Highly Directional Emission from Photonic Crystal Waveguides of Subwavelength Width

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(Received 24 July 2003; published 18 March 2004)

Recently it has been shown that it is possible to achieve directional emission out of a subwavelength aperture in a periodically corrugated metallic thin film. We report on theoretical and experimental studies of a related phenomenon concerning light emitted from photonic crystal waveguides that are less than a wavelength wide. We find that the termination of the photonic crystal end facets and an appropriate choice of the wavelength are instrumental in achieving very low numerical apertures. Our results hold promise for the combination of photonic crystal waveguides with conventional optical systems such as fibers, waveguides, and freely propagating light beams.

DOI: 10.1103/PhysRevLett.92.113903 PACS numbers: 42.70.Qs, 42.25.Fx, 42.82.Et

The diffraction limit is perhaps the most elusive principle in optics. One of its consequences is that light of wavelength λ exiting from a region much smaller than $\lambda/2$ undergoes a strong angular spread and fills out the whole 2π solid angle [1]. Very recently, however, Lezec *et al.* reported on a fascinating experiment where the transmission through a nanoscopic aperture showed an anomalously low divergence [2]. The key issue in that work was that the subwavelength opening was surrounded by a periodic array of corrugations on both sides of a metallic thin film. The authors have explained their observations by considering that an incident laser beam couples to the surface plasmon oscillations in the metallic film via the corrugations on its first side. Subsequently, the surface plasmons scatter from the periodic corrugations of the second side, producing an array of Huygens emitters. Under certain conditions these waves interfere destructively everywhere except about the axis of the aperture, giving rise to a directional emission [3]. In this Letter we show that these phenomena are restricted to neither metallic structures nor the excitation of surface polaritons. We demonstrate both experimentally and theoretically that it is possible to couple out directional beams from subwavelength photonic crystal waveguides if they are terminated properly.

The unique optical features of photonic crystals (PCs) containing defects have attracted the attention of scientists from various fields. Some of the simplest structures of interest are based on line defects. These act as waveguides and have great potential to function as tiny wires for connecting various elements in integrated optical circuits. Efficient coupling directly into and out of a waveguide that is less than a wavelength wide is, however, in general considered to be at odds with the diffraction limit. As a result, several solutions including coupling via out-of-plane gratings [4], combinations of ridge waveguides and tapers [5,6], or evanescent coupling [7] have been investigated. In what follows we show that the angular acceptance of a PC guide depends very strongly on the wavelength of operation and on the crystal termination, providing a handle over its coupling with other elements. We start by giving an experimental example of a very low divergence beam exiting a PC waveguide. We then present the results of finite-difference time-domain (FDTD) simulations that examine this phenomenon in more detail. Finally, we provide evidence that surface modes are excited when the appropriate crystal conditions are met for achieving a low divergence.

In our laboratory we have studied a two-dimensional photonic crystal made of macroporous silicon [8] that is about 100 μm deep and contains an incoupling waveguide, a point defect, and an outcoupling waveguide [see Fig. 1(a)]. The crystal has a lattice constant of $a = 1.5$ μm and the ratio $r/a = 0.43$, whereby r is the radius

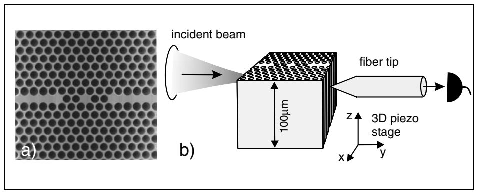

FIG. 1. (a) A scanning electron microscope image of the photonic crystal structure studied in our experiment. (b) The schematics of the setup. The laser beam is focused on the entrance of the first waveguide, and a fiber tip is used to detect the light locally at the output side. The x, y, and z axes define the coordinate system used throughout this work.

of the air holes. This leads to a band gap in the middle infrared spectral region of 3.3–5.4 μm, corresponding to $\omega a/2\pi c = 0.28$–0.45. In our previous work we have performed spectroscopy to record the resonances of this structure [9] and have applied scanning near-field optical microscopy (SNOM) to image the confinement of light about the point defect as well as its propagation along the guides [10]. In the present work we have tuned the laser wavelength to the resonance at $\lambda = 3.84$ μm and have studied the angular intensity distribution of the output beam. We note that since the second guide is long compared to the wavelength, we can treat its outcoupling properties like that of a PC waveguide alone, neglecting the previous history of light in the structure.

Figure 1(b) shows the core of the experimental arrangement. Light from a continuous wave optical parametric oscillator is coupled into the first waveguide of the photonic crystal. A fluoride glass fiber with a core diameter of 9 μm is etched to form a tip with a radius of curvature around 1 μm, serving as a local detector for the optical intensity. The fiber tip is mounted in a SNOM device [9] with a sample-probe distance control mechanism [11]. This allows us to regulate the gap between the tip and the PC facet to better than a few tens of nanometers, which in this experiment corresponds to distances smaller than $\lambda/100$. By using a calibrated piezoelectric element, we can also retract and place the tip at well-defined distances away from the PC exit. At each y location the tip is scanned in the xz plane so as to map the lateral intensity distribution in the output beam.

Figure 2(a) displays the intensity distribution right at the exit of the waveguide while Figs. 2(b)–2(i) show the same at successively increasing y distances up to about 24 μm away from the PC's exit facet. In Fig. 2(j) the blue, black, and red curves display the beam profiles along the z direction from Figs. 2(a), 2(b), and 2(i), respectively. Comparison of these plots reveals that the beam does not undergo a notable spread in this direction upon exiting the PC waveguide. This is not surprising because the light has not experienced any confinement in the PC along this direction.

The central issue of interest in our work concerns the beam divergence along the x direction. Therefore, in Fig. 2(k) we plot the x profiles of images 2(a), 2(b), and 2(i). The blue curve displays the beam cross section when the tip is nearly in contact with the PC surface. One finds that the great majority of the power is contained in a spot with the full width at half maximum of less than 2 μm, corresponding to the initial confinement of light in a subwavelength region about the waveguide. The black and red curves show that as the tip-sample distance is increased, this spot broadens and becomes weaker. The remarkable fact is, however, that its width does not grow nearly as fast as one would have expected for a beam that emerges out of a subwavelength waveguide. At first sight this might appear to violate the laws of diffraction. However, the side lobes of the blue curve in Fig. 2(k) very clearly indicate that, in fact, light is not confined to a subwavelength region. Interestingly, Martin-Moreno *et al.* discuss a similar effect in their theoretical study of light emission out of a nanoscopic aperture in a corrugated metallic film, but the SNOM measurements reported in [2] did not provide direct evidence of this phenomenon. In what follows we show that, although there is no equivalent to plasmon polaritons in photonic crystals, there exist surface modes that can be excited at the PC-air interface, therefore mediating the extension of light to the sides of the waveguide exit. Surface states have been studied for interfaces between layered and homogeneous media in the 1960s and 1970s [12,13] and were reported by Joannopoulos and co-workers in the 1990s for PC structures that are terminated at certain positions [14,15], but they have not been encountered in the laboratory very often.

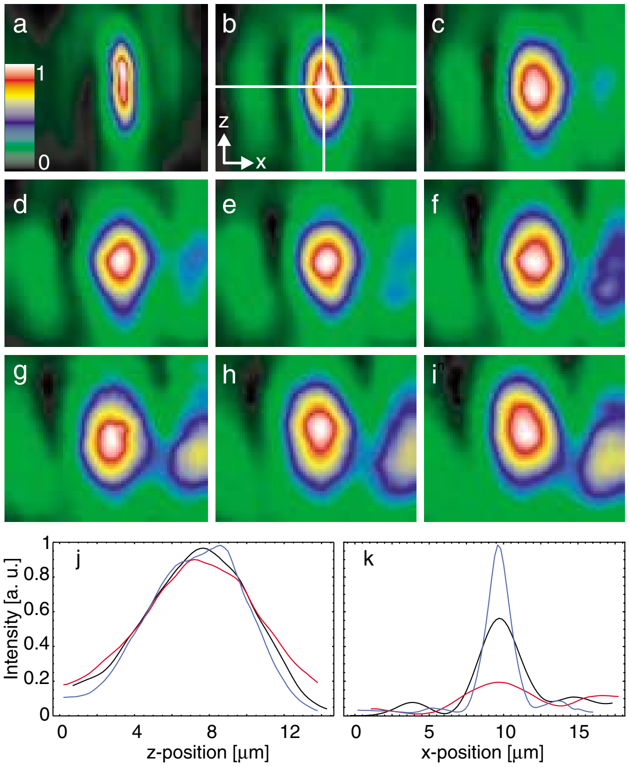

FIG. 2 (color). (a) Lateral intensity distribution as seen by the tip only a few nanometers from the crystal exit. (b)–(i) The same as in (a) but for tip-sample separations of 3.5, 6.5, 9.4, 12.4, 15.3, 18.3, 21.2, and 24.2 micrometers, respectively. The scale of the color code is adapted for each image individually to show the full contrast. (j) Vertical cross sections of (a), (b), and (i) plotted by the blue, black, and red curves, respectively. The heights of the curves are scaled to facilitate the comparison. (k) Horizontal cross sections of (a), (b), and (i) plotted by the blue, black, and red curves, respectively.

In order to investigate the angular spread of the emerging beam, we have performed two-dimensional FDTD calculations. We consider a PC that contains a single straight waveguide but has otherwise the same crystal parameters as the experimentally examined sample in

Fig. 1(a). We set the wavelength to the experimental value of $\lambda = 3.84\ \mu$m corresponding to $\omega a/2\pi c = 0.39$. Figures 3(a)–3(i) display the snap shots of the intensity distribution and wave fronts of the outgoing beam in the xy plane for nine different terminations of the PC structure (see the insets). These images let us verify that the spread of the beam depends on the termination in an extremely sensitive manner, therefore supporting the hypothesis that surface modes might be involved. For example, Figs. 3(b) and 3(h) display very large beam divergence while Figs. 3(d) and 3(e) show output beams that contain more than 70% of their total radiated power within a small full angle of 20°, representing the lowest numerical aperture in these series. In order to facilitate the comparison between the results of measurements and simulations, the symbols in Fig. 3(e) mark the locations where the central spots of images 2(a)–2(i) reach their $\frac{1}{e^2}$ values in the x direction. The very good agreement between the FDTD outcome and the experimental data is clear. Scanning electron microscope images as well as topography images taken with our fiber tip indicate that the termination of the PC used in this work, indeed, corresponds to that in Fig. 3(e).

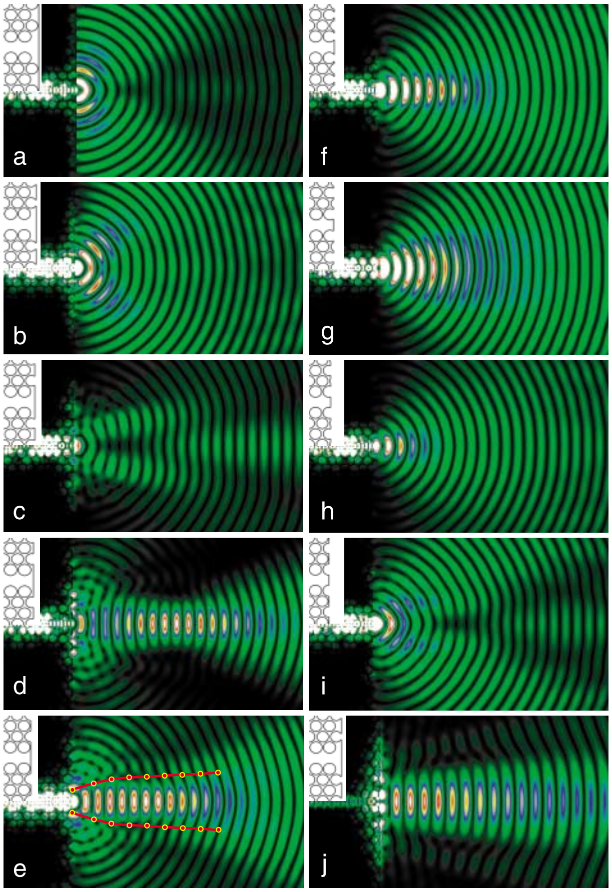

FIG. 3 (color). (a)–(i) Snapshots of the wave front and intensity distribution of light at $\omega a/2\pi c = 0.39$, exiting a photonic crystal waveguide for nine different structure terminations. The inset superposed on the upper left side of each graph displays the PC output termination. The symbols in (e) display the measured widths of the central spot at the corresponding locations. (j) The intensity distribution for the structure in (b) but at $\omega a/2\pi c = 0.33$.

Next we turn our attention to the role of the wavelength of light [3]. In Fig. 4 we have plotted the power that is emitted within 10° of the waveguide axis as a function of $\omega a/2\pi c$. Here one expects that peaks signify an increase of intensity in the forward direction and, therefore, a low beam divergence. The two peaks appearing at about $\omega a/2\pi c = 0.39$ clearly confirm this for the directional outputs found in Figs. 3(d) and 3(e). As a further example, in Fig. 3(j) we plot the intensity distribution for the structure with the termination of Fig. 3(b) but at $\omega a/2\pi c = 0.33$. About 80% of the emission is contained in a highly directional beam, whereas the same structure gave rise to a diffuse output in Fig. 3(b). The data in Fig. 4 lead us to believe that although in practice the optimization of the beam parameters through the control of the structure termination might present difficulties, for any given structure there could exist wavelength regions where the numerical aperture of the output beam is very small.

As a last point of discussion we provide evidence for the existence of surface modes. As was shown experimentally in Fig. 2(a), a comparison between Figs. 3(j) and 3(h) also reveals that a low beam divergence is accompanied by the lateral extension of light at the PC-air interface, whereas light remains confined to the waveguide exit when a large angular spread is obtained. However, the lateral spread of light intensity alone is not sufficient to distinguish between evanescent surface modes and propagating fields caused by scattering. In order to investigate this issue, we turn the problem around and ask how much of the power emitted from a pointlike dipole moment can couple into the waveguide as a function of its separation. Figure 5 shows the result for an

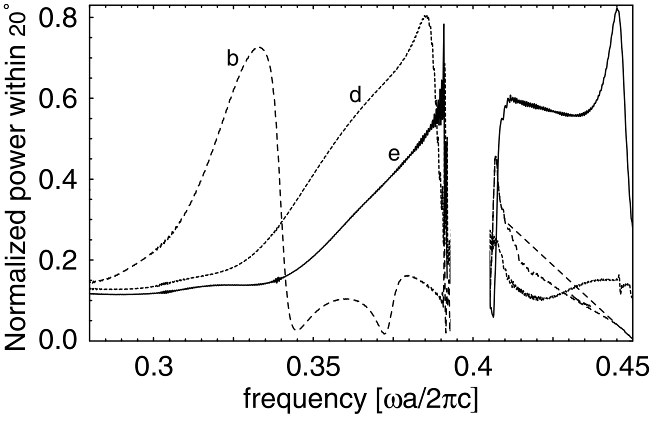

FIG. 4. Power transmitted within 10° of the waveguide axis as a function of $\omega a/2\pi c$ for three different output terminations corresponding to those in Figs. 3(b), 3(d), and 3(e). The region around $\omega a/2\pi c = 0.4$ corresponds to a mini stop band in the structure and is not suitable for guiding [16].

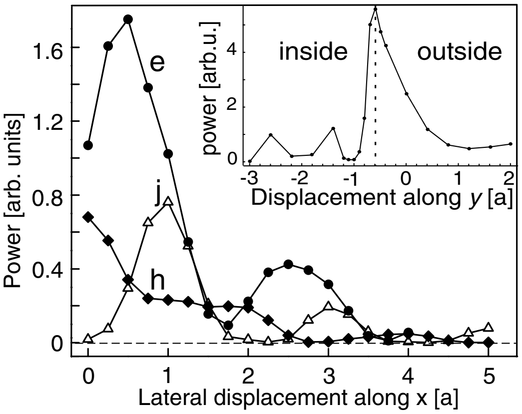

FIG. 5. Power coupled into the waveguide as a function of the lateral displacement of a dipole source from the center of waveguide ($x = 0$). Letters e, h, and j indicate that the terminations correspond to those used in Figs. 3(e), 3(h), and 3(j). The inset shows the power coupled in the waveguide as the dipole is placed at $x = 2a$ but at different positions along the y direction inside and outside the PC structure (marked by the dashed line). The rapid y dependence of the signal is a clear signature of surface bound evanescent modes. Note that all oscillations in this figure are due to the modulations of the dielectric constant in the PC.

emitting dipole placed at a separation $y \ll \lambda$ from the interface and at different displacements from the waveguide output along the x direction. The curves labeled e, h, and j correspond to the PCs with terminations used in Figs. 3(e), 3(h), and 3(j), respectively. In the case of termination h where a very divergent beam exits from a region well localized to the waveguide core we find that a dipole can couple into the waveguide only if it is very close to its end. On the other hand, for terminations e and j, which yield directional emission, the dipole radiation couples into the waveguide very effectively even at lateral separations of several wavelengths from the core. A final proof that, indeed, this is mediated by surface modes is presented in the inset of Fig. 5. Here a dipole is placed at $x = 2a$ and then moved along y inside and outside the PC structure with termination e. As is expected for evanescent surface modes [14,15], the coupling between the dipole and the PC structure drops within a fraction of the wavelength in both directions. As the dipole-PC separation increases, the signal begins to grow slowly at about $y = 2a$ because the dipole enters the line of sight of the waveguide and can couple in directly via propagating fields. We have verified that this is, in fact, the mechanism by which such a dipole would couple into the waveguide when the conditions for a low divergence emission are not met [see, e.g., Fig. 3(h)].

In conclusion, we have demonstrated directional beams with very low divergence angles emerging from photonic crystal waveguides of subwavelength width. We have identified the structure termination and the wavelength of operation as two key parameters and have shown that evanescent surface modes play a central role in the achievement of low divergence beams. Our findings hold technological promise for facilitating the connection of PC waveguides to other optical elements such as fibers, ridge waveguides, or lenses.

We thank Ben Buchler for a careful reading of the manuscript. The experimental part of this work was performed at the University of Konstanz before P. K. and V. S. moved away, and we are grateful to J. Mlynek for continuous support. Our research was funded by the Deutsche Forschungsgemeinschaft (SPP 1113), the European Union (IST project PCIC), U.S. Department of Energy, and Optik-Zentrum Konstanz. C. M. S. thanks the A.v. Humboldt Foundation for financial support.

Note added.—We note that since the submission of this Letter, Martin-Moreno and co-workers have also reported very similar results [17].

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