Demonstration of Ultraslow Modes in Asymmetric Line-Defect Photonic Crystal Waveguides

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***Abstract*—We propose an asymmetric photonic crystal (PC) waveguide, formed by moving the PC cladding on one side of the line defect along the waveguide core. By adjusting the structural parameters, we flatten the slow-mode dispersion curve, exclude the extreme points from the flat band, and avoid the unacceptably large dispersion induced by extreme points. We obtain an ultraflat band with an inflection point corresponding to a slow-light mode with reduced distortion. We utilize the finite-difference time-domain method to verify the inflection-point ultraslow wave.**

***Index Terms*—Dispersion, flat band, group velocity, inflection point, photonic crystal (PC), slow light.**

I. Introduction

RECENTLY, a surge of research activities has focused on photonic crystal (PC) line-defect waveguides, which provide slow light with a small group velocity v_g due to its structural dispersion [1]–[4]. However, there exists a trade-off between the obtained group velocity and signal dispersion [5]–[9]. The authors of [10] have pointed out the principle that slow light should be operated on the flat band rather than the parabolic band occurring near the band edge of the PC waveguide.

Mori and Baba have presented a coupled PC waveguide, where a unique flat band with an inflection point is formed in the photonic bandgap [11]–[15]. The authors of [16] have reported the experimental realization and the light behaviour, on both the spectral and time domain of such a waveguide, where an extremely small group velocity of $0.017c$ is thus observed. However, the fabrication of these complex devices is difficult, which limits their practical utilization.

In this letter, we propose an asymmetric waveguide by moving the PC cladding on one side of the line defect along the waveguide core. We first describe the band engineering of the device. In order to obtain a more flattened inflection-point band, we tune certain structural parameters, including the radius of the basic air holes and the width of the line defect. We optimize the structure by excluding the extreme points from the flat band, with the purpose of avoiding the unacceptable dispersion induced by extreme points. Calculated by the plane wave expansion method [17], the asymmetric device is shown to be characteristic of ultralow v_g (less than 0.01c) and low group velocity dispersion (GVD). Besides, we demonstrate the slow-light propagating in the proposed structure by finite-difference time-domain (FDTD) simulation [18].

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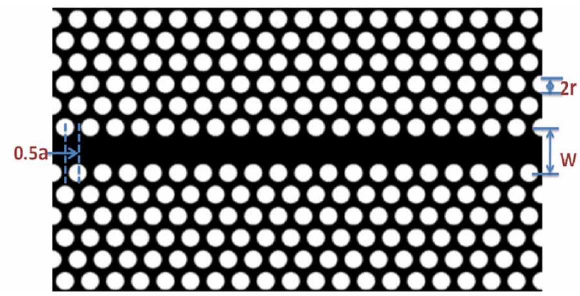

Fig. 1. Structure of the designed asymmetric waveguide with a hexagonal lattice of background index $n = 3.5$. The basic air hole radius (r) and the width (w) of the line defect are design parameters.

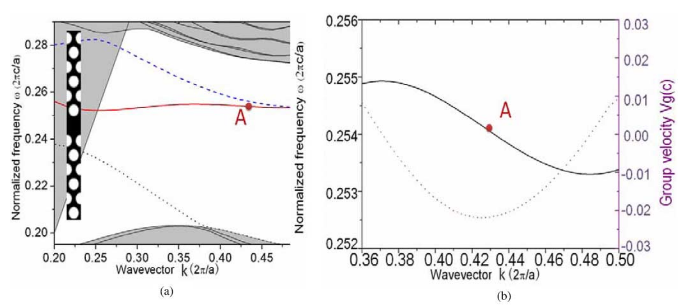

Fig. 2. (a) Typical band diagram showing the normalized frequencies versus normalized wavevectors for the asymmetric waveguide, with $r = 0.3a$ and $\xi = 1.00$. The left inset sketches the supercell used in our PWE calculation. (b) Corresponding band (solid line) and group velocity (dotted line) near the inflection point as a function of wavevector.

II. Design Method

The structure of the asymmetric waveguide is shown in Fig. 1. We make a premise to use silicon $(n = 3.5)$ PC consisting of air holes (radius r) in a triangular lattice (lattice constant a). The width of the line defect is denoted as $W = \sqrt{3}a\xi$, with $\xi = 0.98, 1.00, 1.02$, and 1.05. Note that the structure is asymmetric with respect to the waveguide axis: all air holes in the PC cladding below the defect are moved to the right by $0.5a$ [19].

Fig. 2(a) shows the bands of the waveguide with $r = 0.3a$ and $\xi = 1.00$. Only vertically even, transverse-electric (TE)-like modes are discussed. We are interested in the flattest band marked by the solid line, featuring an inflection point "A". For further clarification of the flat band in the waveguide, we enlarge the region $0.36 < k < 0.50$ around the inflection point and plot the corresponding group velocity v_g, as shown in Fig. 2(b). We observe that v_g approximates $0.02c$ at "A" point $(k = 0.425, \omega = 0.2541)$.

Our design goal is to obtain ultraslow light with v_g in the range $\sim(c/60 - c/1000)$ and a vanishing GVD in a $\sim(3-5)$-nm bandwidth. The GVD parameter β_2 is related to the second-

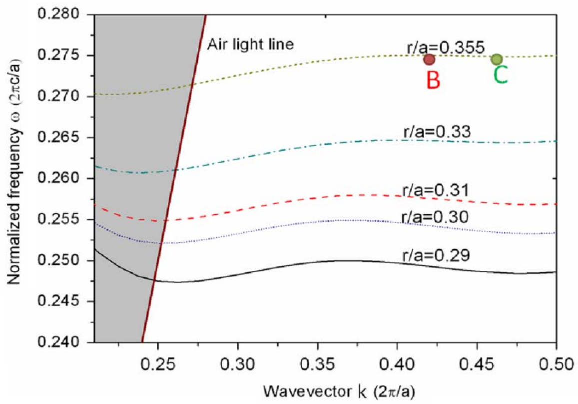

Fig. 3. Moving tendency of the flat band when adjusting the radius (r) of the basic air holes.

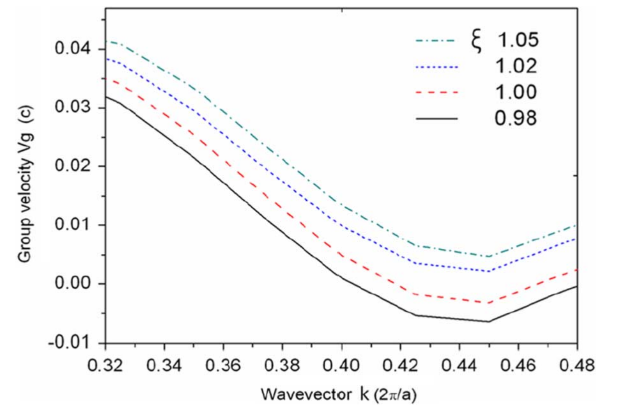

Fig. 4. Dependence of the group velocity on the widths of the asymmetric PC waveguide.

order derivative of the band curve $d^2\omega/dk^2$ as the following expression:

$$\beta_2 = \frac{d^2k}{d\omega^2} = -\frac{1}{\left(\frac{d\omega}{dk}\right)^3}\frac{d^2\omega}{dk^2} = -\left(\frac{1}{v_g}\right)^3\frac{d^2\omega}{dk^2}. \qquad (1)$$

At extreme points, we can infer that the vanishing v_g results in infinite $|\beta_2|$ and unacceptable signal distortion. At the inflection point, the second-order derivative of the curve reaches zero, and the smallest value of $|d^2\omega/dk^2|$ will lead to a minimum of $|\beta_2|$. Therefore, our design principle can be to properly tune the structural parameters, to achieve a flattened band with an inflection point. In other words, the band should be characteristic of ultra-small slope and relatively low second-order derivative.

First, let us study the dependence of the flat band on the radius (r) of the basic air holes. Fig. 3 illustrates the shifting tendency of the photonic bands when r is changed between $0.29a$ and $0.355a$. All flat bands are lying below the light line. When r is increased, the demanded band moves upwards in frequency, and becomes more flattened, which means that the group velocity v_g is reduced. The $r = 0.355a$ structure (with the most flattened band) is used in the following examples.

Then, we consider the most simple case, namely the width change, which is also favorable for manufacturing [6]. We investigate the moving tendency of v_g, when we gradually change the width of the line defect by shifting the boundaries together or away. The tuning records are illustrated in Fig. 4. In the waveguide with $\xi = 1.00$, the absolute value of v_g stays below $0.01c$ between the region of $0.387 \leq k \leq 0.48$. If k approaches 0.419 or 0.467, the absolute value of v_g converges to zero (the case is related to the extreme point B or C in the photonic band, as marked in Fig. 3). From (1), we infer that $|\beta_2|$ diverges to infinity in point B or C, and generates unacceptable signal distortion.

The group velocity v_g and β_2 near the inflection point of the waveguide with $\xi = 1.00$ are shown in Fig. 5(a) as a function of frequency. Between $0.27486(2\pi c/a)$ and $0.27504(2\pi c/a)$, the absolute value of v_g remains well below $0.0045c$. Meanwhile, β_2 is in the magnitude of $10^7 - 10^8$, and turns from positive to negative. $|\beta_2|$ keeps increasing as the frequency approaches "B" or "C", which is consistent with the above discussion.

When the defect width W is increased (decreased), the velocity band moves upward (downward). In details, if W is larger than $\sqrt{3}a(\xi = 1.02$ or $\xi = 1.05)$, v_g grows and becomes positive in the whole window in Fig. 4. In other words, there are no extreme points (zero-v_g points) in the slow-mode region, and thus, extremely large $|\beta_2|$ will not occur.

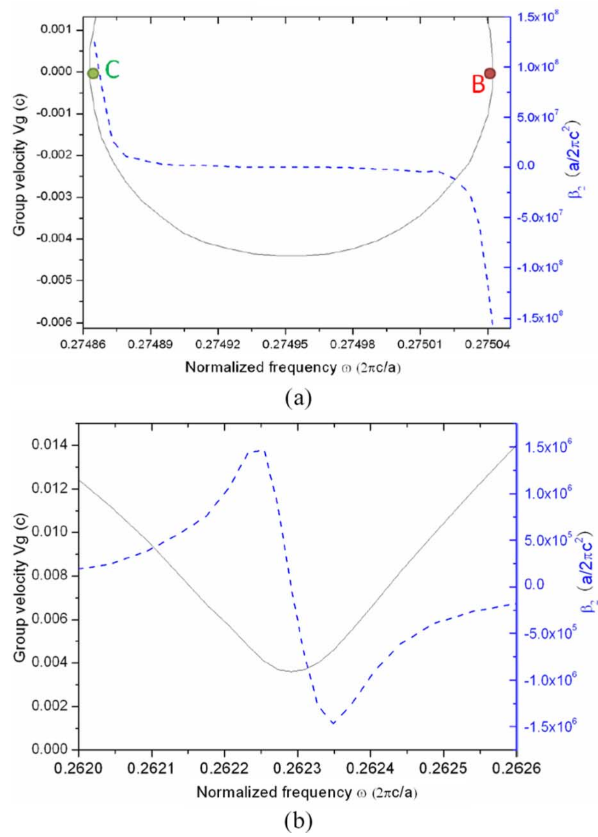

Fig. 5. Corresponding group velocity (the solid line) and GVD (dashed line) near the inflection point as a function of frequency. (a) For the waveguide with $\xi = 1.00$; (b) for the waveguide with $\xi = 1.05$.

Fig. 5(b) illustrates v_g and β_2 of the waveguide with $\xi = 1.05$. Between the frequency $0.2620(2\pi c/a)$ and $0.2626(2\pi c/a)$, v_g stays in the range $0.0038c$–$0.012c$. β_2 keeps approximately below 10^6. β_2 has a positive and a negative part, and in a very narrow region; it goes to zero. Compared to the waveguide with $\xi = 1.00$, the line defect with $\xi = 1.05$ provides a wider

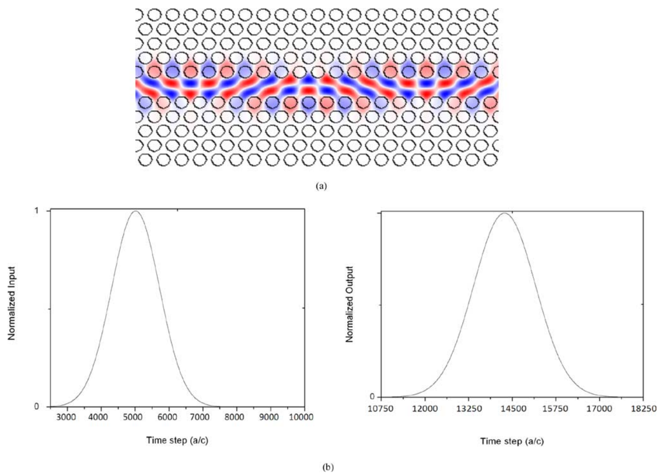

Fig. 6. (a) Static field distribution (TE mode) of the W1.05 with $r = 0.355a$, where red, light red, light blue, and dark blue show intensities from plus to minus. (b) Input and output time waveforms. The central frequency of the Gaussian source is $0.2623(2\pi c/a)$.

transmission window and reduced dispersion, at the cost of increased group velocity.

III. Numerical Result and Discussion

In this section, we investigate the performance of the waveguide with $r = 0.355a$ and $\xi = 1.05$. The inflection-point slow-mode distribution in this waveguide is illustrated in Fig. 6(a).

Here, let us show a performance comparison between the new structure and the ones designed earlier [14]. The average group index $\tilde{n}_g$ is given by

$$\tilde{n}_g = \int_{\omega_0-\Delta\omega/2}^{\omega_0+\Delta\omega/2} n_g(\omega) d\omega/\Delta\omega. \quad (2)$$

Looking at Fig. 5(b), we calculate the average group velocity $\tilde{v}_g$ to be $0.0082c$ in normalized bandwidth $\Delta\omega/\omega = 2.3 \times 10^{-3}$, and $\tilde{n}_g$ is about 122, which gives a normalized delay-bandwidth product $\tilde{n}_g \Delta\omega/\omega \approx 0.281$, while the delay-bandwidth product of [14] was $450 \times 2.1 \times 10^{-4} \approx 0.095$.

Then, we show the FDTD simulation of the slow-light propagation for the optimal flat band. The structure for the waveguide with $r = 0.355a, \xi = 1.05$, and a total length $L = 147a$ is shown in Fig. 1. Perfectly matched absorbing boundary layers are applied to the surrounding of the structure. A Gaussian pulse is centered at $\omega = 0.2623(2\pi c/a)$ and has a frequency width $\Delta\omega = 0.001(2\pi c/a)$. It is wider than the transmission bandwidth in Fig. 5(b), due to the limits of our computation resources (we use Intel 4-cores 2.66-GHz CPU, and the total running time for 60 000 steps is 77 h). We investigate the broadening of the pulse propagating through the waveguide. In order to compare the shape of the optical pulse, we normalize the time waveforms at the input and output ports of the waveguide, as shown in Fig. 6(b). The incident optical pulse with a full width of approximately 4500 a/c is expanded to 5500 a/c at the end of the waveguide. Besides, the total delay t_d between the two peaks of the main lobes is approximately 9276 a/c. The corresponding $\tilde{v}_g$ is $0.016c$ (the average group index $\tilde{n}_g$ is 62.5). Note that the observing $\tilde{v}_g$ is larger than the calculated value $0.0082c$ from (2), mainly because we choose a larger bandwidth $0.001(2\pi c/a)$ in simulation than the transmission window $0.0006(2\pi c/a)$ in Fig. 5(b).

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