Research on the Dispersion Compensation of Slot Photonic Crystal Waveguide

Huiping Tian, Xuan Zhang, Daquan Yang, and Yuefeng Ji, *Member, IEEE*

***Abstract*—Negative group velocity dispersion (GVD) in the slow light region of the slot photonic crystal waveguide (PCW) is used to compensate the positive GVD of the conventional PCW. Through designing the proper structure, we plot the waveforms and field pattern of the light propagation in the waveguide. We find that the waveform gets broaden first for the positive GVD in conventional PCW and recovers through the slot PCW with the negative GVD. The light energy fades away as the light propagated along the PCW, but it can be well confined into the narrow slot, which may effectively enhance the interaction between slow light and the low-index waveguiding material filled in the slot. So the slot PCW can open the opportunities for wide applications such as optical dispersion compensation, optical delay line, and so on.**

***Index Terms*—Dispersion compensation, field pattern, slot photonic crystal waveguide (PCW), waveforms.**

I. Introduction

PHOTONIC crystal (PC) with single line air-holes missing can bring into guiding modes in the photonic band gap (PBG) [1]–[3]. PCW has many advantages such as working under room temperature, great potential bandwidth, and realizing slow light in arbitrary wavelength and so on. Slow light offers a promising approach to realize optical delay line, optical buffers and data synchronization in future all optical communications and information processing systems [1]–[3].

However, the slow light region near the photonic band edge is usually accompanied by large GVD which severely deforms optical pulses and disturbs practical application. To decrease the GVD, several methods have been proposed, such as modifying the waveguide width, changing the air hole size and using micro-fluidic infiltration [2]–[5]. All these methods can only slow down the signal waveform broadening, but cannot eliminate the waveform broaden. Here we will propose a special structure to eliminate the waveform broadening based on slot PCW.

The slot PCW can confine light in a narrow slot filled with low-refractive index material which is more convenient and feasible for fabrication [6]–[9]. The slot PCW can be filled with nonlinear or electrooptical (EO) material to construct various applications, such as all-optical logical switch, modulators and so on [10]. This letter will show that the slot PCW can also be used to compensate dispersion by structure optimizations.

Manuscript received August 03, 2010; revised May 23, 2011; accepted May 29, 2011. Date of publication June 07, 2011; date of current version August 10, 2011. This work was supported in part by NSFC (60707001, 60932004) National 973 Program (2011CB302702), in part by National 863 Program (2009AA01Z214, 2009AA01A345), and in part by NCET (07-0110), China.

The authors are with the State Key Laboratory of Information Photonics and Optical Communications, School of Information and Telecommunication Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China (e-mail: jyf@bupt.edu.cn).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2011.2158812

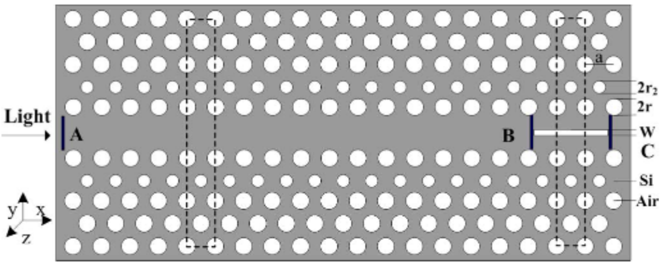

Fig. 1. Schematic diagram of the model of PCW.

Firstly we calculate the band model of the conventional PCW and slot PCW respectively. Then we slightly adjust the parameters of the two types of PCWs to make the even guided mode at the same frequency and to make the GVD in the slow light region of the slot PCW is negative to compensate the positive GVD of the conventional PCW. Finally, through designing the proper structure, we calculate the waveforms and field pattern of the light propagation in the PCW to verify the compensation results.

II. Theoretical Model

We mainly focus on two types of PCWs which are triangular lattice with air holes as shown in Fig. 1. One is the conventional PCW (the left part in Fig. 1) the other is the slot PCW (the right part in Fig. 1). The refractive indexes of the background material Si and the air-holes and the air-slot are 3.5 and 1. The radius of the circular air-holes r is $0.32a$, the radius of the second two rows of air-holes adjacent to the waveguide r_2 is $0.28a$, the width of the slot w is $0.1a$, the lattice constant a is 336 nm. Detector A, B, C are set to detect the waveform of the light signal.

The group velocity v_g of light waves can be given as [1]–[3]:

$$v_g = \frac{\partial \omega}{\partial k} = \frac{c}{n_g}, \tag{1}$$

where ω is the frequency, k is the wave vector, c is the light velocity in vacuum, n_g is the group index. The group velocity in a PCW is strongly dependent on the frequency as quantified by the GVD parameter β_2 [1]–[3] as:

$$\beta_2 = \frac{d(v_g^{-1})}{d\omega} = \frac{d^2k}{dw^2}, \tag{2}$$

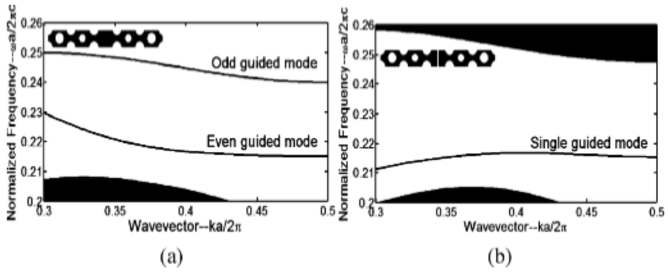

Fig. 2. (a) Band diagram for conventional PCW. (b) Band diagram for slot PCW.

The GVD will broaden the pulse width propagating through the PCW. Hence, the extreme GVD in the conventional PCW will be devastating for the utilization of slow-light [2]. That may severely deform the pulse, reduce the propagation distance and increase the bit error rate.

The condition of dispersion compensation can be written as,

$$\beta_1 L_1 + \beta_2 L_2 = 0, \tag{3}$$

where $L = L_1 + L_2$ is the dispersion-map period, β_j $(j = 1, 2)$ is the GVD parameter of waveguide of length L_j $(j = 1, 2)$. When (3) is satisfied the pulse recovers its initial width after each compensation period [11].

III. Simulation Results

A. The Guided Modes

The dispersion curves for TE polarized mode in conventional PCW and slot PCW are numerically calculated by 2-D plane wave expansion (PWE) method to simplify calculation. The defect modes inside the band gap are studied with a super cell as shown in the inset of Fig. 2. The conventional 2-D triangle lattice PCW with circular air-holes supports: even and odd modes in the PBG [12] as shown in Fig. 2(a). The even gap guided mode concentrate most of its energy in the unstructured part of the waveguide [3], [4]. Here we just discuss the right flat band edge of the even mode which is theoretically slow light region.

We carefully adjust the width of the slot w to $0.1a$ in order to make the even guided modes of the two PCWs at the same frequency. Correspondingly, we simulate the bands of slot PCW in Fig. 2(b), which supports only one even mode in the PBG. The slab mode bands are slightly affected by the insertion of the air-slot [7].

The group velocities at the band edge of the two PCWs are plotted in Fig. 3. In this range both of the group velocities are under $0.045c$. It is addressed as the slow-light regime.

B. The Dispersion Properties in Slow Light Region

In the following, we mainly research the GVD of the slow light region mentioned above. Fig. 4(a) sketches the GVD of even guided mode of conventional PCW. Fig. 4(b) sketches the GVD of even guided mode of slot PCW. We can see that the GVD of the conventional PCW is positive on the order of 10^7 ps^2/km, while the GVD of the slot PCW at normalized frequency of 0.216~0.217 is negative on the order of 10^8 ps^2/km. Therefore, this slot PCW can be used to compensate group velocity dispersion of the conventional PCW.

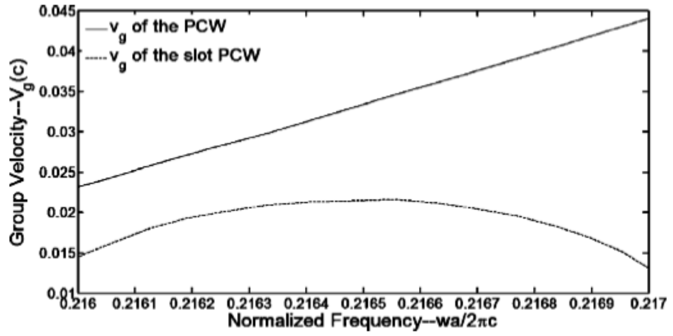

Fig. 3. Group velocities of conventional PCW and slot PCW near the band edge.

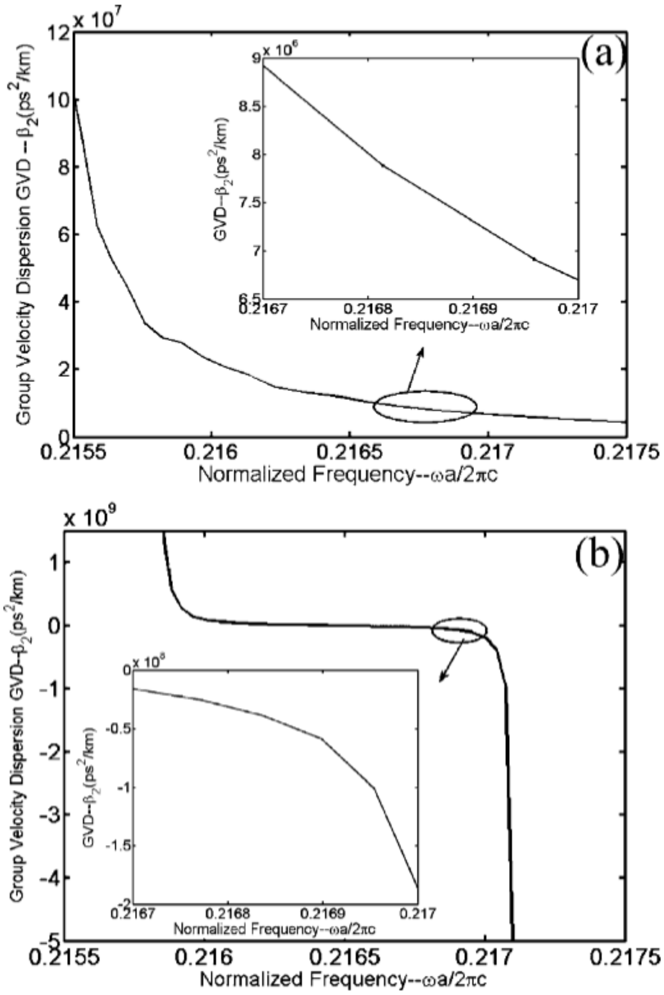

Fig. 4. (a) GVD of conventional PCW near the band edge. (b) GVD of slot PCW near the band edge.

C. The Waveform and Field Pattern in the PCW

In this section we mainly focus on the dispersion compensation structure and analyze the broadening and recovering of the signal pulse. Meanwhile, the delay time and field pattern will be given

Firstly as the opposite GVD property of the above two PCWs mentioned in Section III-B, we design a special structure to realize the dispersion compensation as shown in the Fig. 1. The normalized center frequency of light source is 0.2168.

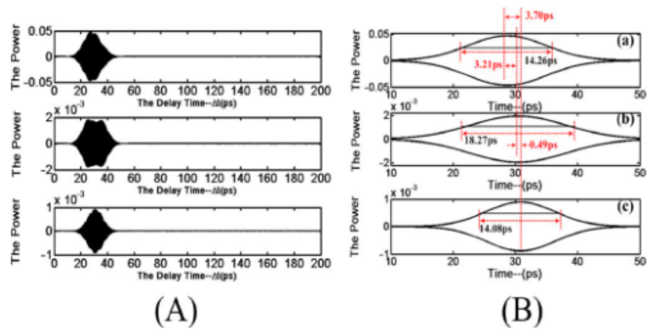

Fig. 5. (A) Waveform of light pulse propagation in PCW at (a) Detector A, (b) Detector B, (c) Detector C; (B) the fitting and enlarging curves of (A).

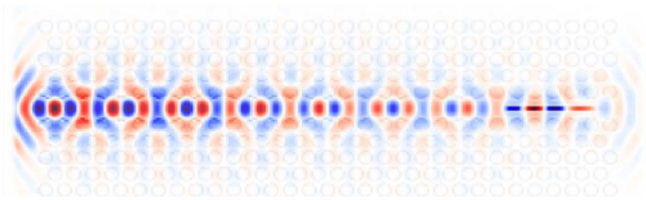

Fig. 6. Field pattern of the designed PCW.

The length L_1 of conventional PCW is $80a$, the length L_2 of slot PCW is $10a$. In order to observe the pulse width we plot the waveforms of light pulse at detector A, B, C in Fig. 5(A) by FDTD (finite-difference time-domain) in MEEP. In MEEP units, a/c is our unit of time, a used as our unit of distance, where c is the velocity in vacuum. We set the time steps as 10000, the resolution as 10. We can see that the waveform becomes broaden while light propagates in the conventional PCW. When the light coupled into the slot PCW and propagated through it, the waveform almost recovers its initial width as shown in Fig. 5(A). We measure the FWHM (full width half maximum) of the fitting curve of the signal envelope at point A, B, C as shown in Fig. 5(B), which are 14.26 ps, 18.27 ps and 14.08 ps, respectively. The results show that the dispersion compensation can be realized in the proposed structure. The loss is about 17 dB.

In addition, by calculation we can get that the whole delay is about 3.70 ps as shown in the figure, which is in accordance with the calculated result from PWE which is about 3.68 ps.

Simultaneously, we calculated the field pattern by FDTD in Fig. 6. The figure show that the energy fades away as the light propagated along the conventional PCW. Then it is coupled and concentrated in the slot which means that this structure can well confine slow light in the narrow slot. This can effectively enhance the interaction between slow light and the low-index wave-guiding material filled in the slot.

IV. Conclusion

Though slightly adjusting the parameters, we make the even guided modes of the two types of PCWs at the same frequency. Negative GVD in the slow light region of the slot PCW is used to compensate the positive GVD of the conventional PCW. We designed the proper structure and plotted the waveforms and field pattern of the light propagation in the PCW. It is found that the waveform got broaden firstly for the positive GVD in the conventional PCW and narrowed down through the slot PCW for the negative GVD. The energy fades away as the light propagated along the PCW, but the light can be well coupled into the narrow slot. So the slot PCW can open the opportunity for wide applications of slow light.

References

[1] T. Baba, "Slow light in photonic crystals," *Nature Photon.*, vol. 2, pp. 465–473, 2008.
[2] L. H. Frandsen, A. V. Lavrinenko, J. F. Pedersen, and P. I. Borel, "Photonic crystal waveguides with semi-slow light and tailored dispersion properties," *Opt. Express*, vol. 14, pp. 9444–9450, 2006.
[3] M. Notomi, K. Yamada, A. Shinya, J. Takahaashi, C. Takahashi, and I. Yokohama, "Extremely large group velocity dispersion of line-defect waveguides in photonic crystal slabs," *Phys. Rev. Lett.*, vol. 87, pp. 253902-1–253902-4, 2001.
[4] 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.
[5] M. E. Heidari, C. Grillet, C. Monat, and B. J. Eggleton, "Dispersion engineering of slow light photonic crystal waveguides using microfluidic infiltration," *Opt. Express*, vol. 17, pp. 1628–1635, 2009.
[6] A. D. Falco, L. O'Faolain, and T. F. Krauss, "Photonic crystal slotted slab waveguides," *Photon. Nanostructures-Fundamental Applicat.*, vol. 6, pp. 38–41, 2008.
[7] J. Wu, Y. Li, C. Yang, C. Peng, and Z. Wang, "Slow light in tapered slot photonic crystal waveguide," *Chin. Sci. Bull.*, vol. 54, pp. 3658–3662, 2009.
[8] A. D. Falco, L. O'Faolain, and T. F. Krauss, "Dispersion control and slow light in slotted photonic crystal waveguides," *Appl. Phys. Lett.*, vol. 92, pp. 083501–083503, 2008.
[9] J. Wu, C. Peng, Y. Li, and Z. Wang, "Light localization in slot photonic crystal waveguide," *Chin. Phys. Lett.*, vol. 26, pp. 014209–014214, 2009.
[10] J. H. Wülbern, A. Petrov, and M. Eich, "Electro-optical modulator in a polymer infiltrated silicon slotted photonic crystal waveguide heterostructure resonator," *Opt. Express*, vol. 17, pp. 304–314, 2009.
[11] G. P. Agrawal, *Nonlinear Fiber Optics, Third Edition & Applications of Nonlinear Fiber Optics*. New York: Elsevier Science, 2001.
[12] S. F. Mingaleev, A. E. Miroshnichenko, and Y. S. Kivshar, "Coupled-resonator-induced reflection in photonic- crystal waveguide structures," *Opt. Express*, vol. 16, pp. 11647–11660, 2008.