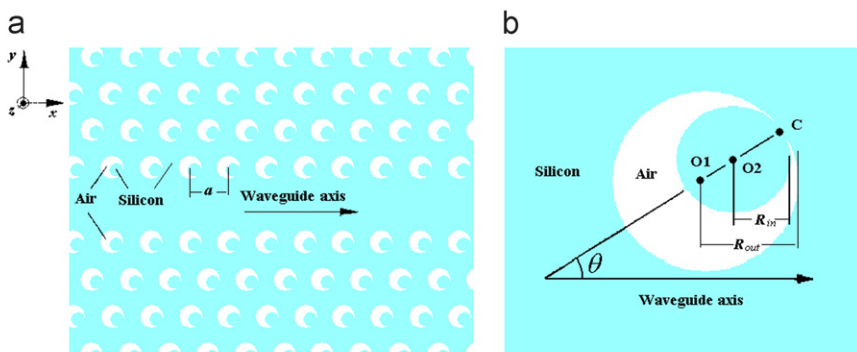

Fig. 1. (a) Schematic picture of the proposed structure. (b) Diagram for a primitive cell and the definition of the angle variable.

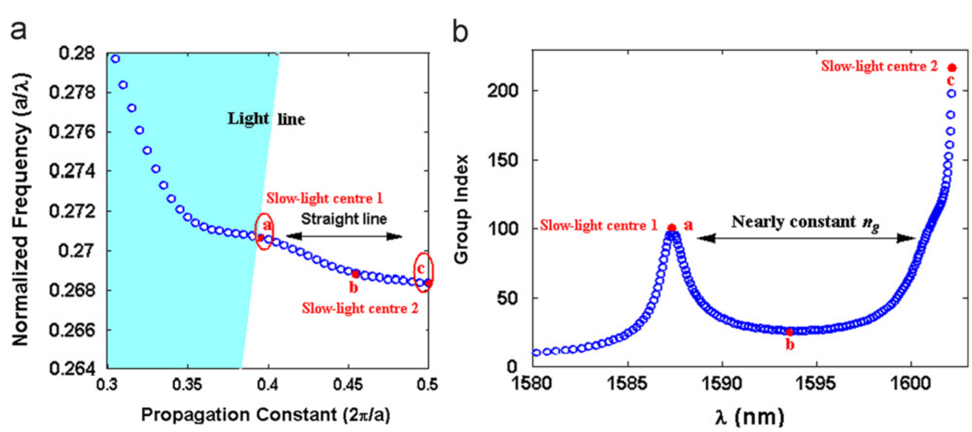

Fig. 2. (a) The dispersion curve of the guided mode for the situation of $\theta=\pi/4$. (b) The curve of group index versus the wave length.