Wavelength division demultiplexing by photonic crystal waveguides with asymmetric corrugated surfaces

Cuilian Liu (刘翠莲), Zhixiang Tang (唐志祥)*, Huiming Dong (董慧敏), Dongmo Song (宋东谟), Zhaoming Luo (罗朝明), Xiaohui Ling (凌晓辉), and Shiming Cao (曹始明)

Key Laboratory for Micro/Nano Optoelectronic Devices of the Ministry of Education,
School of Computer and Communication, Hunan University, Changsha 410082, China
**E-mail: tzx@hnu.edu.cn*

Received March 8, 2010

We propose a new type of wavelength division demultiplexer composed of a photonic crystal waveguide with asymmetric corrugated exit surface. The focus displacement for different symmetric corrugated surfaces is relative to the intensity of the excited surface mode. By systematically investigating the effects of the parameters of the corrugated surface on the focus shift, we demonstrate an on-axis focus by a photonic crystal waveguide with an asymmetric corrugated exit surface at a specific wavelength. The precise equivalences of surface modes at each side of the exit surface are broken. Thus, for the light source with other wavelengths, the emerging beams are off-axis focused at different directions, similar to the function of a wavelength division demultiplexer.

OCIS codes: 240.6690, 130.5296, 050.5298.
doi: 10.3788/COL20100808.0761.

Light emitted from a photonic crystal waveguide (PCW) is commonly diffracted in all directions. Recently, it has been demonstrated that this radiation can be concentrated into a narrow beam using the PCW with periodic modulations at the exit surface[1−5], such as that of the metallic waveguide structure surrounded by corrugated surfaces[6−10]. Moreover, if the surface corrugation is designed properly, a focus can be formed from the constructive interference of the diffracted lights[11−13]. Early studies have indicated that excitation of the surface mode[14−16] is the key factor in shaping narrow beams and that the beam direction is sensitive to surface corrugation. Recently, different surface modes excited by asymmetric surface corrugation have allowed the presentation of an interesting off-axis focus in the far-field region in metal slit[10] and PCW[13], respectively.

In this letter, we use the finite-difference time-domain (FDTD) numerical method to demonstrate an on-axis focusing at a certain wavelength achieved by properly designing the asymmetric corrugated surfaces of a PCW. To the best of our knowledge, this is the first time for a PCW with asymmetric surface to realize on-axis focus. Furthermore, for light source with wavelength smaller (or larger) than this specific one, an off-axis focus can be formed to the right side (or left side) of the axis of the PCW in the far-field region. This function is similar to that of a wavelength division demultiplexer[17−20].

The photonic crystal was formed by a square lattice of cylinders in vacuum, with a width of $y = 7a$ and a breadth of $x = 20a$, and the radius of the cylinder was $r = 0.18a$, where a was the lattice period. The refractive index of the cylinders was $n = 3.4$. A single-mode waveguide was fabricated by removing a row of cylinders along the plane $x = 0$, as shown in Fig. 1, which supported a guided mode for the transverse magnetic (TM) polarization with the normalized frequency a/λ between 0.30 and 0.44, where λ was the wavelength in free space. A corrugated surface was created by decreasing the radius and refractive index of the odd-numbered cylinders of the surface layer (the cylinders were ordered according to their distance to the waveguide) to $0.09a$ and 2.5, respectively. At the same time, the period of the corrugation Λ, which was twice as long as the distance between the odd-numbered and even-numbered cylinders, was reduced to $1.5a$.

For this PCW with symmetric corrugated surface at the output side, an on-axis focus can be shaped for a light source with normalized frequency a/λ between 0.34 and 0.44, i.e., the wavelength from $a/0.44$ to $a/0.34$. In 2005, Yu *et al.* presented a simple and intuitive sketch to understand this similar phenomenon in metallic slit and proposed its physical origin[9]. The excitation of surface plasmon polariton (SPP) plays an important role in the extraordinary (high efficiency and highly directional) emission of this kind of structure. Similarly, PCWs with appropriately corrugated surfaces can support surface electromagnetic modes and shape directional beaming. Given that the mechanisms are similar to ours, we borrowed Yu's sketch to explain and design the off- and on-axis focus in PCW.

We rewrite Eq. (2) of Ref. [9] as

$$k_{\rm sm} \pm m\frac{2\pi}{\Lambda} = k'_x = k_0 \sin\theta, \qquad (1)$$

where $k_{\rm sm}$ represents the wave vector of the surface

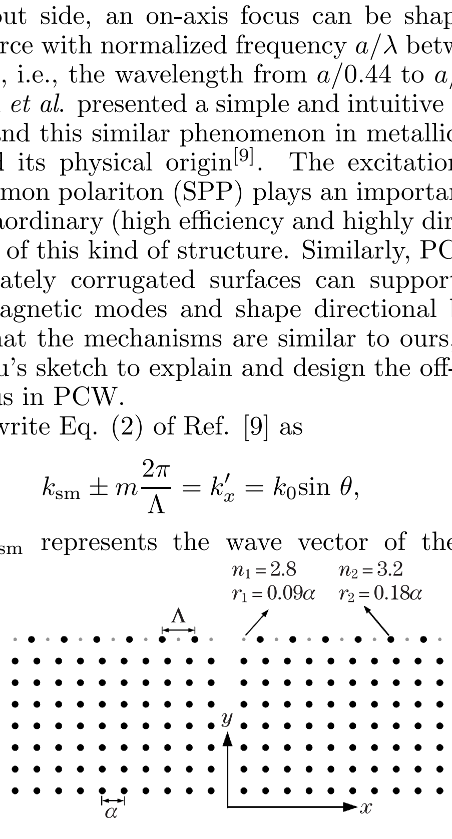

Fig. 1. PCW with symmetric corrugated surface.

1671-7694/2010/080761-03

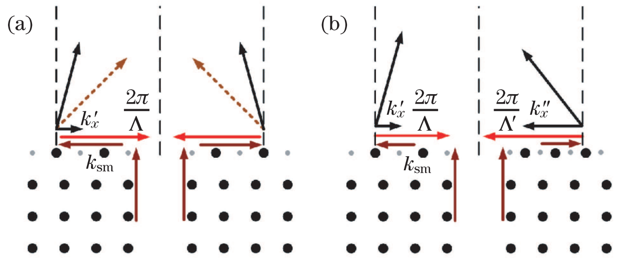

Fig. 2. Schematic for (a) on-axis focus and (b) off-axis focus by the PCW with symmetric and asymmetric corrugated surfaces, respectively.

electromagnetic modes excited by the corrugated exit surface of PCW. As stated in Ref. [9], the sign of $k'_x = k_0\sin\theta$, which is the transverse component of the diffracted wave vector, determines whether or not the emerging beams are focused, where θ is the angle between the wave vector in free space k_0 and the surface normal. Moreover, the value of k'_x affects the position of the focus. It can be seen from Eq. (1) that a small Λ (must be smaller than $2a$) leads to a large k'_x and results in the focus moving closer to the output surface of the PCW, as shown in Fig. 2(a). This deduction coincides with the numerical simulations found in Ref. [13].

However, if each side of the PCW surface is constructed with different corrugated periods of Λ, an off-axis focus will be formed because unequal k'_x values of each side are excited, as illustrated in Fig. 2(b). This phenomenon has been proven in Refs. [10,13]. Moreover, apart from constructing different corrugated periods of Λ, there are other ways of constructing unsymmetrical corrugated surfaces, such as turning odd-numbered or even-numbered cylinders at one side of the exit surface with different radii and refractive indices. Given that each parameter has different effects on k'_x at a certain wavelength, properly designed asymmetric corrugated surfaces can realize equal k'_x for both sides and an on-axis focus. For example, we can increase the period Λ of one side of the exit surface to obtain a decreased k'_x. At the same time, we can adjust the radius and refractive index of odd-numbered or even-numbered cylinders of the other side to obtain an equal k'_x. In this way, an on-axis focus can be achieved although the corrugated exit surface is asymmetric. To the best of our knowledge, this phenomenon has not been demonstrated in any other study.

Prior to designing this kind of asymmetric corrugated surface, we systematically investigated the effect of these parameters on the focus locations (namely k'_x) by means of the FDTD numerical simulations. We mainly considered parameters, such as the radius r_1 and refractive index of odd-numbered cylinders n_1, and those of even-numbered cylinders r_2 and n_2. From the calculated results presented in Fig. 3, we can see that at the same normalized frequency, the focus moves away from the PCW as the radius or refractive index of all cylinders increases. For the same corrugated surface, the distance between the focus and the PCW increases with the normalized frequencies.

Based on the above analyses and by repeatedly adjusting the parameters of the corrugated surfaces, we obtain a feasible scheme wherein the left side of the exit surface is set as $r_1 = 0.08a$, $r_2 = 0.16a$, $n_1 = 2.5$, and $\Lambda = 1.8a$, and the right side is set as $r_1 = 0.115a$, $r_2 = 0.16a$, $n_1 = 2.8$, and $\Lambda = 1.5a$. Owing to the weak influence of n_2 on the focus shift compared with other parameters demonstrated in Fig. 3(d), we keep this parameter invariable. Using an asymmetric exit surface, an on-axis focus is formed at the normalized frequency $a/\lambda = 0.37$, as shown in Fig. 4(b). To break the precise equivalence of k'_x at each side of the exit surface, an off-axis focus should be formed at the normalized frequency close to $a/\lambda = 0.37$. For a light source with normalized frequency smaller than 0.37, such as $a/\lambda = 0.34$, the focus is deflected to the left side of PCW's axis, as shown in Fig. 4(a). On the contrary, as shown in Fig. 4(c), the emerging beams are focused at the right side at the normalized frequency $a/\lambda = 0.39$, which is larger than this specific one. From Figs. 4(a)–(c), we can see that the emerging beams not only focus in different directions but also elongate with different lengths along the radiation direction. Thus, the optical signal with different normalized frequencies near the critical one can be divided into different directions, similar to the function of a wavelength division demultiplexer.

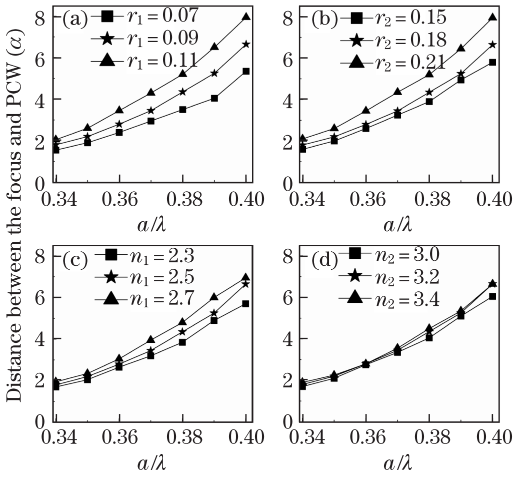

Fig. 3. Dependency of the focus location on the normalized frequency with different parameters of corrugated surface (a) Radius of the odd-numbered cylinder r_1, (b) radius of the even-numbered cylinder r_2, (c) refractive index of the odd-numbered cylinder n_1, and (d) refractive index of even-numbered cylinder n_2.

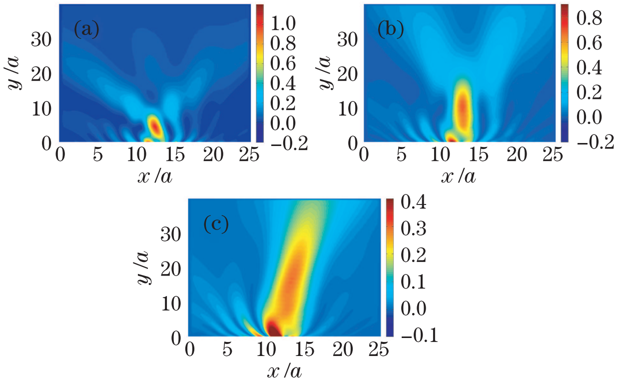

Fig. 4. Intensity distribution of wavelength division demultiplexing by the PCW with asymmetric corrugated surface at (a) $a/\lambda = 0.34$, (b) $a/\lambda = 0.37$, and (c) $a/\lambda = 0.39$.

In conclusion, we have proposed a simple method to gain a qualitative understanding of the physical origin of the focus shift, which is formed by the symmetric modulation at the PCW exit surface. By systematically investigating the effects of the parameters of the corrugated exit surface on the focus shift, we have designed a kind of PCW with an asymmetric corrugated exit surface and obtained an on-axis focus at a certain wavelength. As far as we know, this is the first time that an on-axis focusing method using a PCW with asymmetric corrugated surface has been realized. The precise equivalences of the surface modes at each side of the exit surface are broken for light source with other wavelengths; thus, the focuses are formed at different directions with different focal lengths. This function is similar to the function of a wavelength division demultiplexer. Although focuses with different wavelengths have not been sufficiently distinguished in our simulations, a small difference can be detected through the sensitive metal nanowire waveguides based on surface plasma. In addition, through the use of this mechanism, a significant difference can be achieved by introducing metallic or non-circular components to the asymmetric corrugated surface.

This work was supported by the Hunan Provincial Natural Science Foundation of China (No. 08JJ3121) and the Specialized Research Fund for the Doctoral Program of Higher Education of China (No. 20090161120029).

References

1. P. Kramper, M. Agio, C. M. Soukoulis, A. Birner, F. Müller, R. B. Wehrspohn, U. Gösele, and V. Sandoghdar, Phys. Rev. Lett. **92,** 113903 (2004).
2. E. Moreno, F. J. García-Vidal, and L. Martín-Moreno, Phys. Rev. B **69,** 121402(R) (2004).
3. S. K. Morrison and Y. S. Kivshar, Appl. Phys. Lett. **86,** 081110 (2005).
4. R. Moussa, B. Wang, G. Tuttle, Th. Koschny, and C. M. Soukoulis, Phys. Rev. B **76,** 235417 (2007).
5. W. Śigaj, Phys. Rev. B **75,** 205430 (2007).
6. H. J. Lezec, A. Degiron, E. Devaux, R. A. Linke, L. Martín-Moreno, F. J. García-Vidal, and T. W. Ebbesen, Science **297,** 820 (2002).
7. L. Martín-Moreno, F. J. García-Vidal, H. J. Lezec, A. Degiron, and T. W. Ebbesen, Phys. Rev. Lett. **90,** 167401 (2003).
8. F. J. García-Vidal, H. J. Lezec, A. Degiron, T. W. Ebbesen, and L. Martín-Moreno, Phys. Rev. Lett. **90,** 213901 (2003).
9. L. Yu, D. Lin, Y. Chen, Y. Chang, K. Huang, J. Liaw, J. Yeh, J. Liu, C. Yeh, and C. Lee, Phys. Rev. B **71,** 041405(R) (2005).
10. S. Kim, H. Kim, Y. Lim, and B. Lee, Appl. Phys. Lett. **90,** 051113 (2007).
11. F. J. García-Vidal, L. Martín-Moreno, H. J. Lezec, and T. W. Ebbesen, Appl. Phys. Lett. **83,** 4500 (2003).
12. E. H. Khoo, A. Q. Liu, T. H. Cheng, J. Li, and D. Pinjala, Appl. Phys. Lett. **91,** 221105 (2007).
13. H. Chen, Y. Zeng, X. Chen, J. Wang, and W. Lu, Phys. Lett. A **372,** 5096 (2008).
14. R. Moussa, Th. Koschny, and C. M. Soukoulis, Phys. Rev. B **74,** 115111 (2006).
15. B. Wang, W. Dai, A. Fang, L. Zhang, G. Tuttle, Th. Koschny, and C. M. Soukoulis, Phys. Rev. B **74,** 195104 (2006).
16. E. H. Khoo, A. Q. Liu, and J. H. Wu, Opt. Express **13,** 20 (2005).
17. A. Q. Liu, E. H. Khoo, T. H. Cheng, E. P. Li, and J. Li, Appl. Phys. Lett. **92,** 021119 (2008).
18. S. Chen, G. Zhu, T. Yu, Q. Liao, N. Liu, and Y. Huang, Acta Opt. Sin. (in Chinese) **29,** 2898 (2009).
19. W. Kong, M. Yun, M. Wang, and F. Shan, Acta Opt. Sin. (in Chinese) **29,** 818 (2009).
20. K. Wen, R. Wang, J. Wang, and J. Li, Chinese J. Lasers (in Chinese) **35,** 1962 (2008).