Wavelength division demultiplexing by photonic crystal waveguides with asymmetric corrugated surfaces

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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.

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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 $a / \lambda$ between 0.30 and 0.44, where $\lambda$ 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 0.09$a$ and 2.5, respectively. At the same time, the period of the corrugation $\Lambda$, 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 $a / \lambda$ 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

$$k_{sm} \pm m \frac{2\pi}{\Lambda} = k_x' = k_0 \sin \theta,$$

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

\begin{tabular}{l}
$n_1 = 2.8$ \\
$r_1 = 0.09a$ \\
$n_2 = 3.2$ \\
$r_2 = 0.18a$
\end{tabular}

Fig. 1. PCW with symmetric corrugated surface.
justing the parameters of the corrugated surfaces, we
malized frequencies.

between the focus and the PCW increases with the nor-
increases. For the same corrugated surface, the distance
PCW as the radius or refractive index of all cylinders
normalized frequency, the focus moves away from the
results presented in Fig. 3, we can see that at the same
r
index of odd-numbered cylinders
emerging beams are focused, where
diffracted wave vector, determines whether or not the
surface of PCW. As stated in Ref. [9], the sign of
electromagnetic modes excited by the corrugated exit
surfaces, respectively.

Fig. 2. Schematic for (a) on-axis focus and (b) off-axis fo-
cus 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 $\theta$ is the angle be-
tween 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 $\Lambda$
(must be smaller than $2\pi$) 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 $\Lambda$, an off-axis fo-
cus will be formed because unequal $k'_{x}$ values of each
side are excited, as illustrated in Fig. 2(b). This phe-
nomenon has been proven in Refs. [10,13]. Moreover,
apart from constructing different corrugated periods of
$\Lambda$, 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 $\Lambda$
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 knowl-
edge, 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 con-
sidered 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 nor-
malized frequencies.

Based on the above analyses and by repeatedly ad-
justing 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 pa-
rameter 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 radi-
adion direction. Thus, the optical signal with different
normalized frequencies near the critical one can be di-
vided 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 demu-
ltiplexing 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.

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