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Engineering of directional emission from photonic-crystal waveguides

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We analyze, by the finite-difference time-domain numerical method, different ways to enhance the directional emission from photonic-crystal waveguides through the recently predicted beaming effect. We demonstrate that the substantial enhancement of the light emission can be achieved by adjusting the input wavelength, using a positive surface corrugation, increasing the refractive index of the surface layer, and inducing a near-surface mode. © *2005 American Institute of Physics.* [DOI: 10.1063/1.1870133]

One of the recent advances in the physics of photonic crystals is the discovery of enhanced transmission and highly directional emission from photonic-crystal waveguides predicted theoretically by Moreno *et al.*[1] and demonstrated independently in experiment by Kramper *et al.*[2] These results provide a new twist in the study of surface modes in photonic crystals. Indeed, it is generally believed that surfaces and surface modes are a highly undesirable feature of photonic crystals, unlike point defects which are useful for creating efficient waveguides with mini-band gaps inside the photonic band gaps of a periodic structure. However, appropriate corrugation of the surface layer may lead to coherent enhancement of the radiating surface modes and highly directional emission of the light from a truncated waveguide.[1,2]

The major motivation for the discovery of highly directional emission from photonic-crystal waveguides is largely provided by the physics of extraordinary optical transmission through subwavelength hole arrays in metallic thin films[3] and beaming of light from single nanoscopic apertures flanked by periodic corrugations.[4] In both those cases, an incident light beam couples to surface oscillations via corrugations in a metallic film, and is then emitted from the other side of the film being enhanced by its other corrugated surface. For photonic-crystal waveguides, properties of the surface layer[1] or terminated surface[2] provide a key physical mechanism for the excitation of surface modes, their constructive interference, and subsequent highly directed emission.

In this paper, we study, by means of the finite-difference time-domain numerical method, directional emission from a photonic-crystal waveguide achieved by appropriate corrugation of the photonic crystal interface, following the original suggestion.[1] We demonstrate several ways to enhance the light beaming effect by varying the surface properties and surface modes of a finite two-dimensional photonic crystal created by a square lattice of cylinders in vacuum. In particular, we optimize the input wavelength, the corrugation at the surface, and the refractive index of the surface layer. We demonstrate that, in comparison with the previously published results,[1] the substantial enhancement of the light emission and improved beaming effect is achieved by decreasing the input source wavelength, increasing the refractive index of the surface layer, and finally by using a positive (i.e., opposite to that of Ref. 1) corrugation displacement. We also measure the power of surface modes and reflected power and

confirm that the enhancement of the directional emission through the beaming effect links closely to the manipulation of the surface modes supported by the photonic crystal interface.

We consider a finite photonic crystal, of width $z=9a$ and breadth $x=50a$, created by a square lattice of cylinders with dielectric constant $\epsilon_r=11.56$ (e.g., GaAs at a wavelength of 1.5 μm) and radius $r=0.18\,a$, where a is the lattice period. A row of cylinders removed along the plane $x=0$ forms a single-mode waveguide (see Fig. 1) that supports a guided mode with frequencies between $\omega=0.30\times2\pi c/a$ and $\omega=0.44\times2\pi c/a$ propagating in the plane normal to the cylinders, with the electric field parallel to them. For source frequencies within the band-gap range, waveguide modes are well confined within the waveguide, and any subsequent
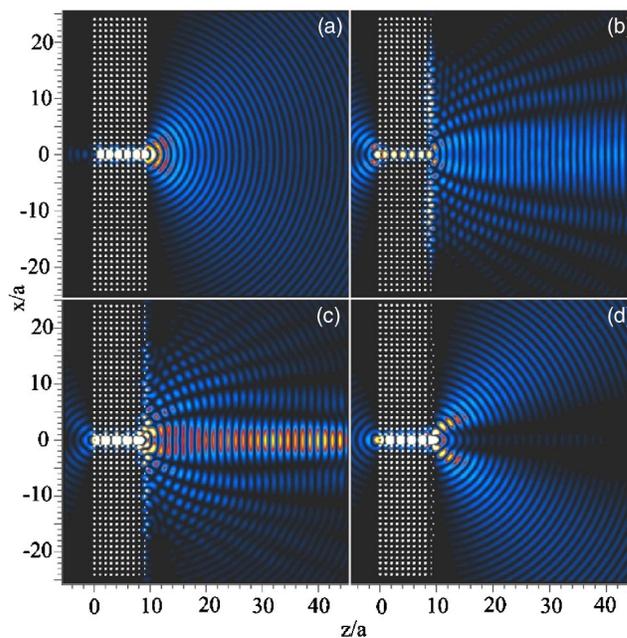

FIG. 1. (Color online) Spatial distribution of the Poynting vector for the light emitted from a photonic waveguide: (a) unchanged surface; (b) surface cylinders with $r_s=0.09$ and $N=9$ even-numbered cylinders displaced by $\Delta z=-0.3\,a$ (see Ref. 1); (c) surface cylinders with $r_s=0.09$, refractive index $n_s=3.6$, and $N=9$ odd-numbered cylinders displaced by $\Delta z=+0.4\,a$; in addition, the radius of the cylinders in the layer prior to the surface layer is reduced to $r_{s-1}=0.135\,a$; (d) surface cylinders with $r_s=0.09$, refractive index $n_s=4.5$, and $N=9$ odd-numbered cylinders displaced by $\Delta z=+0.4\,a$.

transmission from the waveguide is not effected by the width of the photonic crystal.

When a source is placed in the waveguide at the point $z=0$, it excites waves that propagate along the waveguide and are then emitted at the waveguide exit (at $z=9a$). Since no surface modes are supported by a simple truncated slab, the light radiating from the waveguide undergoes uniform angular diffraction as demonstrated in Fig. 1(a) for the spatial distribution of the Poynting vector calculated for the source frequency $\omega=0.408\times2\pi c/a$.

To characterize the transmission from the photonic-crystal waveguide, we measure the directed power P_D, normalized to the input power, incident upon a cross-sectional length of $2a$ centered at $x=0$ and $z=45\,a$. A likewise normalized measure is taken of the reflected power P_R incident upon a cross-sectional length of $20\,a$ centered at the input to the waveguide, $x=0$ and $z=-a$. This reflected power is considered a close measure of all reflected power. For the bulk photonic crystal with standard surface layer the directed power is $P_D=0.0123$, and the reflected power is $P_R=0.0158$.

Distribution of the Poynting vector for the directional emission from the photonic-crystal waveguide demonstrated by Moreno et al.[1] is shown in Fig. 1(b). These results are produced by altering the surface layer geometry in two ways. Firstly, by reducing the radius of the surface cylinders to the value $r_s=0.5r=0.09\,a$, and thereby creating the conditions for a surface mode to exist at the truncated surface. And secondly, by displacing $N=9$ even-numbered cylinders (numbered consecutively away from the waveguide) on both sides of the waveguide by $\Delta z=-0.3\,a$ along the z axis of the crystal, thus enhancing radiation of surface modes. Our calculations show that the directed power for such a structure is $P_D=0.0723$, while the reflected power is substantially large, $P_R=0.2635$. To further characterize the enhanced beaming effect, we measure one-half of the total surface mode power, P_S, incident upon a cross-sectional length $2\,a$ positioned centrally at $x=24\,a$, $z=9\,a$; again normalized to the input power. Moreover, to characterize the containment of the directed power we measure the width of the central lobe of the directed emission w_L between the first nulls at $z=45\,a$. For the geometry considered in Ref. 1, the surface mode power is $P_S=0.0030$, while the width of the central lobes is $w_L=18.1\,a$.

A drawback of the design suggested in Ref. 1 is a large amount of the reflected power. We find that the reflected power can be reduced by increasing the input wavelength from $\lambda=2.45\,a$ to $\lambda=2.5578\,a$. This causes the reflected power to decrease to $P_R=0.048$, while increasing the directed power and surface mode power marginally to $P_D=0.0768$ and $P_S=0.0484$, respectively. A measure of the average wave impedance in the vicinity of the waveguide shows that the increased wavelength reduces the impedance from $\sim1000\ \Omega$ to $\sim320\ \Omega$.

In order to increase the directional power, we alter the surface layer structure by shifting the odd-numbered cylinders *forward* by the distance of $\Delta z=0.4\,a$, while leaving the even-numbered cylinders on the lattice sites (i.e., no displacement). As the increased distance due to this corrugation over that of the uncorrugated distance is 7.7%, the applied wavelength is increased proportionally to $\lambda=2.6386\,a$. This new surface produces the directed power of P_D $=0.154\,18$ and decreased reflected and surface mode
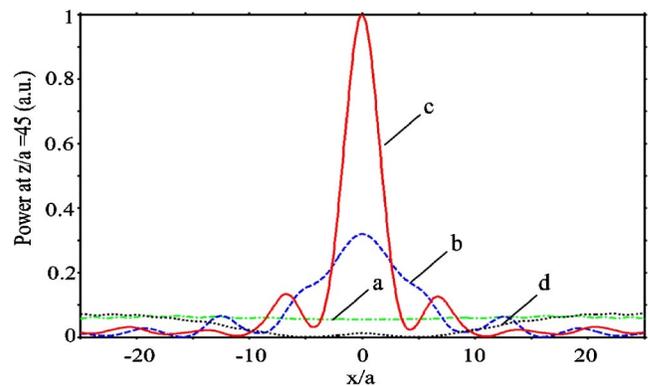

FIG. 2. (Color online) Power density incident upon the cross section at $z=45\,a$ for (a) unchanged surface; (b) surface configuration from Ref. 1; (c) optimal surface configuration with the maximized beaming; (d) with the surface refractive index $n=4.5$.

$P_R=0.0318$ and $P_S=0.0100$, respectively. Furthermore, the central lobe of the directed emission is now contained within $w_L 7.79\,a$.

Our analysis shows that an improvement to the directed power can be achieved by *increasing* the refractive index of the surface layer from $n_s=3.4$ to $n_s=3.6$. This results in the directed power increasing to $P_D=0.1689$, while decreasing the reflected and surface-mode power to $P_R=0.0295$ and $P_S=0.0023$, respectively. The width of the directed beam's central lobe resulting from the increased surface layer's refractive index is $w_L=9.553\,a$.

Additional improvement of the directed power can be achieved by decreasing the radius of the cylinders one layer prior to the surface layer, $z=8\,a$ to $r_{s-1}=0.135\,a$. This change induces a near-surface defect mode that leaks coherently into the surface layer before being radiated, increasing the directed power to $P_D=0.2104$, the reflected power, to $P_R=0.1028$, and decreasing the surface power to $P_S=0.0078$. The width of the central lobe of the directed emission becomes $w_L=8.642\,a$. The spatial distribution of the Poynting vector for this optimal design is shown in Fig. 1(c). A comparison of the significantly enhanced beaming over the standard interface and that of Ref. 1 is provided in Fig. 2, for a cross section of the power density measured at $z=45\,a$.

Control of the directed emission is achieved through the manipulation of the refractive index of the surface layer cylinders. This is illustrated in the attenuation of the directed power shown in Fig. 1(d), where the refractive index of the surface cylinders is increased to the value $n=4.5$. In this case, the outgoing beam splits, the directed power vanishes, and the surface-mode is in cut-off with a localized state formed within the first two surface cylinders next to the waveguide exit. Figure 2(d) shows a cross section of the power density measured at $z=45\,a$ for the beam splitting depicted in Fig. 1(d).

The effect of a change of the surface refractive index is shown in Fig. 3 where the index is varied from $n=2.4$ to $n=4.4$. As already mentioned, the refractive index of the surface layer has a effect on both the directed and reflected powers, suggesting that it could be used not only for achieving a control over the beaming effect but also for matching the waveguide to the surrounding media.

The optimum input wavelength for beaming is determined by the surface layer's lattice pitch, the surface corrugation, and the surface layer's refractive index. A smaller
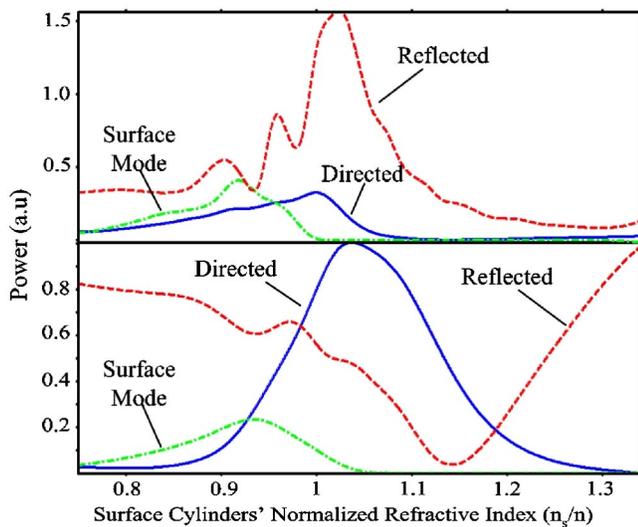
FIG. 3. (Color online) Normalized power density incident upon a cross-sectional length of $2a$ centered at $x=0$ and $z=45a$ as the normalized refractive index of the surface cylinders varies. Top: surface layer used in Ref. 1. Bottom: With the surface cylinders' radius reduced to $r_s=0.09a$ and the refractive index $n_s=3.6$, with $N=9$ odd-numbered cylinders displaced $\Delta z = +0.4a$, and the radius of the cylinders in the layer prior to the surface layer reduced to $r_{s-1}=0.135a$.
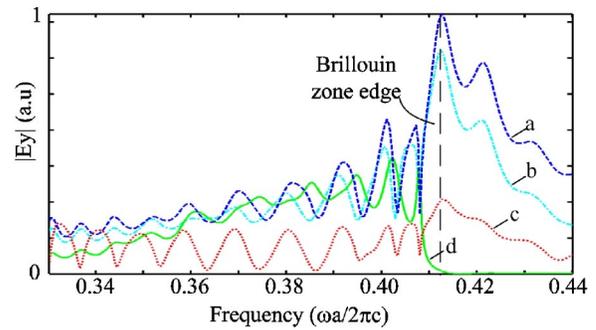
FIG. 4. (Color online) Frequency response of the electric field for an uncorrugated surface with cylinders of radius $r_s=0.09a$ at (a) first cylinder adjacent to the waveguide exit; (b) second cylinder adjacent to the waveguide exit; (c) reflected from waveguide entry; and (d) $x=24a$, $z=9a$ on the surface layer.

distance between the surface layer cylinders results in a narrower zero-order beam, in a similar way to a longer input wavelength. The surface corrugation and refractive index both influence the frequency of the surface mode. A positive corrugation, where alternative surface cylinders are moved forward from their lattice sites, causes a decrease in the surface mode. Likewise, an increased surface layer refractive index causes a decrease in the frequency. Additionally, the input wavelength controls the coupling to the surface cylinders. Maximum coupling is achieved at the Brillouin zone (BZ) frequency where the group velocity vanishes (see Fig. 4). However, as power is delivered to the the surface serially from the first cylinder adjacent to the waveguide exit large reflections occur at the BZ frequency, and the propagation along the surface is not readily achieved. As such, the opti-

mum input wavelength for a positive surface corrugated with an increased surface refractive index is lower than that of the unaltered surface mode.

In conclusion, we have studied different ways for engineering the beaming effect in photonic crystals. We have revealed that the substantial enhancement of the light emission and improved light beaming can be achieved by decreasing the input source wavelength, increasing the refractive index of the surface layer and finally by using a positive corrugation displacement. We have provided a link of the observed enhancement of the directional emission with the properties of the surface modes supported by the photonic crystal interface.

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