Flat Band Slow Light in Symmetric Line Defect Photonic Crystal Waveguides

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***Abstract*—Flat band slow light in symmetric line defect photonic crystal waveguides formed by adding dielectric pillars in the air holes nearest to the waveguide core is investigated. By adjusting the radii of the new dielectric pillars, a linear band in the photonic band structure appears which denotes low group velocity dispersion. High average group index of 74.4 with 2.3-nm bandwidth is demonstrated in an optimized waveguide by finite-difference time-domain simulation.**

***Index Terms*—Dispersion, photonic crystal (PC), slow light.**

I. Introduction

SLOW light in line defect photonic crystal (PC) waveguides has attracted a great deal of attention in recent years because it is compatible with on-chip integration and room-temperature operation, and can offer wide-bandwidth and dispersion-free propagation [1]. Due to the extremely large first-order dispersion which arises from complicated photonic band properties, slow light propagation in PC waveguides with group velocities below $c/300$ was experimentally demonstrated [2]. However, there are the large group velocity dispersion (GVD) and higher order dispersion observed in the slow light regime of PC waveguide [3], which would cause a signal distortion [4]. Thus, there exists a trade-off between the frequency bandwidth and the effective group index [1]–[5]. To decrease or eliminate these drawbacks, modifications of the conventional PC waveguides are proposed, including varying the waveguide width [6]–[8], utilizing coupled PC waveguides [9], and so on. But these methods will destroy the symmetry of the PC [10] and it is impossible to create efficient sharp bends in these PC waveguides, thereby limiting the applications. Nonuniform holes sizes [11], [12] and PC with ring-shaped holes [13], [14] can maintain the symmetry of the PC, but their slow light performances reported are not as good as expected.

In this letter, we propose a novel modified line defect PC slab waveguide formed by adding dielectric pillars in the air holes nearest to the waveguide core to solve the problems above. The novel PC waveguide is expected to maintain the symmetry of the PC and also achieve ultralow group velocity with ultralow GVD. We first describe the band engineering of the device by using the two-dimensional (2-D) plane wave expansion (PWE) method [15] with equivalent index [16] of the slab. In order to obtain a linear band, we then tune certain structural parameters, including the radii of the new dielectric pillars and the PC air holes. While a suitable radii of dielectric pillar is achieved, a linear band in the photonic band structures and a flatten step like shape in the group velocity curve exhibit. In addition, an optimized symmetric PC waveguide having an average group index of 74.4 with 2.3-nm bandwidth is demonstrated with no obvious waveform distortion in the finite-difference time-domain (FDTD) method simulation, which verifies the band structures analysis.

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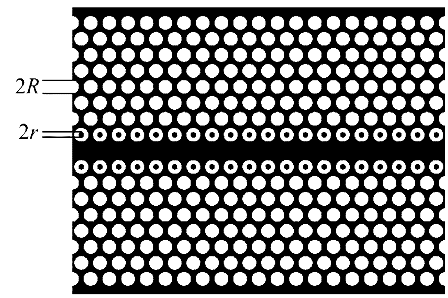

Fig. 1. Schematic structure of the symmetric line defect PC waveguide. Black denotes silicon and white denotes air.

II. Structural Analysis

A triangular lattice PC slab consisting of circular air holes (radii R) with lattice constant a in a dielectric silicon background ($\varepsilon = 12$) is assumed as the basic structure. As shown in Fig. 1, the waveguide is formed by omitting one line of the holes in the perfect PC, and additional dielectric pillars (radii r) are added in the air holes nearest to the waveguide core. Because the three-dimensional calculation of the band frequency is very time consuming, 2-D analysis with a slab equivalent index of 2.9 is adopted [16], which is precise enough to estimate the group velocity in slow light regime.

Fig. 2 presents the photonic bands of the main propagation modes of the single line defect PC waveguides when the polarization is assumed to be transverse-electric (TE)-like. As r increases, the band shifts to lower frequencies, changing its shape from down-facing to linear, and then to up-facing. In order to obtain the dispersion-free waveguide, a linear photonic band should be chosen. So r must be precisely controlled, and the bandwidth of the linear section is uniquely determined. The

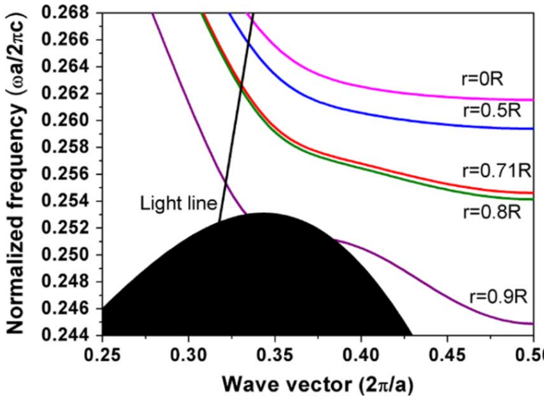

Fig. 2. Photonic band of the main propagation mode of PC line defect waveguide for $R = 0.3335a$, and r is taken as a parameter. The shadow area shows the extend bands of the perfect PC.

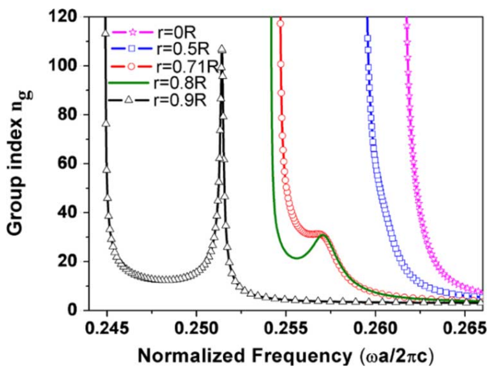

Fig. 3. Group index n_g characteristics of PC waveguide, R is fixed to 0.3335 a and r is varied corresponding to Fig. 2.

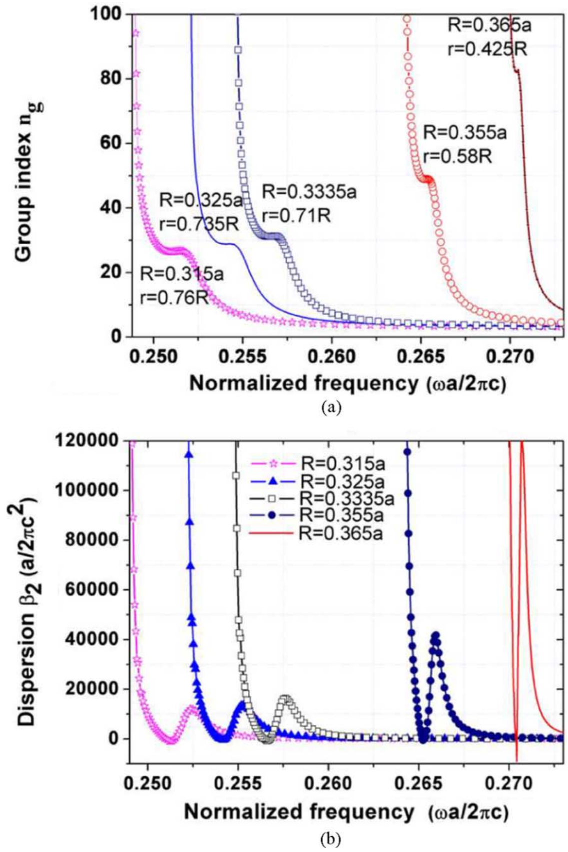

Fig. 4. (a) Group index n_g characteristics of PC waveguide, R is varied and r is optimized to obtain the low GVD characteristics. (b) Dispersion characteristics corresponding to (a).

slowing up of the flat band can be understood through the following. The modes of line defect PC waveguides can be categorized as either index guided or gap guided [3]. An anti-crossing between these two types of modes determines the local shape of the mode dispersion curves [6]. The holes nearest to the line defect waveguide are the physics conjunction of index guided and gap guided modes. Changing these holes can change the intrinsic interaction of the index guided and gap guided modes, and can be used to tune the dispersion curve and thus to obtain a flat band slow light region. The linear photonic band is below the light line which is the lowest band of the 2-D silica PCs system, and it means a good light confinement in the vertical direction of the slab.

Fig. 3 shows the group index n_g characteristics as a function of the normalized frequency. $n_g = |c/V_g|$, and c is the light velocity in vacuum, the group velocities V_g are obtained by using the inbuilt function of MPB [15]. For $r = 0R$ and $0.5R$, exponent shapes of n_g are observed, and a step-like behavior is found at $r = 0.71\,R$, which shows an ideal low GVD characteristic and a high group index. For r larger than the ideal value, the step shape changes to a pulse peak gradually, which indicates an increasing of GVD. The group index characteristics shown in Fig. 3 meet the band structure shown in Fig. 2 very well.

The optimum r for the high group index and low GVD characteristics also depends on R, since the slab mode band can be shifted by changing R. Fig. 4(a) demonstrates the n_g characteristics when R is varied and r is optimized accordingly. As R is increased, the optimum r is decreased, and the high group index with low GVD characteristic appears at higher frequencies, exhibiting a larger n_g and narrower bandwidth. For the GVD is defined as $\beta_2 = d^2k/dw^2$, Fig. 4(b) shows the GVD characteristics corresponding to the parameters in Fig. 4(a). If we regard $\beta_2 = 10000(a/2\pi c^2)$ as ultralow dispersion, which is two orders of magnitude smaller than [8], the corresponding dispersion is about 7.42 ps^2/mm for a typical application of PC with the period a around 420 nm for a center wavelength of 1550 nm. Then the ultralow dispersion bandwidth for slow light can be obtained through Fig. 4(b). At $n_g = 82$ with $\Delta\omega/\omega = 0.06\%$ for $R = 0.365a$, it means a 0.93-nm bandwidth centering at 1550 nm, and $n_g = 26$ with $\Delta\omega/\omega = 0.896\%$ for $R = 0.315a$. One can choose the high n_g and narrow bandwidth or low n_g and wide bandwidth according to different applications. For dense wavelength-division-multiplexing devices, 0.8-nm bandwidth is needed, so we do not try a higher n_g by additionally increasing the R. From Fig. 4(b), negative β_2 values and positive β_2 values for different normalized frequencies are also observed for the same waveguide structure. Therefore, dispersion compensation would be easily performed by serially cascading two sections of waveguide with opposite β_2 for the same wavelength by slight modifications of the PC period. As a result, the slow light bandwidth can be broadened effectively.

III. Numerical Simulations

Pulse light propagation through the optimized waveguides is also studied by FDTD [17] simulation. The PC waveguide

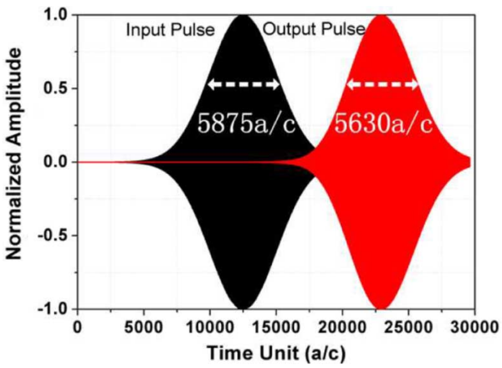

Fig. 5. Time pulse shapes detected at the input detecting point and the output detecting point in PC waveguide. The amplitudes of Hz filed for input and output pulse are normalized according to their maximum amplitudes, respectively.

has $R = 0.365\ a, r = 0.425R$, and a total length $L = 141\ a$, which are chosen according to the previous PWE result and also considerations of the fabrication easiness. Perfectly matched absorbing boundary layers are applied to the surroundings of the structure in the FDTD simulation. A Gaussian pulse source is centered at $0.2703(2\pi c/a)$ with a frequency width $\Delta\omega = 0.0004(2\pi c/a)$. Because Maxwell's equations are scale invariant, as the Meep [17] user guide said, some characteristic length scale (here we chose the lattice constant a of the PC) can be used as the unit of distance. But in order to obtain a center wavelength of 1550 nm, the lattice constant a of the PC should be chosen as 418.965 nm. In this case, the corresponding bandwidth is about 2.3 nm. The minimum fabrication line width of the waveguide is also calculated about 88 nm accordingly. Due to the limitation of our computation resources, the bandwidth of the source is wider than the previous PWE analysis. Fig. 5 shows the normalized pulse shapes corresponding to the time step propagation through the input detecting point and the output detecting point in PC line defect waveguide. The input detecting point is posited at $0.5a$ behind the input port and the output detecting point is posited at $0.5a$ before the output port. So the distance L_d between them is $140a$. At the input detecting point, the pulse maximum altitude for Hz field is at 12523 a/c, while it is at 22940 a/c at the output detecting point. The total delay t_d between the two peaks is approximately 10417 a/c. The average n_g can be obtained from $t_d/L_d = 74.4$, which is highly close to the previous PWE calculation. The slight difference between the two values mainly results from the different bandwidths chosen in the two methods. The half-maximum at full-width of the incident optical pulse is 5875 a/c at the input detector; while that of the output pulse is 5630 a/c. The relative pulse shape distortion is only 4.17%, so we can draw the conclusion that the signal can be transmitted without obvious distortion owing to the ultralow dispersion and also the limited simulation length of the waveguide.

IV. Conclusion

Flat band slow light in a novel symmetric line defect PC waveguide has been investigated. By carefully choosing the radii r of the dielectric pillars in the air holes nearest to the waveguide core, a linear band structure appears in the proposed PC waveguide, and the group index n_g and normalized bandwidth $\Delta\omega/\omega$ of the ultralow GVD characteristics can be tailored. Using the FDTD method, a PC waveguide with an average group index value of 74.4 within a wavelength range of 2.3 nm is demonstrated without obvious waveform distortion. In addition, the bandwidth also can be easily extended by cascading two sections of waveguide with negative and positive dispersion parameters by modifications of the PC period. Compared with the previous line defect PC waveguide, the proposed PC waveguide exhibits ultralow group velocity and ultralow GVD characteristics while maintaining the symmetry of the PC waveguide. The novel PC waveguide can provide various applications, such as optical buffer memories, efficient optical switches, and especially in enhanced light-matter interaction both in the linear and nonlinear regime with a simple and straight structure.

References

[1] T. Baba, "Slow light in photonic crystals," *Nat. Photon.*, vol. 2, pp. 465–473, 2008.
[2] Y. A. Vlasov, M. O'Boyle, H. F. Hamann, and S. J. McNab, "Active control of slow light on a chip with photonic crystal waveguides," *Nature*, vol. 438, pp. 65–69, 2005.
[3] M. Notomi, K. Yamada, A. Shinya, J. Takahashi, C. Takahashi, and I. Yokohama, "Extremely large group-velocity dispersion of line-defect waveguides in photonic crystal slabs," *Phys. Rev. Lett.*, vol. 87, p. 253902, 2001.
[4] R. J. P. Engelen, Y. Sugimoto, Y. Watanabe, J. P. Korterik, N. Ikeda, N. F. van Hulst, K. Asakawa, and L. Kuipers, "The effect of higher-order dispersion on slow light propagation in photonic crystal waveguides," *Opt. Express*, vol. 14, pp. 1658–1672, 2006.
[5] T. F. Krauss, "Slow light in photonic crystal waveguides," *J. Phys. D, Appl. Phys.*, vol. 40, pp. 2666–2670, 2007.
[6] A. Y. Petrov and M. Eich, "Zero dispersion at small group velocities in photonic crystal waveguides," *Appl. Phys. Lett.*, vol. 85, pp. 4866–4868, 2004.
[7] M. D. Settle, R. J. P. Engelen, M. Salib, A. Michaeli, L. Kuipers, and T. F. Krauss, "Flatband slow light in photonic crystals featuring spatial pulse compression and terahertz bandwidth," *Opt. Express*, vol. 15, pp. 219–226, 2007.
[8] J. Ma and C. Jiang, "Demonstration of ultraslow modes in asymmetric line-defect photonic crystal waveguides," *IEEE Photonic Technol. Lett.*, vol. 20, no. 14, pp. 1237–1239, Jul. 15, 2008.
[9] D. Mori, S. Kubo, H. Sasaki, and T. Baba, "Experimental demonstration of wideband dispersion-compensated slow light by a chirped photonic crystal directional coupler," *Opt. Express*, vol. 15, pp. 5264–5270, 2007.
[10] M. Loncar, J. Vuckovic, and A. Scherer, "Methods for controlling positions of guided modes of photonic-crystal waveguides," *J. Opt. Soc. Amer. B*, vol. 18, pp. 1362–1368, 2001.
[11] L. H. Frandsen, A. V. Lavrinenko, J. Fage-Pedersen, and P. I. Borel, "Photonic crystal waveguides with semi-slow light and tailored dispersion properties," *Opt. Express*, vol. 14, pp. 9444–9450, 2006.
[12] S. Kubo, D. Mori, and T. Baba, "Low-group-velocity and low-dispersion slow light in photonic crystal waveguides," *Opt. Lett.*, vol. 32, pp. 2981–2983, 2007.
[13] M. Mulot, A. Saynatjoki, S. Arpiainen, H. Lipsanen, and J. Ahopelto, "Slow light propagation in photonic crystal waveguides with ring-shaped holes," *J. Opt. A, Pure Appl. Opt.*, vol. 9, pp. S415–S418, 2007.
[14] J. Hou, D. Gao, H. Wu, and Z. Zhou, "Polarization insensitive self-collimation waveguide in square lattice annular photonic crystals," *Opt. Commun.*, vol. 282, pp. 3172–3176, 2009.
[15] S. G. Johnson and J. D. Joannopoulos, "Block-iterative frequency-domain methods for Maxwell's equations in a planewave basis," *Opt. Express*, vol. 8, pp. 173–190, 2001.
[16] D. S. Gao and Z. P. Zhou, "Nonlinear equation method for band structure calculations of photonic crystal slabs," *Appl. Phys. Lett.*, vol. 88, p. 163105, 2006.
[17] A. Farjadpour, D. Roundy, A. Rodriguez, M. Ibanescu, P. Bermel, J. D. Joannopoulos, S. G. Johnson, and G. Burr, "Improving accuracy by subpixel smoothing in FDTD," *Opt. Lett.*, vol. 31, pp. 2972–2974, 2006.