Highly directive radiation from sources embedded inside photonic crystals

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In this work, we have experimentally and theoretically studied the angular distribution of power emitted from a radiation source embedded inside a photonic crystal. Our results show that it is possible to obtain highly directive radiation sources operating at the band edge of the photonic crystal. Half power beam widths as small as 6° have been obtained. Our results also show that the angular distribution of power strongly depends on the frequency and on the size of the photonic crystal. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1623010]

Photonic crystals (PCs) are artificial periodic structures, which strongly modify the dispersion properties of electromagnetic waves (EM) waves. Since PCs may control the propagation of EM waves in certain directions, they have recently attracted much attention. Many interesting phenomena such as enhancement and suppression of spontaneous emission,[1,2] propagation of photons via hopping over coupled defects,[3,4] and localized donor and acceptor modes,[5,6] have been suggested and observed. One of the major reasons behind this interest on PCs is the possibility of the control of emission from radiation sources by using PCs. There are two main problems in the control of emission: enhancement or suppression of radiation and the confinement of the emitted power to a narrow angular region. The problem of the enhancement or suppression have been investigated by several authors.[1,7,8] Moreover, PCs have been used, especially in the antenna community, to improve the angular confinement of power from radiation sources.[9–14] In most of these works the sources are not inside the PCs and PCs have been used either as a cover or a substrate.[9–12] On the other hand, other researchers investigated radiation properties of sources inside PCs.[13,14]

In this work, we study the angular distribution of power from a radiation source embedded inside a PC. We show that it is possible to confine the emitted power to a very narrow angular region at certain frequencies. Moreover, we show that the size of the PC is a critical parameter. This letter will be organized as follows: we will first discuss the properties of PCs relevant to our study and then we will present our experimental and theoretical results.

One of the points we will use in our discussion is the band structure of the PC used in our study. The PC that we used in our experiments and calculations is a two-dimensional (2D) square array of cylindrical alumina rods. The alumina rods have a radius of 1.55 mm and a dielectric constant of 9.61. The separation between the center of the rods along the lattice vectors is 1.1 cm. Band structure of the corresponding infinite PC for TM-polarized EM waves is given in Fig. 1. Throughout the letter we consider only TM-polarized EM waves. From the band structure we observe that at the upper band edge (the minimum of the second band) only the modes along $\Gamma - X'$, where X' represents all directions having the same symmetry properties of X point, are allowed to propagate inside the PC. For the modes near the upper band edge $k_{\parallel} = k_x \approx 0$. Apart from an additive reciprocal lattice vector, $k_{\parallel}$ is conserved at the air-PC interface.[15] Hence, we conclude that for a source embedded inside the PC and operating at the upper band edge frequency, the emitted waves should be appreciably transmitted from the PC to air only along $\Gamma - X$ direction. In addition, the modes near the upper band edge are air modes, i.e., most of the energy of the EM waves are concentrated in the low dielectric material region as the waves propagate through the PC [Fig. 2(a)]. Hence, when the waves near the upper band edge emerge from the surface of the PC, most of the power will flow through low dielectric material region of the PC [Fig. 2(b)]. In conclusion, we can regard the exit points as radiation sources.

It is well-known that the group velocities for the modes near the band edges are fairly reduced compared to the group velocity of EM waves propagating in free space.[16] Delay time measurements presented in Fig. 3 show that the group velocities for the modes near the upper band edge are reduced up to 22 times in comparison to air. Delay time is defined as $\tau_p = \partial \varphi / \partial \omega$.[17] Here, φ is the net phase difference between the phase of the EM wave propagating inside the photonic crystal and the phase of the EM wave propagating in free space. The reduced group velocities at the upper band edge result in phase differences between the radiators. Since

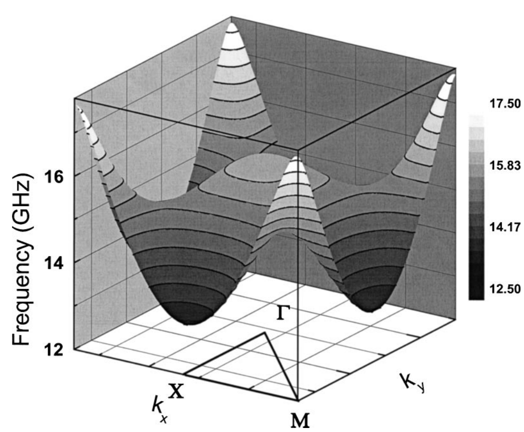

FIG. 1. The second TM-polarized band is shown over the whole first Brillouin zone.

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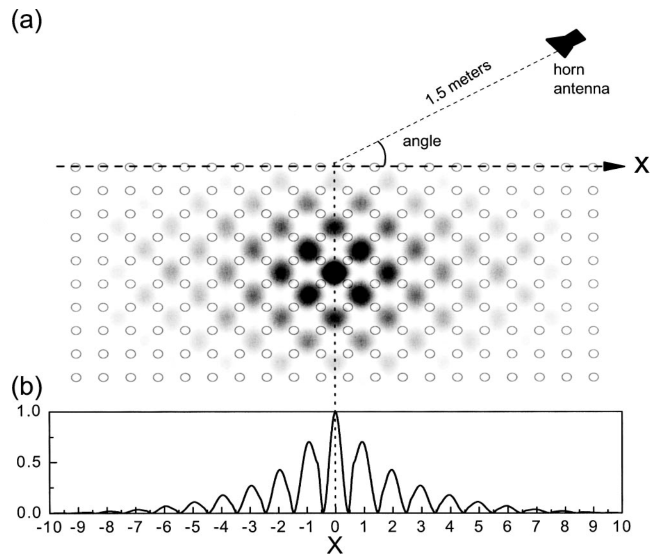

FIG. 2. (a) Experimental configuration for a 2D 20 × 10 square array. The source is at the center of the PC. Also, the contour plot of the electric field intensity for a source radiating at the band edge frequency is shown. Electric field intensity is mostly localized in air. (b) Electric field intensity along the *X* axis.

at the upper band edge the modes are allowed to propagate only along $\Gamma - X'$, these radiation sources will have a uniform distribution of phase differences.

Combining the results of the discussions of the previous paragraphs, we conclude that the surface of the PC can be regarded as a system of radiation sources. All of these sources operate at the upper band edge frequency and have similar spatial and temporal distribution of power with a uniform phase difference between the radiators. This system of radiators is similar to an antenna array. Since all the radiators of the system radiate in $\Gamma - X$ direction, we expect the emitted power from a source embedded inside the PC to be confined to a narrow angular region.

In our experiments and finite difference time domain calculations, we calculated and measured the angular distribution of power emitted from a monopole source embedded inside a 2D square array of cylindrical alumina rods. The monopole source used in the experiments is obtained by removing 0.5 cm of the cladding from a coaxial cable and leaving the central conductor. An HP-8510C network analyzer is used to excite the monopole source and to measure the power emitted from the monopole source. Figure 2 shows the details of experimental configuration.

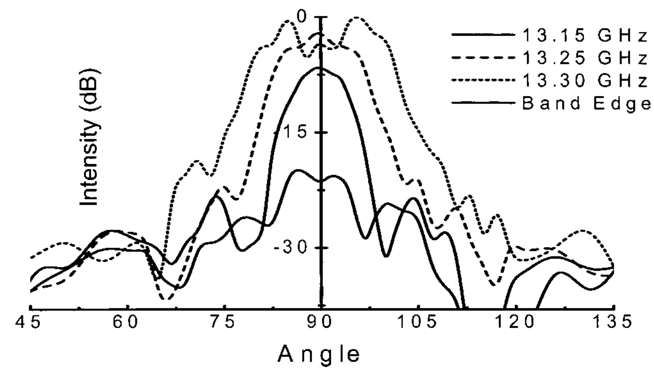

FIG. 4. Measured far field radiation patterns for various frequencies near the upper band edge. The crystal size is 32 × 16.

We carried out the measurements and the calculations for various frequencies and for various crystal lengths. Crystal length is defined as the number of layers along *x* axis. Since the PC used in experiments is a 2D structure, we are interested in the angular distribution of power on the plane perpendicular to the axis of the rods. The measured far field radiation patterns for a square array of 32×20 alumina rods at various frequencies near the upper band edge are presented in Fig. 4. The minimum half power beam width is obtained at 13.21 GHz and it is found to be 8°. The measured delay time data presented in Fig. 2 shows that the maximum delay time occurs at 13.21 GHz. Comparing the delay time data with the band structure of the corresponding infinite PC we conclude that the upper band edge is at 13.21 GHz. Hence, the minimum half power beam width is obtained at the upper band edge frequency. Figure 4 shows that the angular distribution of power strongly depends on the radiation frequency. The radiation patterns are wider for frequencies higher than the upper band edge frequency. This can be explained by the presence of equal frequency modes along different directions at frequencies higher than the upper band edge frequency.

We have also measured the angular distribution of power at the upper band edge frequency for various crystal lengths. The measured and calculated far field radiation patterns are presented in Fig. 5. We have measured half power beam widths of 8°, 7°, 6°, and 12° for crystal lengths of 32, 28, 24, and 20, respectively. The measured half power beam widths show that there is an optimum crystal length, which is found

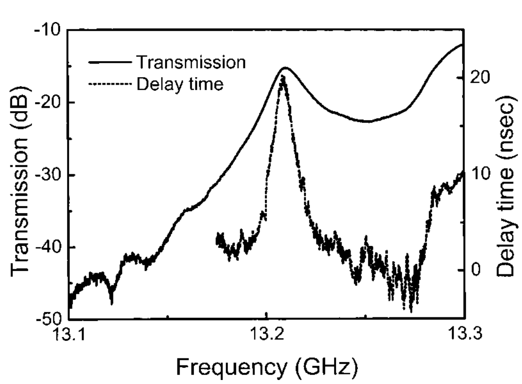

FIG. 3. Measured transmission and delay time near the upper band edge for the PC used in our experiments.

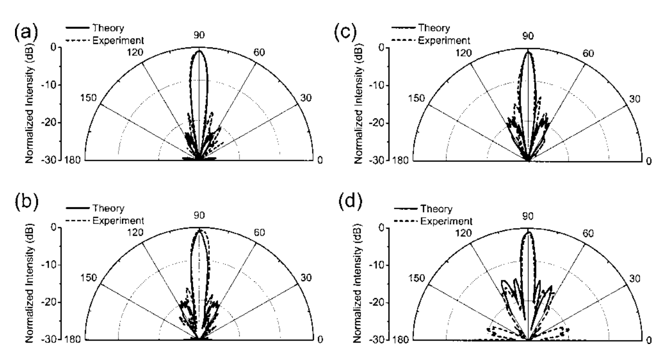

FIG. 5. Measured and calculated far field radiation patterns at the upper band edge frequency for various crystal lengths. (a) 32 × 16, (b) 28 × 16, (c) 24 × 16, and (d) 20 × 16 layers.

to be 24 layers in our case. The minimum half power beam width is obtained for 24 layers and it is found to be 6°. From Fig. 5 and the measured half power beam widths we also observe that as the crystal length is changed from its optimum value, radiation patterns and half power beam widths also change. The change is more significant when the layer number is decreased from its optimum value. This can be explained by the fact that the strength of the radiators decreases rapidly as we move away from the center of the PC [Fig. 2(b)]. Hence, the effect of increasing the crystal length on the radiation patterns is less significant when compared to the effect of decreasing the crystal length.

In summary, we have demonstrated that by using PCs it is possible to confine the emitted power to a narrow angular region for a source embedded inside a PC and radiating at the band edge frequency. A minimum half power beam width of 6° have been obtained for a source operating at the upper band edge frequency of the PC. This is the minimum experimental value obtained from sources based on PCs. Our results also show that the far field radiation pattern of an antenna embedded inside a PC strongly depends on the frequency and on the crystal size. The findings of our work can be used to improve the performance of certain devices such as antennas and light emitting diodes.

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