Slow Light Tuning in Annular Slotted Photonic Crystal Waveguide with Incoming Polymer

Kongtao Zhu*, Hongxue Yang1 and Hui Du1

1Department of Computer Science, College of Electronic Communication and Engineering, Beijing Polytechnic, Beijing, 100176, China

*Corresponding author’s: zhukongtao@bpi.edu.cn

Abstract. An advanced post-processing scheme of reconfigurable dielectric infiltration into an annular slotted photonic crystal waveguide (ASPhCW) is proposed in this paper. Ionic liquids have had prominent effects in enhancing the optical properties of photonic crystals, especially in the aspect of tuning the transmission rate and velocity through optical materials. Using the two-dimensional plane wave expansion method, the flat band dispersion of the slow light is obtained and the tuning of the operating wavelength of the crystal could be realized by incoming polymer technology. The operating wavelength tuning range could be as large as 459.27nm and the group index could be tuned as high as 44.8 with a near zero group velocity dispersion. Using this method, a high group index equaling 45 with the bandwidth equaling 11.3nm and the normalized delay bandwidth product (NDBP) equaling 0.25 is realized. This incoming polymer technology provides an effective method of getting flat band of slow light flexibly and makes it possible to offer longer delay and low group velocity after fabrication.

1. Introduction

Photonic crystal waveguides (PhCWs) have great advantages in controlling light by using the guided modes in the photonic band gap (PBG). Slow light could be obtained by tuning the speed of light through the band dispersion of PhCW. A great many of PhCW structures have been designed to realize slow light both in theory and experiments[1, 2], and slow light PhCW is proved to be a compromise solution for buffering[3, 4], optical delay lines devices[5], memory[6], optical switches[7], etc. However, there are still several problems to be solved if these slow light PhCWs are applied in optical devices.

The first problem is that slow light modes with large group velocity dispersion (GVD) would destroy the pulse shape and produce intense degradation in high speed optical signal transmission. To the contrary, low GVD values are good properties in slow light optical devices[8]. To get low GVD parameters, flat band is necessary in slow light optical devices designing, because low GVD parameters and constant group index values are mostly derived from the flat band dispersion. Various structures have been proposed and fabricated to realize the flat band, such as PhC slab[9, 10], PhC rods[11], coupled cavity waveguide[12], etc.

Among them annular PhCWs (APhCWs) show good PBG properties ever since they are designed and fabricated[13]. Lots of theoretical analysis and experiments are published to tune the PBG by changing the parameters, such as turning the shape from circle to eclipse[14], shifting the radius of the annular holes[15], changing the position of the annular holes[16], etc. Then another problem that cautious designing and strict fabrication process are required. Serious deterioration would emerge even if a slight fabrication deviation should happen. Therefore constricted fabrication accuracy is
required and this limits the development of PhCW. Incoming polymer technology[17] emerge and relax the requirements of the fabrication precision standards. Among them, room temperature ionic liquids possess high refractive index and strong electrostatic field and makes the tuning flexible and controllable[18, 19].

This paper adopts the model of annular slotted PhCW(ASPhCW) and the post-processing method of infiltrating both low and high index reconfigurable dielectric to tune slow light property. The flat band dispersion is realized and light is highly confined in the waveguide core. The process of infiltrating the reconfigurable dielectric is illustrated. The effects of the refractive index values of the infiltrated dielectric to the group index, the wavelength, the bandwidth and the NDBP is discussed later.

2. Design and modeling
The ASPhCW adopt the Silicon on Insulator (SOI) platform and the silicon slab (ε = 12, melting points = 1410°C) have triangular lattice of air holes (radii r = 0.34a, lattice constant a = 520 nm) and an air slot (width w = 0.28a) in the center of the slab as shown in figure 1. It has a silica base and the annular holes are formed by adding silicon pillars (radii r1 = 0.17a, ε = 12) to the first and second lines of air holes adjacent to the slot. In the calculation, two-dimensional (2D) plane-wave-expansion method (PWEM) is used. The slab thickness h is set to 210 nm and the effective slab index is 2.9 in the calculation.

![Figure 1. Schematic structure of the ASPhCW. Radii r = 0.34a, r1 = 0.17a. kx represents the wavevector of propagation. The slot width w = 0.28a. Black denotes silicon. Gray denotes the high index reconfigurable dielectric with the refractive index ns and white denotes the low index reconfigurable dielectric with the refractive index nh.](image)

A post-processing scheme is designed by infiltrating reconfigurable dielectric with different refractive index into the waveguide to tune the band diagram. The refractive index of most opto-fluidic is between 1.3-1.7, which limit the tuning range of the PBG. Therefore, gaseous and solid dielectric is adopted to infiltrate into the PhCW to obtain low and high index reconfigurable infiltration. Some organics, whose refractive index could be as high as that of the liquids, are gaseous in room temperature, like 1-Fluoropropane( C3H7F, CAS NO: 460-13-9, index: 1.3115), 2,2-Difluoropropane( C3H6F2, CAS NO: 420-45-1, index: 1.2904). The required low index gaseous dielectric could be obtained by mixing these gas with air in specific concentration. Also some high index solid, which have low melting points, could be infiltrated as fluid into the PhCW at high temperature and then solidify into crystal in room temperature, such as antimony trisulfide(Sb2S3, index: 4.064, melting point: 550°C, soluble in hydrochloric acid), thallium iodide(TlI, index: 2.78, melting point: 440°C, soluble in concentrated sulfuric acid). The required high index solid dielectric could be obtained by mixing these two solids in specific concentration for their nearly equal molecular weight(Sb2S3: 339.7, TlI: 331.3). The infiltration could be removed by immersing the device into hydrochloric acid and concentrated sulfuric acid successively.

Based on the data of refractive index above and using the effective index theory, the effective refractive index values of the dielectric infiltrated into the round holes and annular holes nh and the
slot $n_s$ is reasonably set to 1.00-1.30(gas), 1.30-1.80(fluid) or 2.20-4.00(solid). The supercell method is adopted, which is set to be $a \times 11a$ in the calculation.

The Massachusetts Institute of Technology Photonic-Bands (usually as MIT Photonic-Bands, or MPB) package is used to calculate the dispersion curves for transverse-electric polarized light-wave, in which the electric field is confined in the plane of propagation, in the ASPhCW. The group velocity $v_g$ of the guided modes can be got from the slope of the dispersion curve.

$$v_g = \frac{d\omega}{dk} = \frac{c}{n_g}$$

Here, $\omega$ is the frequency, $k$ is the wavevector in the propagation direction (it is $k_x$ in figure 1), $c$ is the velocity of light in vacuum, $n_g$ is the group index. From this formula, $n_g$ can be expressed as

$$n_g = c \frac{dk}{d\omega}$$

The GVD value $\beta_2$ is given by the second order derivative of the dispersion relation as

$$\beta_2 = \frac{d^2k}{d\omega^2} = -\frac{1}{c} \frac{dn_g}{d\omega}$$

The delay-bandwidth product is considered as an essential factor for slow light property. The NDBP, which is more useful and convenient, is given by

$$NDBP = n_g \times \frac{\Delta\lambda}{\lambda_c}$$

Here, $\Delta\lambda$ is the bandwidth, $\lambda_c$ is the central wavelength (subscript c represents central).

3. Results and Discussions

To illustrate the effects of the reconfigurable dielectric infiltrated into the slot, the dispersion curves, the group index curves and the GVD values are compared for $n_s = 1.00, 1.73, 3.08$, which means that there are gas, fluid or solid in the slot respectively, as shown in figure 2. In the band diagram, there is one even mode and one odd mode in the PBG. They are both lying below the light line, which infers that the modes are localized in the crystal in the vertical direction (perpendicular to the calculating plane). For slow light, the even mode is the subject of study. It can be seen that the slope of the even mode is decreased in the larger wavevector region, which indicates that the group index $n_g$ is increased rapidly when the wavelength is large. In figure 2(a) (b) (c), the dispersion curves are pulled down to lower frequency region when $n_s$ is increased. The even mode is shifted greatly from 0.330-0.364 to 0.258-0.284, in terms of $\omega a/2\pi c$. At the same time, the PBG and the odd mode are shifted slightly. In figure 2(d) (e) (f), the effects of $n_s$ to the even mode are explicitly revealed. In figure 2(d) (f), there are step curves in the group index diagrams, which indicate a flat band property of the even mode. In Fig.2 (e), there is no step curves and the flat band property disappears. It can be seen that when fluid is infiltrated into slot, the odd mode and the even mode intersect with each other and then the flat band of the even mode is disappeared. When there is gas or solid in the slot, the odd mode and the even mode separate from each other and the flat band appears. From figure 2, it can also be seen that when $n_s$ is increased, the even mode is pulled down to the dielectric band and the central wavelength is red-shifted. The flat band is first disappeared and then appeared again. The group index $n_g$ is increased from 17.2 to 42.7, with the NDBP enlarging from 0.15 to 0.21. The GVD values are also given in the figure 2 (d) (e) (f). They are all under $10^{-20}s^2/m$, which would not cause the degradation in signal transmission.

Based on the results above, it is obvious that solid infiltration into the slot is preferred. Because, solid dielectric has higher refractive index and the group index $n_g$ could be increased through the
Figure 2. Comparisons of the dispersion curves, the group index curves and the GVD values for different refractive index values of the reconfigurable dielectric infiltrated into the slot. (a) (b) (c) Band diagrams for \( n_s = 1.00, 1.73, 3.08 \). Thick lines represent the light line, the even mode and the odd mode, respectively. The horizontal and the vertical axis indicate the wavevector in the propagation direction \( (k_x \text{ in figure 1}) \) and the normalized frequency. The dashed lines indicate the up and bottom edges of the PBG region. (d) (e) (f) Group index \( n_g \) and the GVD value \( \beta_2 \) as the function of the wavelength \( \lambda \) for the even mode in (a) (b) (c), respectively. Solid lines represent the group index curves and the dotted lines represent the GVD values.

Infiltration. This phenomenon can be understood clearly with the electromagnetic variation theorem. In waveguide, the low frequency modes are concentrated in the high dielectric region and the high frequency modes are concentrated in the low dielectric region. Enlarging the high dielectric in the central region would reduce the energy of the modes and pull the guided mode down to the low frequency region. The infiltrated reconfigurable dielectric into the slot shifts the operating wavelength to longer wavelength region as a result. Besides the dielectric in the slot weakens the coupling between the slot and the empty holes on both sides of the edge. The bandwidth is narrowed and the slope of the dispersion curve is decreased. Therefore the group index is increased with the increasing of \( n_s \) as figure 2 illustrated.
Correspondingly, the dielectric infiltrated into the round holes and annular holes should have low refractive index, so that the coupling between the slot and the holes remain weak and the low frequency modes are confined in the center of the waveguide. Therefore, only the effects of the

![Figure 3](image1.png)

Figure 3. (a) The even mode of the guided band in the ASPhCW for different refractive index values of the reconfigurable dielectric infiltrated into the round holes and annular holes. (b) The group index \( n_g \) as a function of the wavelength \( \lambda \) for different refractive index values of the reconfigurable dielectric.

refractive index of the gaseous dielectric infiltrated into the round holes and annular holes to the dispersion curves and the group index curves are studied, as shown in figure 3. It is shown that the even mode of the guided band in the ASPhCW is pulled down to low frequency region. The corresponding constant \( n_g \) is decreased and disappearing gradually. It can be seen that \( n_g \) is 17.2, 15.4, 13.8 and 12.6 for \( n_h = 1.00, 1.05, 1.10 \) and 1.14. The bandwidths are 13.67nm, 14.30nm, 14.71nm, 16.63nm and the NDBP values are 0.15, 0.14, 0.13, 0.13, respectively. The central wavelength is red-shifted from 1561.15nm to 1651.42nm. Similarly with the slot case above, the increasing of the refractive index values of the gaseous dielectric infiltrated into the round holes and annular holes causes the enlargement of the high dielectric region. Thus the energy of the modes is reduced and the mode is shifted to the low frequency region. Moreover the infiltration of the gaseous dielectric enhances the coupling of the slot and the ring-shape-holes, because they are in the low dielectric region. As a result, the bandwidth of the even mode is enlarged and the slope of the dispersion curve is increased too. Therefore the group index \( n_g \) is decreased with the increasing of the refractive index of the low index gaseous infiltrated into the holes.

![Figure 4](image2.png)

Figure 4. The group index \( n_g \) as a function of the wavelength \( \lambda \) for different refractive index values of the high and low index reconfigurable dielectric infiltrated into the ASPhCW.

It should be noted that the increasing of \( n_g \) is usually accompanied by the decreasing of the bandwidth and the increasing of the bandwidth is also accompanied by the decreasing of \( n_g \). It means that the largest \( n_s \) or the smallest \( n_h \) is not the best option for NDBP. To optimize the optical property
of the waveguide, the slot and the holes are infiltrated with gaseous and solid dielectric respectively. In the simulation, the central slot is infiltrated with the high index solid dielectric with the effective refractive index \( n_s \), meanwhile the annular holes and the round holes are infiltrated with low index gaseous dielectric with the effective refractive index \( n_h \), as shown in figure 1. After a large amount of calculations, it is found that the constant group index values could be 41.6, 35.8, 31.8, 28.5, 25.6, with all the NDBP values equaling about 0.17, as shown in figure 4. By tuning \( n_s \) slightly, the constant group index and the NDBP could be optimized to larger values. The optimized values of \( n_h \) and \( n_s \) with the constant group index \( n_g \), the central wavelength \( \lambda_c \), the bandwidth \( \Delta \lambda \) and the NDBP are summarized in Table 1. It can be seen that the constant \( n_g \) could be tuned from 17.2 to 44.8. The central wavelength \( \lambda_c \) could be tuned from 1561.15nm to 2020.42nm. The NDBP values could be as large as 0.25, increased by 69%.

| \( n_h \) | \( n_s \) | constant \( n_g \) | \( \lambda_c \) (nm) | \( \Delta \lambda \) (nm) | NDBP |
|-----|-----|------|--------|--------|------|
| 1.00 | 1.00 | 17.2 | 1561.149 | 13.66725 | 0.15023 |
| 1.00 | 3.05 | 41.6 | 2000.862 | 8.39188 | 0.17452 |
| 1.00 | 3.13 | 44.8 | 2006.742 | 11.28347 | 0.25185 |
| 1.05 | 3.00 | 35.8 | 2002.827 | 9.68893 | 0.17393 |
| 1.05 | 3.10 | 39.4 | 2010.178 | 12.87635 | 0.25228 |
| 1.10 | 2.97 | 31.8 | 2006.026 | 10.94265 | 0.1737 |
| 1.10 | 3.07 | 34.9 | 2013.607 | 14.56561 | 0.2527 |
| 1.14 | 2.93 | 28.5 | 2009.192 | 12.2737 | 0.174 |
| 1.14 | 3.03 | 31.2 | 2017.021 | 16.35199 | 0.25304 |
| 1.18 | 2.90 | 25.6 | 2012.322 | 13.6748 | 0.17426 |
| 1.18 | 3.00 | 28.0 | 2020.418 | 18.25202 | 0.25348 |

The values of \( n_s \) and \( n_h \) in the calculation are reasonable and realizable. The opto-fluidic infiltration technique has been experimentally realized in 100nm scale[20]. Therefore this infiltration of high and low index reconfigurable dielectric scheme is realizable from the fabrication point of view. Owing to the flexibility of this scheme, it is possible to tune the operating wavelength and the slow light parameters of the optical devices.

4. Conclusion
In general, it is demonstrated that tuning the central wavelength and the group index of the slow light in the ASPhCW can be realized by infiltrating the crystal with high and low index reconfigurable dielectric. The guided mode of slow light could be tuned from having constant group index equaling 17.2 with 13.66nm bandwidth centered at 1561.15nm to owing constant group index equaling 44.8 with 8.39nm bandwidth centered at 2006.74nm. The corresponding NDBP values could be as large as 0.25. This post-processing scheme provides a realizable method of tuning the crystal flexibly and enlarging NDBP by about 69%.

Acknowledgments
This work was financially supported by the Research Project of Peking Polytechnic (2020Z007-KXZ, 2020Z169-KXZ).

References
[1] Baba, T. (2008) Slow light in photonic crystals. Nat. Photonics., 2: 465-473.
[2] Corcoran, B., Monat, C., Grillet, C., Moss, D. J., Eggleton, B. J., White, T. P., O'Faolain, L., and Krauss, T. F. (2009) Green light emission in silicon through slow-light enhanced third-
harmonic generation in photonic-crystal waveguides. Nat. Photonics., 3: 206-210.

[3] Rawal, S., Sinha, R. K., and Rue, R. M. D. L. (2009) Slow light miniature devices with ultra-flattened dispersion in silicon-on-insulator photonic crystal. Opt. Express., 17: 13315-13325.

[4] Adachi, J., Ishikura, N., Sasaki, H., and Baba, T. (2010) Wide Range Tuning of Slow Light Pulse in SOI Photonic Crystal Coupled Waveguide via Folded Chirping. IEEE. J. Sel. Top. Quant., 16: 192-199.

[5] Hao, R., Cassen, E., Kurt, H., Hou, J., Roux, X. L., Marris-Morini, D., Vivien, L., Gao, D., Zhou, Z., and Zhang, X. (2010) Novel Kind of Semislow Light Photonic Crystal Waveguides With Large Delay-Bandwidth Product. IEEE Photon. Technol. Lett., 22: 844-846.

[6] Wu, M. H., Lei, C. U., Zhang, W. M., and Xiong, H. N. (2010) Non-Markovian dynamics of a microcavity coupled to a waveguide in photonic crystals. Opt. Express., 18: 18407-18418.

[7] Zablocki, M. J., Sharkawy, A., Ebil, O., Shi, S., and Prather, D. (2010) Electro-optically switched compact coupled photonic crystal waveguide directional coupler. Appl. Phys. Lett., 96: p. 081110.

[8] Engelen, R. J. P., Sugimoto, Y., Watanabe, Y., Korterik, J. P., Ikeda, N., Hulst, N. F. V., Asakawa, K., and Kuipers, J. P. (2006) The effect of higher-order dispersion on slow light propagation in photonic crystal waveguides. Opt. Express., 14: 1658-1672.

[9] Hamachi, Y., Kubo, S., and Baba, T. (2009) Slow light with low dispersion and nonlinear enhancement in a lattice-shifted photonic crystal waveguide. Opt. Lett., 1072-1074.

[10] Monat, C., Corcoran, B., Ebil-Heidari, M., Grillet, C., and Krauss, T. F. (2009) Slow light enhancement of nonlinear effects in silicon engineered photonic crystal waveguides. Opt. Express., 17: 2944-2953.

[11] Sterke, C. M. D., Dossou, K. B., White, T. P., Botten, L. C., and Mcphedran, R. C. (2009) Efficient coupling into slow light photonic crystal waveguide without transition region: Role of evanescent modes. Opt. Express., 17: 17338-17343.

[12] Jägerská, J., Thomas, N. L., Zabelin, V., Houdré, R., and Baets, R. (2009) Experimental observation of slow mode dispersion in photonic crystal coupled-cavity waveguides. Opt. Lett., 34: 359-361.

[13] Säynäjoki, M., Mülol, J., Ahopelto, J., and Lipsanen, H. (2007) Dispersion engineering of photonic crystal waveguides with ring-shaped holes. Opt. Express., 15: 8323-8328.

[14] Mirjalili, S. M. (2015) Ellipse-ring-shaped-hole photonic crystal waveguide. Optik., 126: 56-60.

[15] Mirjalili, S. M., Abedi, K., and Mirjalili, S. (2013) Optical buffer performance enhancement using Particle Swarm Optimization in Ring-Shape-Hole Photonic Crystal Waveguide. Optik., 124: 5989-5993.

[16] Zhu, K. T., Deng, T. S., Sun, Y., Zhang, Q. F., and Wu, J. L. (2012) Design of wideband and low group velocity based on coupled cavity waveguides. Opt. Commun., 285: 2611-2614.

[17] Abood, I., Elshahat, S., and Ouyang, Z. (2020) High Figure of Merit Optical Buffering in Coupled-Slot Slab Photonic Crystal Waveguide with Ionic Liquid. Nanomaterials., 10: p. 1742.

[18] Jin, Hwan, Park, Ik, Jang, Gyeong, Woo, Kim, Hyuna, and Lee. (2019) High transmittance and deep RGB primary electrochromic color filter for high light out-coupling electro-optical devices. Opt. Express., 27: 25531-25543.

[19] Higashino, Y., Isobe, T., Matsushita, S., and Nakajima, A. (2020) Preparation and properties of transparent solid–liquid hybrid materials using porous silica with silicone oil or ionic liquid. Mater. Res. Bull., 130: p. 110902.

[20] Intonti, F., Vignolini, S., Türck, V., Colocci, M., Bettotti, P., Pavesi, L., Schweizer, S. L., Wehrspohn, R., and Wiersma, D. (2006) Rewritable photonic circuits. Appl. Phys. Lett., 89: p. 211117.