Modified Slab Photonic Crystal Structure for Delay Time Enhancement Using Capsule Shaped Holes

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Abstract
A slow group velocity photonic crystal slab waveguide is designed using capsule shaped air holes in hexagonal lattice. The presented design achieves nearly flat band waveguiding with group-index of 21-36 over the normalized bandwidth (Δω/ω) of 1.38%~0.4%.

Introduction

The interest in manipulating the speed of propagating light has increased dramatically in recent years for applications such as optical delay lines [1], optical buffers [2], and all- optical switches [3]. In addition, the strong light-matter interaction due to the small group velocity enhances the absorption values , non- linearity, and gain values per unit length which benefits numerous of optical devices, such as detectors, amplifiers, and lasers [4]. Several research groups have achieved low group velocity dispersion (GVD) by adjusting the waveguide width [5], the size of the first two innermost rows of holes [6], the displacement of the first two rows [7], or by chirping the property of photonic crystals [8].
In this paper, a design of photonic crystal slab waveguide with a nearly constant group index of 21 over 22.7nm centered at λ=1.55μm is reported, which could provide an alternative path to approach the flat band photonic crystal waveguides.

An air-bridged silicon photonic crystal slab waveguide with a hexagonal lattice and "capsule" shaped air holes is considered in the calculations. As shown in Fig. 1 (a), *a*, *t*, *2r+l* and *2r* denotes the periodicity, the slab thickness, the total length of capsule, and the width of the capsule, respectively. The refractive index of the slab, *n*, is 3.46 at λ=1.55μm and *t* is 0.6*a*. The band structure of the photonic crystal, as illustrated in Fig. 1 (b), is calculated using BandSOLVE™ of the RSoft Photonics CAD Design Suite based on three dimensional plane-wave- expansion (PWE) method.
The group velocity of a guided and the group velocity dispersion (GVD) are defined as $v_g \equiv \frac{\partial \omega}{\partial k}$ and $GVD = \frac{\partial\left(1/v_g\right)}{\partial \omega}$, respectively. In photonic crystal slab waveguide modes, there coexist gap guided modes and index guided modes. A high GVD happens at the anticrossing point where gap guided modes and index guided modes couple with each other. One can tailor the dispersion curve and shift the anticrossing point by engineering the line defect. Frandsen et al. proposed an approach to "flatten" the dispersion curve by perturbing the size of the periodic holes of the two innermost rows

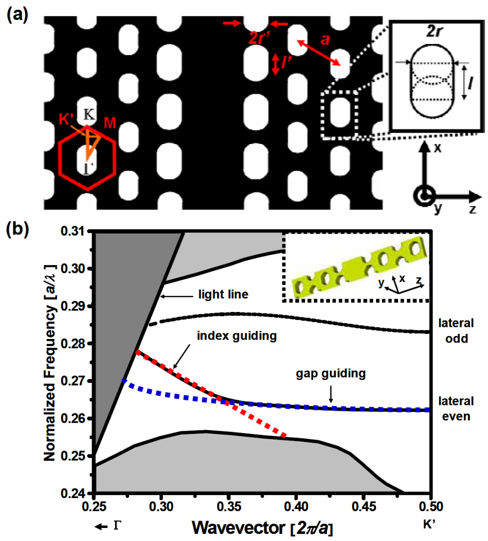

Fig. 1. (a) The geometry of the capsule shaped hole photonic crystal waveguide with hexagonal lattice. Two half circles with diameter of *2r* at both terminals and a rectangle with a width of *2r* and length of *l* in the middle assemble the capsule. (b) A typical band diagram of the capsule shaped photonic crystal. The red dot line indicates the index guided regime and blue dot curve shows the gap guided regime. The inset illustrates the supercell.

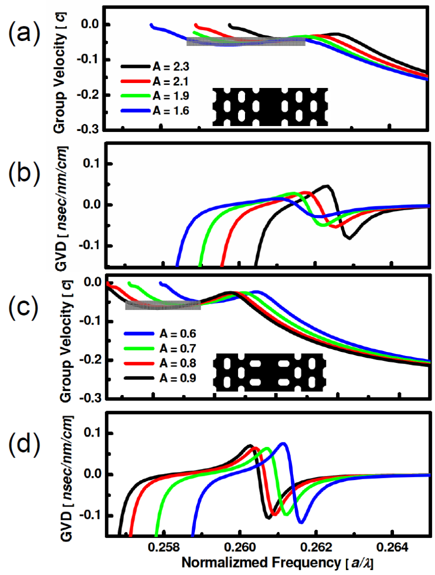

Fig. 2. The cgroup velocities of the guided modes are shown in (a) A>1 and (c) A <1 . The gray bar marked the regime that the group velocity fluctuation is within ± 10 %. The corresponding GVD of the guided modes are shown in (b) A>1 and (c) A <1 .
Aspect ratios of outside holes except for the innermost rows are kept fixed. r=0.162a, l=0.35a, which corresponds to an aspect ratio of 2.08, and area of the hole of 0.196a2. Under this condition, the designed photonic crystal waveguide can provide a sufficient bandgap width for operation wavelength at 1.55μm for a=400~450nm.

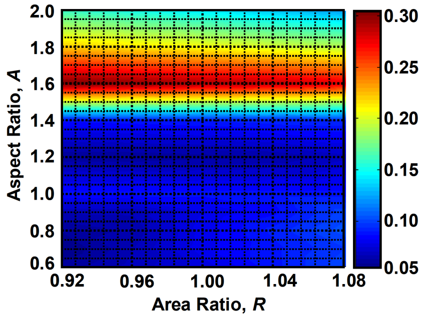

Fig. 3. Systematic calculation of product *ng(Δω/ω)* as a function of area ratio *R* and aspect ratio *A*. The color bar indicates the product which is calculated to be within 0.03 to 0.3, when *R* is in the range of 0.92 to 1.08 and *A* is from 0.6 to 2.0.

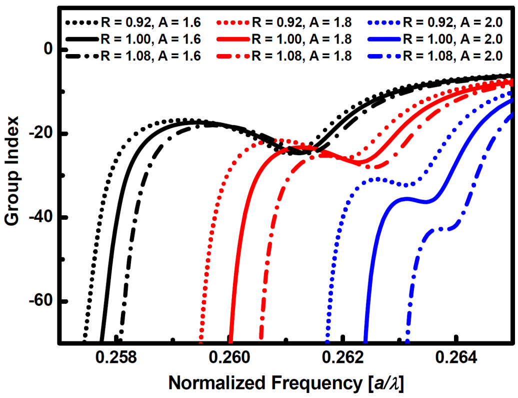

Fig. 4. An approaching constant group index with change of the relative area ratio R. When R is around 1.0, a nearly constant group index of 36 can be achieved with aspect ratio of 2.0.

around the defect [9]. The approach that this paper presents, aims to control the shift of gap guided mode, thus flattening the dispersion curve by manipulating the aspect ratio of the capsule shaped air holes.

The aspect ratio of the capsule shaped holes is defined as

$$A=\begin{cases}\dfrac{2r+l}{2r}, A>1\\ \dfrac{2r}{2r+l}, A<1\end{cases} \qquad (1)$$

Where *r* is the radius of curvature at the two terminals of the "capsule", and *l* is the length of the straight portion of the "capsule" as shown in Fig. 1 (a). *r'* specifically denotes that of the inner most rows, and so does *l'*. To observe the effect of tuning the aspect ratio of holes at the inner most rows on the dispersion relation, group velocity as well as the GVD, aspect ratios of the innermost holes are changed with a fixed area equal to the outside holes for *A* values smaller and greater than 1 [Fig. (2)]. Note that an aspect ratio smaller than 1 is realized by rotating the holes of the inner most rows close to the line defect 90 degree around the center of the hole, as shown in the insets of Figs. 2(a) and 2(c).

For A>1, as *A* increases, both the index guided mode and gap guided mode move towards higher frequency, but with the tendency that the gap guided modes moving faster than the index guided mode, a sharper GVD happens at a lower wavevector when *A* increases. Figure 2 (a) and (b) show two sets of comparison of group velocity and GVD respectively at the above mentioned aspect ratios. The GVD tends to vanish as *A* decreases. However, when *A*<1, the trend of dispersion relation is opposite. It is when *A* decreases, that the gap guided regime will move towards a higher frequency and form a sharp dispersion. The corresponding group velocity and GVD for different A values smaller than 1 are shown in Fig. 2 (c) and (d), respectively, to illustrate such phenomenon.

To further flatten the band, one can combine the manipulation of aspect ratio as well as the size of the innermost holes. Figure 3 shows the influence of holes' size in combination with *A* on pursuing a nearly constant group index. The systematic calculation of the product of group index (n_g) and normalized bandwidth ($\Delta\omega/\omega$) [6] covers a range of *A* from 0.6 to 2.0 and *R* from 0.92 to 1.08. Here *R* denotes the relative area ratio of inner most holes and outside holes, where

$$R=\frac{\pi r'^2+2r'\cdot l'}{\pi r^2+2r\cdot l} \qquad (2)$$

For example, *R* = 1 indicates that all the capsule holes have the same size regardless of their locations in the waveguide. By slightly tailoring the relative area ratio *R*, an almost constant group index can be achieved. A flat band slow light region can be traced at the maroon area where the product n_g ($\Delta\omega/\omega$) reaches its highest value above 0.3 and the group index keeps almost constant when *A* is around 1.6. Figure 4 further explains the combination effects of area and the aspect ratio to achieve a nearly constant group index. When the hole area is fixed, group index increases and is flattened as aspect ratio increases; while under the same aspect ratio, a higher area ratio *R* can induce a "flatter" band, but at the same time sacrifice the normalized bandwidth. Therefore, an almost optimized flat band which is marked correspondingly as the gray region in Fig. 2 (a) and as the black solid curve in Fig. 4 with normalized bandwidth ($\Delta\omega/\omega$) of 1.38 % can be achieved, and the maximum group index-bandwidth product $n_g(\Delta\omega/\omega)$ is 0.304. As shown in Fig. 4, the optimized design exhibits a nearly constant group index of 21 over 22.7 nm and 32 over 8 nm at λ=1.55μm, which corresponds to a 700 ps and 1.1 nsec delay time with bandwidth of 2.8 THz and 1 THz for a centimeter long device, respectively.

References

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