

Delay-Time-Enhanced Flat-Band Photonic Crystal Waveguides with Capsule-Shaped Holes on Silicon Nanomembrane

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Abstract—A slow-group-velocity- and low-group-velocity-dispersion photonic crystal slab waveguide is designed by using capsule-shaped air holes in hexagonal lattice. The theoretical study shows that adjusting the aspect ratio of holes in the innermost rows can fine-tune the dispersion tail. The presented design can achieve nearly flat-band photonic crystal waveguides with group index of 21–36 over the normalized bandwidth ($\Delta\omega/\omega$) of 1.38%–0.4%. We also discuss the effects of the change in the holes' aspect ratio combined with a slight size adjustment. The group index in the range of 21–43 for normalized bandwidth of about 1.5%–0.3% is obtained with the combination effect. The optimized designed exhibits a nearly constant group index of 21 over 22.7 nanometer bandwidth at $\lambda = 1.55 \mu\text{m}$.

Index Terms—Group velocity dispersion, photonic crystal waveguide, slow group velocity.

I. 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], [3], and all optical switches [4]. The possibility to compress the energy and signal provides the opportunity for reducing the footprint of the devices. In addition, the strong light–matter interaction due to the small group velocity enhances the absorptions, non linearity, and gains per unit length that benefits numerous optical devices, such as detectors, amplifiers, and lasers [5], [6]. In recent years, the engineered slow-light photonic crystals have drawn a great deal of attention by researchers because of the flexibility in design and compatibility for on-chip applications. Slow-light 3-D semiconductor photonic crystals with a complete band gap are ideal candidates, however their fabrication is challenging. Planar photonic crystal slabs fabricated on semi-

conductor membrane, such as silicon-on-insulator (SOI) wafers, where light is confined in-plane by the band gap of 2-D photonic crystals [7]–[9] or by 2-D negative refractive index photonic crystals [10] and vertically by total internal reflection of index contrast are alternative solutions because of their relative ease of fabrication. However, the narrow bandwidth due to the highly dispersive group velocity of the photonic crystal slabs in the slow-light regime restricts their applications [11]. Several research groups have achieved low group velocity dispersion (GVD) by adjusting the waveguide width [12]–[14], the size of the first two innermost rows of holes [15], [16], the displacement of the first two rows [17], or by chirping the property of photonic crystals [18]. In this paper, a design of photonic crystal slab waveguide with a nearly constant group index of 21 over 22.7 nm centered at $\lambda = 1.55 \mu\text{m}$ is reported, which could provide an alternative path to approach the flat-band photonic crystal waveguides.

II. DESIGN OF PHOTONIC CRYSTAL SLAB WAVEGUIDE

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 $2r$ denote 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 $\lambda = 1.55 \mu\text{m}$ and t is $0.6a$. The slab is laid on the x - z plane and a line waveguide is formed by removing a single row of holes along x -direction in real space that is corresponding to the Γ K-direction of the reciprocal lattice. Due to the introduction of the line defect, the Brillouin Zone edge is shifted from K to K' instead [19]. The band structure of the photonic crystal, as illustrated in Fig. 1(b), is calculated using BandSOLVETM of the Rsoft Photonics CAD Design Suite based on 3-D plane-wave-expansion (PWE) method and projected from the Γ M-direction onto the Γ K'-direction, which gives the boundary of the first Brillouin zone. The defect modes inside the band gap are studied by replacing a 1×1 unit cell with a supercell that is 1 unit in the x -direction and 6 units in the z -direction in the PWE calculation, as shown in the inset of Fig. 1(b). The figure also shows a lateral even-guided mode and a lateral odd-guided mode, and both of them are vertical even modes. The vertical even mode is defined as the mode symmetric with respect to the x - z plane. The lateral even-guided mode is defined as the mode symmetric with respect to the x - y plane, which is a fundamental mode, while the lateral odd-guided mode

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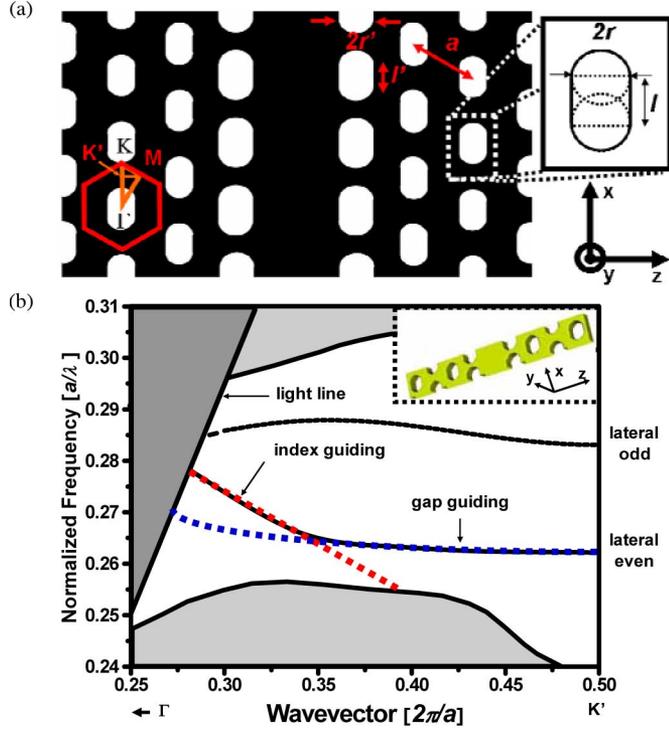


Fig. 1. (a) Geometry of the capsule-shaped hole photonic crystal waveguide with hexagonal lattice. Two half circles with diameter of $2r$ at both terminals and a rectangle with a width of $2r$ and length of l in the middle assemble the capsule. (b) Typical band diagram of the capsule-shaped photonic crystal. The red dot line indicates the index-guided regime and blue dot curve shows the gap-guided regime. The inset illustrates the 1×6 supercell in plane, which has six periods in the vertical direction to ensure that the defect is sufficiently isolated.

is a higher order mode. The group velocity of a guided mode is calculated from its definition as the derivative of the angular frequency over the wavevector

$$v_g \equiv \frac{\partial \omega}{\partial k}. \quad (1)$$

The derivative of the reciprocal group velocity over the frequency gives the GVD

$$\text{GVD} = \frac{\partial(1/v_g)}{\partial \lambda}. \quad (2)$$

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 [11]. One can tailor the dispersion curve and shift the anticrossing point by engineering the parameters of the line defect. Frandsen *et al.* have proposed an approach to “flatten” the dispersion curve by perturbing the size of the periodic holes of the two innermost rows close to the defect [15]. An alternative new 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.

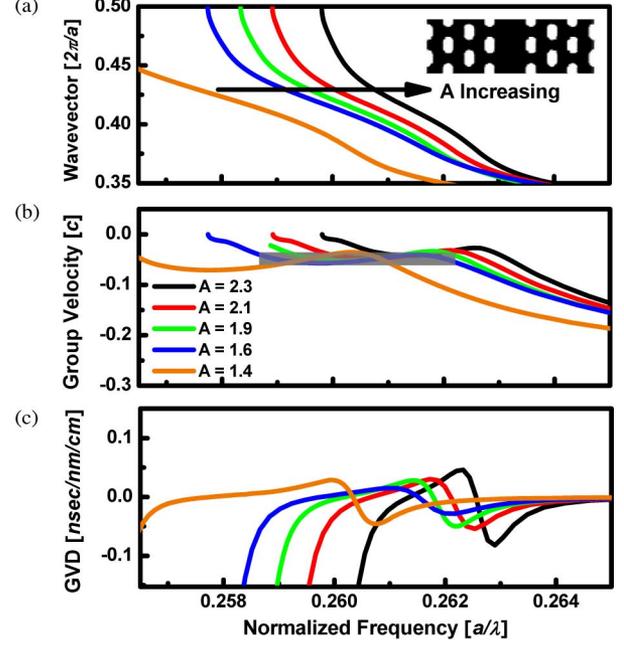


Fig. 2. (a) Waveguide mode dispersion with various aspect ratios that are larger than one, with fixed area ratio R equal to one. The guiding modes move toward higher frequency as the aspect ratio is increased. (b) Corresponding group velocities of the guided modes. The gray bar marked the regime that the group velocity fluctuation is within $\pm 10\%$. (c) Corresponding GVD of the guided modes indicate that in the flat-band regime the GVD fluctuation is smaller than ± 0.07 ns/(nm·cm) for the case of $A = 2.3$, and is smaller than ± 0.05 ns/(nm·cm) for the rest cases.

The aspect ratio of the capsule-shaped holes is defined as

$$A = \begin{cases} \frac{2r' + l'}{2r'}, & A > 1 \\ \frac{2r'}{2r' + l'}, & A < 1 \end{cases} \quad (3)$$

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' especially denotes that of the innermost rows, and so does l' . The dispersion relations of the calculated fundamental modes with various values of A are illustrated, respectively, in Fig. 2(a) and Fig. 3(a) under two different conditions. Corresponding schematic structures of the photonic crystal waveguide with aspect ratio of the holes bigger than 1 and smaller than 1 are shown in the insets of Fig. 2(a) and Fig. 3(a) accordingly. Aspect ratios of outside holes except for the innermost rows are fixed during the calculation, where the radius r is $0.162a$, the length l is $0.35a$, which corresponds to an aspect ratio of 2.08, and area of the hole of $0.196a^2$. The area ratio, which is defined as R , denotes the relative area ratio of innermost holes over outside holes

$$R = \frac{\pi r'^2 + 2r'l'}{\pi r^2 + 2rl}. \quad (4)$$

In the calculations of Figs. 2 and 3, R is kept as 1, which indicates that all the capsule holes have the same size irrespective of their locations in the waveguide. Under this condition, the designed photonic crystal waveguide can provide a

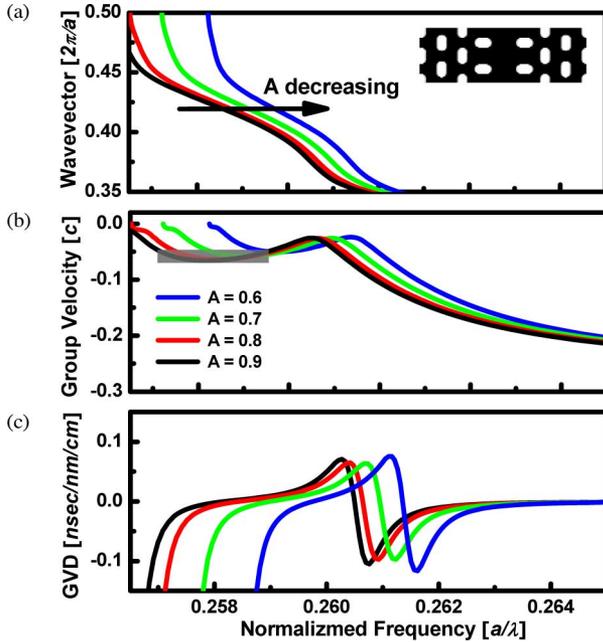


Fig. 3. (a) Waveguide mode dispersion with various aspect ratios that are smaller than one, with fixed area ratio R equal to one. The guided modes move toward higher frequency as the aspect ratio is decreased. (b) Corresponding group velocities of the guided modes. The gray bar marked the regime that the group velocity fluctuation is within $\pm 10\%$. (c) Corresponding GVD of the guiding modes that indicate that in the flat-band regime the GVD fluctuation is smaller than ± 0.1 ns/(nm·cm).

sufficient bandgap width for operation wavelength at $1.55 \mu\text{m}$ with corresponding periodicity within 400–450 nm.

III. RESULTS AND DISCUSSIONS

To observe the effect of tuning the aspect ratio of holes at the innermost 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. Aspect ratios of 1.4, 1.6, 1.9, 2.1, and 2.3 are chosen as an example. The trend is clear as A increases, both the index-guided mode and gap-guided mode move toward 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. Fig. 2(b) and (c) shows two sets of comparison of group velocity and GVD, respectively, at the aforementioned aspect ratios. The GVD tends to vanish as A decreases, but increase after $A = 1.6$.

An aspect ratio smaller than 1 is realized by rotating the holes of the innermost rows close to the line defect 90° around the center of the hole, which is shown as the inset of Fig. 3(a), and A is defined as in (3). When $A < 1$, the trend of dispersion relation is opposite. It is when A decreases, that the gap-guided regime will move toward a higher frequency and form a sharp dispersion. Corresponding dispersion relation, group velocity and GVD with aspect ratios of 0.6, 0.7, 0.8, and 0.9 are shown in Fig. 3(b) and (c) to illustrate such phenomenon. These aspect ratios are reciprocals of 1.67, 1.43, 1.25, and 1.11. For instance, if A changes from 0.6 to 0.7, it can be considered to change an amount of 16.67%, which is similar to the degree of change when

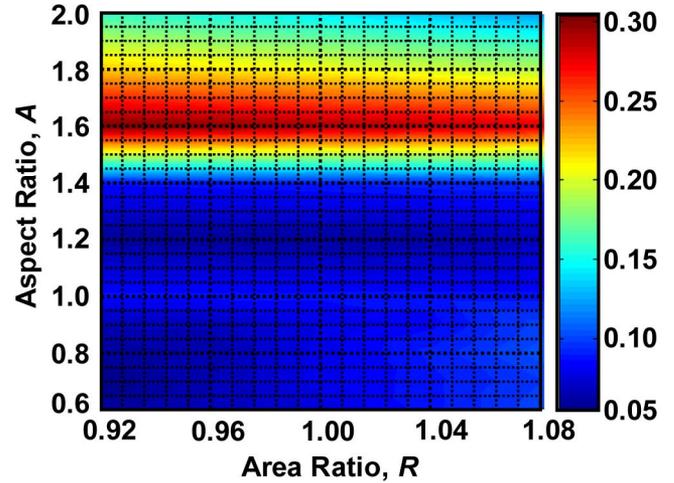


Fig. 4. Systematic calculation of product $n_g(\Delta\omega/\omega)$ as a function of area ratio R and aspect ratio A . The color bar indicates the product that is calculated to be within 0.03 to 0.3, when R is in the range of 0.92 to 1.08 and A is from 0.6 to 2.0.

A changes from 1.6 to 1.9 in $A > 1$ case. However, with the same amount of change in aspect ratio, when $A < 1$, Fig. 3(a) shows that gap-guided regime moves much faster than under the $A > 1$ case, which indicates that with a small aspect ratio (< 1) of the innermost holes, the gap-guided modes are more sensitive to the change of the aspect ratio. Furthermore, one can observe that in the case of $A > 1$, the designed structure can control the GVD within 0.05 ns/(nm·cm) with properly chosen aspect ratio with group index around 30.

The effect of the manipulation of aspect ratio as well as the size of the innermost holes is also studied to show the influence of holes' size in combination with A on pursuing a nearly constant group index and to further investigate the tolerance of the design. Fig. 4 illustrates the systematic calculation of the product of group index (n_g) and normalized bandwidth ($\Delta\omega/\omega$) [16] covering a range of A from 0.6 to 2.0 and R from 0.92 to 1.08. The bandwidth $\Delta\omega$ is defined as the frequency range that is corresponding to the change of group index within $\pm 10\%$, where the group index is considered constant [17]. The relative area ratio R is slightly tailored to represent a possible deviation of the area ratio caused by fabrication process. Fig. 4 indicates that a flat-band slow-light region can be traced at the maroon area where the product $n_g(\Delta\omega/\omega)$ [15] reaches its highest value above 0.3 and the group index keeps almost constant when A is around 1.6. The calculation shows under the condition that A is fixed at 1.6, when the increment of R is less than 4%, the product $n_g(\Delta\omega/\omega)$ remains almost constant, and when the R is slightly decreased to the range of 0.92–0.94, the product $n_g(\Delta\omega/\omega)$ slightly increases to 0.304. In other words, with slight R change within 10%, the product of $n_g(\Delta\omega/\omega)$ remains nearly constant at 0.3. This result reveals one of the advantages of such design, the robustness against the change of hole sizes, if a proper aspect ratio is chosen. This advantage can release the stringent requirement of controlling precise hole sizes during the fabrication process. Fig. 5 further explains the effect of aspect ratio combined with area change to achieve a nearly constant group index. When the hole area is fixed, in the flat-band

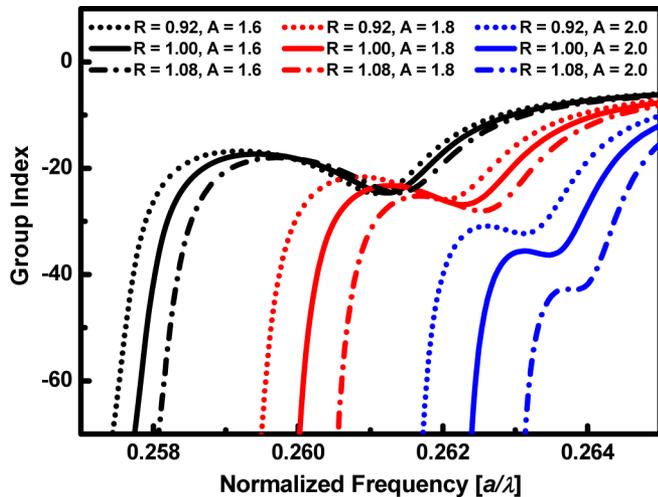


Fig. 5. Approaching constant group index with change of the relative area ratio R . When R is around 1.0, a nearly constant group index of 36 can be achieved with aspect ratio of 2.0.

region, the average group index increases and the fluctuation is reduced as aspect ratio increases; while under the same aspect ratio, a higher area ratio R can reduce the fluctuation. In a previously reported method by changing positions of first two rows of holes, the group index fluctuation in the flat-band region increases as the group index increases [17], which indicates the GVD increases at a higher group index. In comparison, in the proposed design the fluctuation of group index in the flat-band region remains almost to the same extent when the group index increases as shown in Fig. 5. With proper choice of aspect ratio, a vanishing GVD within ± 0.05 ns/(nm-cm) is achieved which is twice smaller than the data reported as in [13] under similar group index. Under such circumstances, an almost optimized flat band, which is marked correspondingly as the gray region in Fig. 2(b) and as the black solid curve in Fig. 5, 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.

IV. CONCLUSION

Slow-group-velocity photonic crystal waveguide with vanishing GVD by using capsule-shaped air holes on hexagonal lattice is proposed. Theoretical study on the effect of fine-tuning the aspect ratio of the innermost holes on flattening the GVD is briefly introduced. A nearly flat-band photonic crystal waveguides with group index of 21–36 over the normalized bandwidth ($\Delta\omega/\omega$) of 1.38%–0.4% can be achieved with this design. In combination with the size tuning effect, group index in the range of 21–43 for normalized bandwidth about 1.5%–0.3% is obtained. The optimized design exhibits a nearly constant group index of 21 over 22.7 nm and 32 over 8 nm at $\lambda = 1.55 \mu\text{m}$, which corresponds to a 700 ps and 1.1 nsc delay time with bandwidth of 2.8 and 1 THz for a centimeter-long device, respectively. The proposed idea can lead to an alternative route to achieve flat band, and the studied effect can contribute an extra degree of freedom to the design and fabrication of slow-light photonic crystal slab waveguides with vanishing GVD.

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