Front. Phys. 12(1), 124204 (2017)
DOI 10.1007/s11467-016-0598-x

RESEARCH ARTICLE

Ultraslow-light effects in symmetric and asymmetric waveguide structures with moon-like scatterers

Yong Wan, Xiao-Hui Ge, Sheng Xu, Yue Guo, Feng Yuan†

College of Physics Science, Qingdao University, Qingdao 266071, China
Corresponding author. E-mail: †yuan@qdu.edu.cn
Received March 25, 2016; accepted May 12, 2016

Ultraslow-light effects in two-dimensional hexagonal-lattice coupled waveguide with moon-like scatterers were theoretically studied using the plane-wave expansion method. For symmetric structures, simulations showed that slow light with high group index can be achieved by shifting the scatterers and adjusting the radius of moon-like scatterers. The maximum group index was over 8.0×10^4. For asymmetric structures, simulations showed that slow light with flat band and high group index can be obtained by shifting the scatterers, adjusting the radius of moon-like scatterers, and rotating the scatterers. The maximum group index was over 5.7×10^5 with a "saddle-like" relationship between the frequency and group index.

Keywords moon-like scatterer, slow light, coupled waveguide, photonic crystal

PACS numbers 42.70.Qs, 42.15.Eq, 42.82.Et

Frontiers of Physics

1 Introduction

There has been growing interest in the research of slow light effect [1–4] for many years. It has great potential for use in all-optical computing and communication systems, e.g., optical buffers, microphotonic sensors, and devices that enhance nonlinearity effects [5–7]. There are mainly two types of photonic crystal waveguides (PCWs) for slow light, i.e., line-defect waveguides and coupled-resonator waveguides [8, 9]. Line-defect waveguides can achieve slow light with wide band and low group index ranging from several to several hundred, while coupled-resonator waveguides can generate ultraslow light with group index above 10^3 and even up to 10^6, which, however, may be accompanied with very narrow band and high dispersion.

Many successful attempts have been made to obtain optimized slow light effects. For line-defect waveguides, it is useful to adjust the radius of circles [10–12] and the width of line defects [13, 14], and to introduce heterostructures [15–17]. For coupled-resonator waveguides, it is effective to adjust the radius of holes and the size of microcavities, change the distance between adjacent microcavities, and shift the location of surrounding rods [18–22]. However, it is not easy to obtain optimized ultraslow light effects. Some existing researches [23, 24] also combined two kinds of PCWs, called coupled waveguides (CWs), to achieve low group velocity and low dispersion.

In this paper, we study the slow-light effect in two-dimensional (2D) moon-like CWs by using the plane-wave expansion (PWE) method. The symmetry of individual cells is broken by introducing a reduced symmetrical moon-like structure. Moon-like scatterers are assumed to be formed by the intersection of Si rods and circular air holes. The degree of freedom to manipulate light propagation arises because of rotational sensitivity of CWs. Numerical simulations show that slow light with decent flat band can be realized, and the structures with slow light and group index up to 5.7×10^5 can be achieved by shifting the scatterers, adjusting the radius of moon-like scatterers, and changing the symmetry of the structure.

2 Simulations

In order to investigate the effects of symmetry on CWs, two kinds of configurations were built. Figure 1 shows the coupled waveguides consisting of moon-like scatterers containing both microcavities and line defects. Figure 1(a) is the geometry of the moon-like scatterer. Figure 1(b) is an example of the symmetrical structure, and

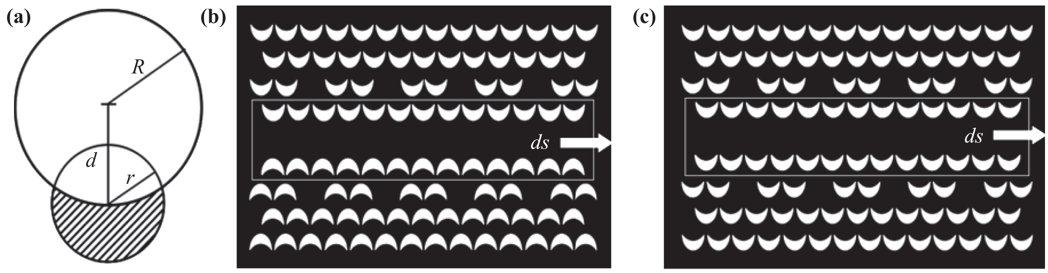

Fig. 1 **(a)** The geometry of moon-liked scatterer; **(b)** A kind of symmetrical structure with both microcavity and line defect; **(c)** The asymmetrical structure after rotation.

in Fig. 1(c) the structure is asymmetrical under rotation. Assume the material is silicon ($n_{si} = 3.5$), and denote the lattice constant of the structure, the top and bottom radius of the moon-like scatterer, the center distance, and the transverse shifting inside the white line by a, R, r, d ($d = R$ here), and ds, respectively, as shown in Fig. 1.

The simulation process for the structures in Figs. 1(b) and (c) is as follow. We adjusted the parameters r, R, and ds in accordance with the lattice constant a so as to find the appropriate bandgap and acceptable wide and flat band regions for transverse electric (TE)-like polarized modes. In the supercell calculation based on the PWE, we set the number of plane waves in each axis to be 32 and the eigenvalue tolerance to be 10^{-8} for sufficient calculation precision.

The established relationship between group index and dispersion is given by the following formula [25]:

$$n_g = \frac{c}{v_g} = c\frac{\mathrm{d}k}{\mathrm{d}\omega} = n_{eff} + \omega\frac{\mathrm{d}n_{eff}}{\mathrm{d}\omega}, \tag{1}$$

where n_g is the group index. For slow light, i.e., $n_g \gg n_{eff}$, where n_{eff} is the effective group index, and the normalized frequency f can be expressed as $f = \omega a/(2\pi c)$. Here, ω is the central angle frequency of the incident pulse, c is the speed of light in vacuum, $k = 2\pi n_{eff}/\lambda$, with λ being the wavelength corresponding to the working frequency. Thus, Eq. (1) can be simplified as

$$n_g = \frac{a}{2\pi}\frac{\mathrm{d}k}{\mathrm{d}f}. \tag{2}$$

3 Results and discussion

For the symmetrically coupled waveguides with moon-like scatterers, which contain both microcavities and line defects, flat band and large group index n_g could be achieved by adjusting the parameters r, R, and ds. Figure 2 shows the variation of the slow-light effect in the TE modes of symmetrically coupled waveguides with moon-like scatterers. The linear region of the curves represents the ideal slow-light region.

Figure 2(a) shows the curves for f and k as the parameter r varies for fixed $R = 1.0a$ and $ds = 0.2a$. In Fig. 2(b) the parameter R varies with $r = 0.39a$ and $ds = 0.2a$ fixed, and in Fig. 2(c) the parameter ds varies with $R = 1.0a$ and $r = 0.39a$ fixed. It was observed that for $r = 0.38a - 0.39a$, $R = 0.9a - 1.1a$, and $ds = 0.19a - 0.20a$, the linear region is well achieved for CWs with the normalized wave number $ka/(2\pi) > 0.39$. With higher precision of the parameters, a maximum of n_g of about 8.0×10^4 was observed for $R = 1.0a$, $r = 0.391a$, $ds = 0.2a$ and $f \approx 0.231$. The value of n_g decreased rapidly as f increased, as shown in Fig. 2(d).

To break the symmetry of the structure, we built asymmetrically coupled waveguides with moon-like scatterers. The asymmetrical structures were achieved by rotating the aforementioned symmetrical structure slightly. Flat band and larger group index could also be obtained by adjusting the parameters r, R, and ds. An interesting "saddle-like" behavior of the curves for f and n_g could be observed after breaking the symmetry of the structure.

Figure 3 shows the variation of the slow-light effect in this situation. Figure 3(a) shows the curves for f and k as the parameter r varies for fixed $R = 1.0a$ and $ds = 0.15a$. In Fig. 3(b) the parameter R varies with $r = 0.38a$ and $ds = 0.15a$ fixed, and in Fig. 3(c) the parameter ds varies with $R = 1.0a$ and $r = 0.38a$ fixed. It was observed that for $r = 0.36a - 0.38a$, $R = 0.8a - 1.0a$, and $ds = 0.15a - 0.16a$, the linear region is well achieved for CWs with the normalized wave number $0.36 < ka/(2\pi) < 0.39$. With better precision of the parameters, the peak of n_g (about 5.7×10^5) could be observed for $R = 1.0a$, $r = 0.381a$, $ds = 0.15a$, and $f \approx 0.215$, as shown in Fig. 3(d).

After the rotation of the moon-like scatterers with respect to the line defects, the flat band was larger than that of the symmetrical structures without rotation. When the parameters of the asymmetrical structures were adjusted properly, the curves for f and n_g

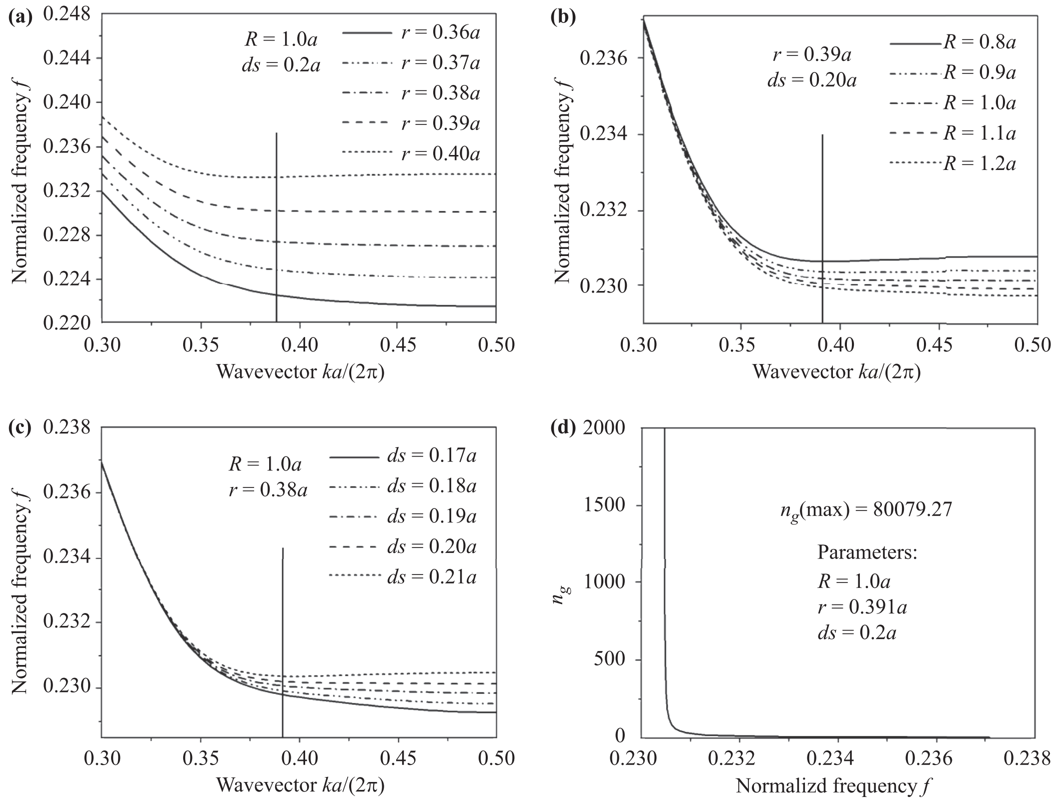

Fig. 2 The variation of **(a)** f and k as varying parameter r; **(b)** f and k as varying parameter R; **(c)** f and k as varying parameter ds; **(d)** n_g and f with optimized parameters.

exhibited a "saddle-like" behavior, as shown in Fig. 3. Moreover, the maximum of n_g could be much higher than that of the symmetrical structures.

In summary, different combinations of the structure parameters R and r could affect the relationship between f and k, so that flat band of slow light can be adjusted slightly. Moreover, it is useful to shift (by changing the value of ds) and rotate (through the asymmetrical structure) the scatterers so as to improve the flat band. The value of n_g and the corresponding frequency change for $R = 1.0a$ and various values of r and ds are shown in Table 1. The maximum of n_g for the asymmetrical moon-like coupled waveguides could reach up to 5.7×10^5, which was also much higher than that of the symmetrical structures.

Moreover, the asymmetry of structures can influence the slow-light effect of moon-like coupled waveguides. As shown in Fig. 3(c), the curves for f and n_g exhibits a "saddle-like" behavior. Generally, the curves for f and n_g monotonically decrease rapidly, and the bandwidth of slow light is very small, even though the half peak value of the group index n_g is chosen. The advantage of this "saddle-like" behavior is that the bandwidth of slow light increases significantly (when the half peak value of group index n_g is chosen), while the peak value of the group index n_g remains the same or even becomes larger.

The "saddle-like" behavior of the group index is a phenomenon but not a property of the slow-light effect. The mechanism for this "saddle-like" behavior is that there are three kinds of dispersions, i.e., positive dispersion, negative dispersion, and flat-band dispersion in the dispersion curve, simultaneously. Because the principle of dispersion compensation, i.e., the positive or negative dispersion can be compensated for by the flat-band dis-

Table 1 Optimized parameters and maximum group index for different models.

Model	Symmetrical structure				Asymmetrical structure			
r/a	0.381	0.381	0.391	0.391	0.381	0.381	0.391	0.391
ds/a	0.150	0.200	0.150	0.200	0.150	0.200	0.150	0.200
f	0.227	0.226	0.229	0.231	0.215	0.217	0.218	0.220
n_g	8.8×10^3	2.1×10^3	2.7×10^3	8.0×10^4	5.7×10^5	6.2×10^3	3.5×10^4	4.3×10^3

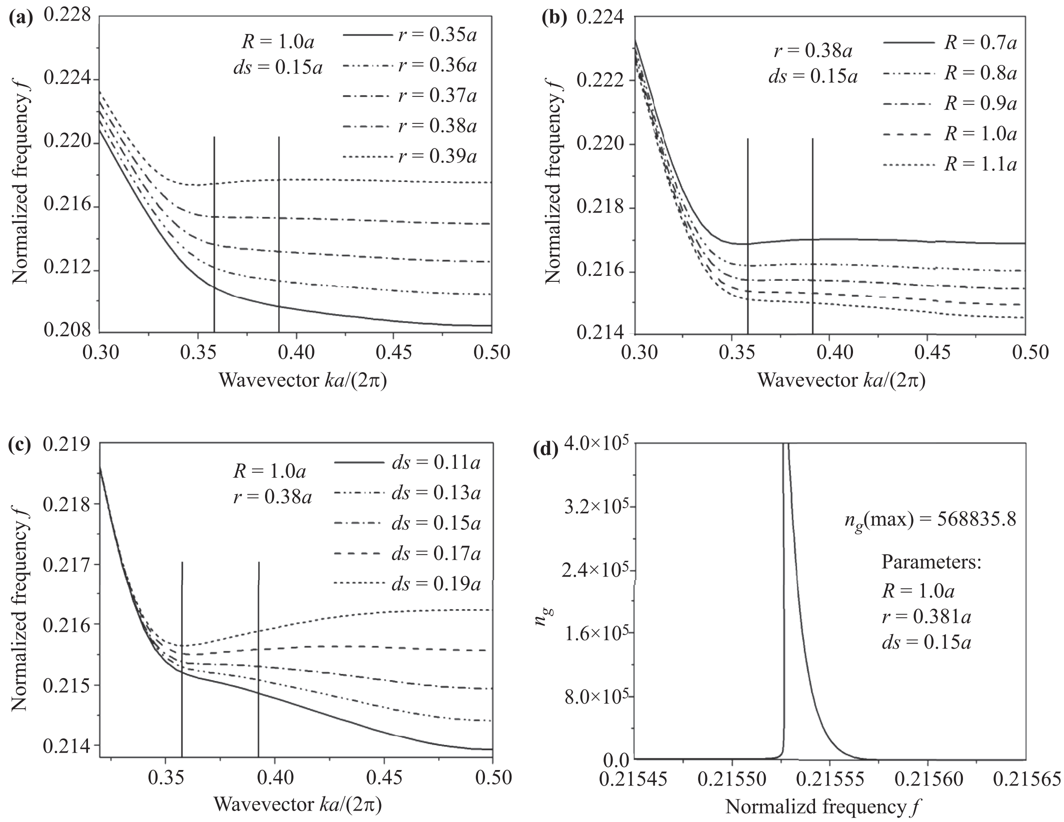

Fig. 3 The variation of **(a)** f and k as varying parameter r; **(b)** f and k as varying parameter R; **(c)** f and k as varying parameter ds; **(d)** n_g and f with optimized parameters.

persion, and because the total dispersion can have a small change and reduce the signal distortion after the compensation in the transmission process, the asymmetric structure enhances the slow-light effect. While the slow light of the symmetric structure in Fig. 2 is a result of the backscatter principle, a large group index can be easily generated at the Brillouin zone boundaries.

Finally, the slow-light effect of CWs has great potential uses in all-optical computing fields because of the property of large group index and low group velocity. The large group index is an important parameter in estimating slow light. Both the two types of CWs can achieve large group index by introducing moon-like scatterers, shifting the scatterers, adjusting the radius of moon-like scatterers, and changing the symmetry of the structure.

4 Summary

The slow-light effect in CWs with 2D hexagonal lattices was theoretically studied using the PWE. The results showed that CWs with moon-like scatterers achieve high group index by adjusting the parameters properly, and thus practical utility of these structures is evident. In order to obtain better results, such as fewer scattering, better flat band, and higher group index, the structures can be optimized by rotating the scatterers, introducing new types of defects, and changing the dielectric constants of the structures. To summarize, the slow-light effect with decent flat band and high group index can be achieved by reducing the symmetric characteristics, e.g., shifting or rotating the scatterers.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant Nos. 11144007 and 61307050).

References

1. T. F. Krauss, Slow light in photonic crystal waveguides, *J. Phys. D* 40(9), 2666 (2007)
2. T. Baba, Slow light in photonic crystals, *Nat. Photonics* 2(8), 465 (2008)
3. Y. Hamachi, S. Kubo, and T. Baba, Slow light with low dispersion and nonlinear enhancement in a lattice-shifted photonic crystal waveguide, *Opt. Lett.* 34(7), 1072 (2009)
4. P. Kanakis, T. Kamalakis, and T. Sphicopoulos, Designing slow-light photonic crystal waveguides for four-wave mixing applications, *Opt. Lett.* 39(4), 884 (2014)

5. Y. Xu, L. Xiang, E. Cassan, D. Gao, and X. Zhang, Slow light in an alternative row of ellipse-hole photonic crystal waveguide, *Appl. Opt.* 52(6), 1155 (2013)
6. B. Wang, M. A. Dündar, R. Nötzel, F. Karouta, S. He, and R. W. van der Heijden, Photonic crystal slot nanobeam slow light waveguides for refractive index sensing, *Appl. Phys. Lett.* 97(15), 151105 (2010)
7. C. Monat, B. Corcoran, M. Ebnali-Heidari, C. Grillet, B. J. Eggleton, T. P. White, L. O'Faolain, and T. F. Krauss, Slow light enhancement of nonlinear effects in silicon engineered photonic crystal waveguides, *Opt. Express* 17(4), 2944 (2009)
8. K. Inoue, H. Oda, N. Ikeda, and K. Asakawa, Enhanced third-order nonlinear effects in slow-light photonic-crystal slab waveguides of line-defect, *Opt. Express* 17(9), 7206 (2009)
9. N. Matsuda, H. Takesue, K. Shimizu, Y. Tokura, E. Kuramochi, and M. Notomi, Slow light enhanced correlated photon pair generation in photonic-crystal coupled-resonator optical waveguides, *Opt. Express* 21(7), 8596 (2013)
10. S. Kubo, D. Mori, and T. Baba, Low-group-velocity and low-dispersion slow light in photonic crystal waveguides, *Opt. Lett.* 32(20), 2981 (2007)
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* 14(20), 9444 (2006)
12. C. Li, H. Tian, C. Zheng, and Y. Ji, Improved line defect structures for slow light transmission in photonic crystal waveguide, *Opt. Commun.* 279(1), 214 (2007)
13. 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* 15(1), 219 (2007)
14. A. Di Falco, L. O'Faolain, and T. F. Krauss, Dispersion control and slow light in slotted photonic crystal waveguides, *Appl. Phys. Lett.* 92(8), 083501 (2008)
15. C. Xiong, C. Monat, A. S. Clark, C. Grillet, G. D. Marshall, M. J. Steel, J. Li, L. O'Faolain, T. F. Krauss, J. G. Rarity, and B. J. Eggleton, Slow-light enhanced correlated photon pair generation in a silicon photonic crystal waveguide, *Opt. Lett.* 36(17), 3413 (2011)
16. N. Ozaki, Y. Kitagawa, Y. Takata, N. Ikeda, Y. Watanabe, A. Mizutani, Y. Sugimoto, and K. Asakawa, High transmission recovery of slow light in a photonic crystal waveguide using a hetero group-velocity waveguide, *Opt. Express* 15(13), 7974 (2007)
17. T. P. White, L. C. Botten, C. Martijn de Sterke, K. B. Dossou, and R. C. McPhedran, Efficient slow-light coupling in a photonic crystal waveguide without transition region, *Opt. Lett.* 33(22), 2644 (2008)
18. L. Hui, T. Huiping, L. Changhong, and J. Yue-Feng, Research on new type of slow light structure based on 2D photonic crystal coupled cavity waveguide, *Acta Physica Sinica* 58(3), 2049 (2009)
19. K. Tian, W. Arora, S. Takahashi, J. Hong, and G. Barbastathis, Dynamic group velocity control in a mechanically tunable photonic-crystal coupled-resonator optical waveguide, *Phys. Rev. B* 80(13), 134305 (2009)
20. K. Üstün and H. Kurt, Ultra slow light achievement in photonic crystals by merging coupled cavities with waveguides, *Opt. Express* 18(20), 21155 (2010)
21. N. Matsuda, E. Kuramochi, H. Takesue, and M. Notomi, Dispersion and light transport characteristics of large-scale photonic-crystal coupled nanocavity arrays, *Opt. Lett.* 39(8), 2290 (2014)
22. H. Kurt, M. Turduev, and I. H. Giden, Crescent shaped dielectric periodic structure for light manipulation, *Opt. Express* 20(7), 7184 (2012)
23. S. Kocaman, X. Yang, J. F. McMillan, M. B. Yu, D. L. Kwong, and C. W. Wong, Observations of temporal group delays in slow-light multiple coupled photonic crystal cavities, *Appl. Phys. Lett.* 96(22), 221111 (2010)
24. T. Baba, T. Kawaaski, H. Sasaki, J. Adachi, and D. Mori, Large delay-bandwidth product and tuning of slow light pulse in photonic crystal coupled waveguide, *Opt. Express* 16(12), 9245 (2008)
25. Y. Wan, K. Fu, C. Li, and M. Yun, Improving slow light effect in photonic crystal line defect waveguide by using eye-shaped scatterers, *Opt. Commun.* 286(1), 192 (2013)