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Directive emissions from subwavelength metamaterial-based cavities

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We use experiment and theory to demonstrate a mechanism for directive emissions, which involves a double-plate resonance cavity made with metamaterials. In contrast to other mechanisms employing Fabry-Pérot cavities, photonic crystals, or zero index materials, our system is significantly thinner than the working wavelength and requires a smaller lateral size. We show the physics to be governed by *subwavelength* resonance modes unique to such metamaterial-based cavities. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1881797]

Directive electromagnetic (EM) wave radiations are highly desirable in practice. The conventional method to achieve the directive emission is based on the Fabry-Pérot (FP) cavity, which requires a thickness *precisely* half of the working wavelength.[1,2] If the wavelength is long, this restriction makes such cavities too bulky. Recently, Temelkuran *et al.* employed the defect resonance inside a photonic band gap (PBG) to realize the directive emission.[3] While the idea is different from the FP cavity, the system must be several times of the working wavelength in *all dimensions*, a natural consequence of the Bragg mechanism for PBG systems.[4] In 2002, Enoch *et al.* used the refractive properties of a zero-index material interface to realize the directive emission.[5] We again note that the idea is based on a *bulk* material, which should be big enough to achieve the desired effect.[5]

In this letter, we propose an alternative mechanism for directive emissions. Compared with existing ones, the thickness of our system is *significantly thinner* than the working wavelength, and the required lateral size is also substantially reduced. We perform experiments and finite-difference-time-domain (FDTD) simulations[6] to demonstrate our concept, and reveal several unusual properties of this mechanism as well as the governing physics.

A conventional FP cavity consists of two parallel reflectors, separated by a distant d, with the first one 100% reflecting for EM waves and the second one allowing some transmission. Resonance modes are found at frequencies f satisfying

$$-4\pi f d/c + \Delta\phi_1 + \Delta\phi_2 = m2\pi, \qquad (1)$$

where c is the speed of light, $\Delta\phi_{1(2)}$ is the reflection phase of the first (second) reflector. The conventional reflectors[1,2] have $\Delta\phi_{1(2)}=\pi$, so that the lowest mode satisfying Eq. (1) is $d=c/2f=\lambda/2$. This defines the lower limit of the cavity thickness.

The half wavelength restriction can be lifted if we replace one plate by a metamaterial reflector which does *not* reflect with $\Delta\phi=\pi$. For instance, high-impedance reflectors[7–10] reflect with $\Delta\phi=0$ at some particular frequencies. Working at these frequencies, a cavity only requires a thickness $d=\lambda/4$. This idea can be pushed even further. Since all metamaterials are dispersive,[7–10] such reflectors can reflect with *arbitrary* phases depending on f, which can in principle remove the lower limit on the cavity thickness.

We adopt the mushroom structure[7] to demonstrate this concept, although other configurations[8–10] can achieve the same effect with appropriate designs. Figure 1(c) schematically shows our experimental setup. The left-hand side plate is a metallic mesh [period=4 mm, line width=0.4 mm, see Fig. 1(a)] printed on a 1.6-mm-thick printed circuit board (PCB) substrate ($\varepsilon=2.2$). This plate allows ~4% transmission for EM waves at ~8 GHz. The right-hand side plate is a 100% reflecting mushroom structure[7] with its top view picture shown in Fig. 1(b). The period of the pattern is 7 mm and the width of each air gap is 0.5 mm. The inner dielectric layer is the same PCB layer and the diameter of each metallic via is 0.7 mm. The lateral size is 195 mm × 195 mm for both plates. We put a 14-mm-long dipole antenna inside the cavity, and measured the radiation patterns (both E and H

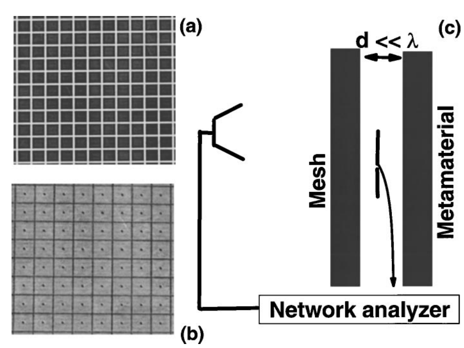

FIG. 1. Top view pictures for the mesh layer (a) and the metamaterial surface (b). (c) Schematic picture of the experimental setup.

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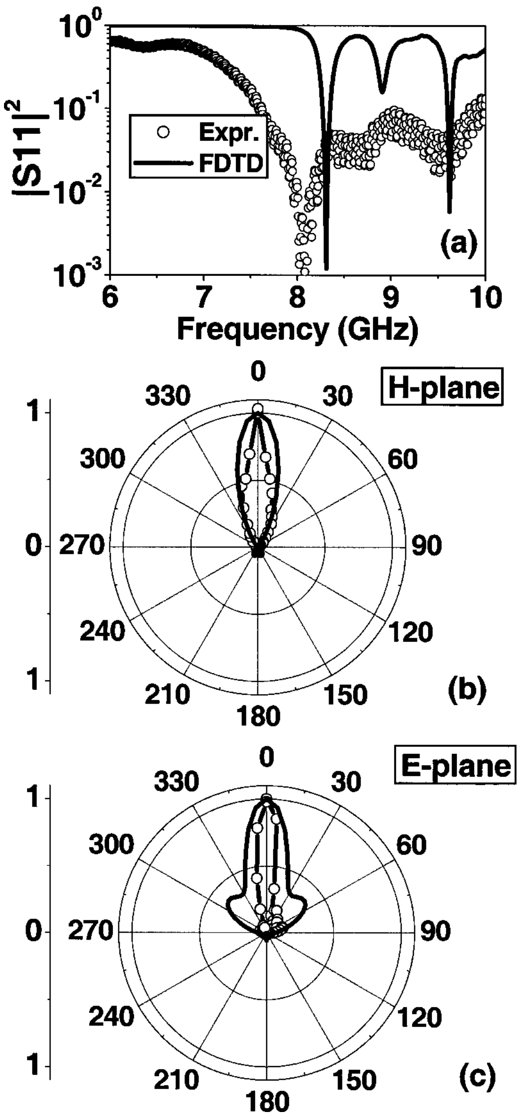

FIG. 2. (a) Return loss spectra for a 14-mm-long dipole antenna inside the 3-mm-thick cavity, obtained by experiment (symbols) and FDTD simulations (line). Radiation patterns on H plane (b) and E plane (c) for $f = 8.29$ GHz, obtained by experiments (symbols) and FDTD simulations (solid lines). We note that the simulated sample is smaller than the actual sample.

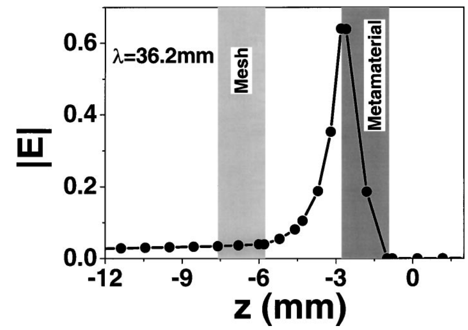

FIG. 3. Stabilized E field pattern along the central line perpendicular to the plates, calculated by the FDTD simulations.

plane). Both the antenna and the receiver were connected to an Agilent network analyzer 8722ES. Figure 2 shows the measured results for the case of $d = 3$ mm. From the return loss spectrum shown in Fig. 2(a), we see a clear dip around 8.1 GHz indicating the existence of a resonance mode. Two additional dips appear at ~8.9 and ~9.7 GHz, but they do not correspond to directive emissions. Shown in Figs. 2(b) and 2(c) are the measured H- and E-plane radiation patterns for $f = 8.29$ GHz,[11] which are highly directive. The half power width is estimated as 20° in H plane and 16° in E plane, yielding a directivity $D \approx 129$.[3,5] We notice that our working frequency (8.29 GHz) is much lower than 14.65 GHz adopted in Ref. 5 but our lateral size (195 mm) is smaller than that of Ref. 5 (226 mm). This probably explains the lower D value obtained here.[12] However, we emphasize that our thickness is only 3 mm, *over an order of magnitude smaller* than the working wavelength ~36 mm. We thus have a subwavelength (at least along one direction) cavity for directive emissions.

We performed FDTD simulations to understand the experimental findings. Limited by the computational power, we studied a smaller model system, in which the mesh layer has a lateral size of 72 mm × 72 mm and the mushroom layer of 70 mm × 70 mm. The calculated results are shown in Fig. 2 as solid lines.[13] Reasonably good overall agreement is seen compared with experiments. For example, even the dips at ~8.9 and ~9.7 GHz were reproduced. The calculated patterns are obviously broader than the measured ones, since we have adopted smaller plates in our simulations. This also implies that the directivity can be enhanced if one takes larger plates or adjusts the working frequency to a higher one.

Figure 3 shows the FDTD calculated E-field pattern inside and outside our cavity. We find that EM wave is zero outside the right plate and leaks through the left one. Distinct from a usual FP mode where the E field is a maximum in the middle and is (nearly) zero at the cavity boundaries, here we find the E field is a maximum at the surface of our metamaterial. To understand the physics origin, we calculated the reflection phases for both plates, and plotted the results in Fig. 4(a). In our calculations, we considered infinitely large plates and studied small units of the structures by imposing symmetry conditions on the boundaries. We find that $\Delta\phi_2$ is very close to 180° for the mesh layer, as expected. However, $\Delta\phi_1$ for metamaterial varies continuously from 180° to −180° as frequency increases, and is exactly 0° at $f = 7.1$ GHz. Putting $\Delta\phi_{1(2)}$ into Eq. (1), we got the working wavelength λ (for the lowest mode) as a function of d, and the results are shown in Fig. 4(b) by a solid line. Measured and simulated results are shown together for comparison.[14] Except for some kinks caused by typical finite-size effects, the agreements among analytical, brute-force FDTD and experimental results are quite satisfactory. We note that a resonance mode exists for a continuous range of cavity thickness, indicating the present effect is rather robust. The dependence of λ on d is quite different from a linear one for a conventional FP cavity, caused by the dispersive nature of our metamaterial. In particular, the resonance wavelength is *much longer* than the cavity thickness, a property not existing in other mechanisms.[1–3,5]

This model helps us to understand the resonance mode. With $\Delta\phi_{1(2)}$ known from Fig. 4(a), the E-field distribution of the mode can be easily obtained. A straightforward calculation shows that the maximum field *indeed* appears at the metamaterial boundary, confirming the FDTD results (see Fig. 3). Such a unique field distribution, and thus the sub-

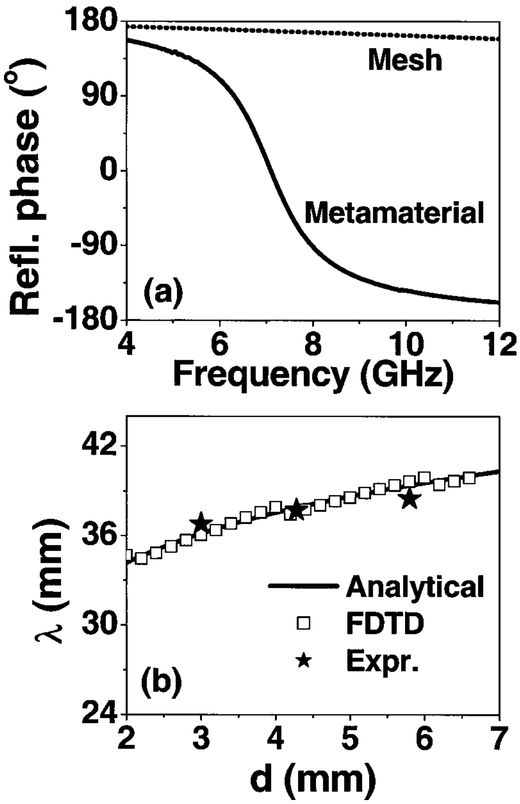

FIG. 4. (a) FDTD calculated reflection phase as the functions of frequency for the mesh layer (dashed) and the metamaterial layer (solid). (b) The thickness dependence of the cavity mode wavelength, obtained by the analytical model (line), FDTD simulations (open symbols), and experiments (solid stars).

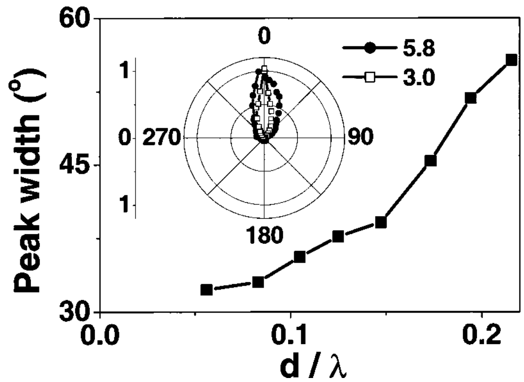

FIG. 5. Half power width of the *H* plane pattern as a function of the cavity thickness, calculated by the FDTD simulations. Inset: a comparison of the measured *H*-plane patterns for cavities with different thicknesses specified in the legend (in unit of mm).

wavelength cavity effect, is achieved by the unconventional reflection phase at the metamaterial surface.

The reduction in thickness also implies a possible reduction in lateral size. The closer the two plates are together, the more effectively will the source be "shadowed" by the plates, so that the directivity will increase. Shown in Fig. 5 is the FDTD calculated half power width (on the *H* plane) as a function of the cavity thickness. The thinner the cavity, the better the directivity. The inset to Fig. 5 compares the measured *H*-plane patterns for a thin cavity and a thick one, which directly confirms this conclusion.[15] Here, the working wavelength is 36.2 mm for the $d=3$ mm cavity and 38.5 mm for the $d=5.8$ mm one, corresponding to the first and third stars in Fig. 4(b). Figure 5 implies that, to achieve the same directivity, a conventional FP cavity (with $d/\lambda=0.5$) requires a much larger lateral size than ours.

To summarize, we demonstrated a mechanism for directive emissions. The constructed system is significantly subwavelength in thickness and requires a smaller lateral size.

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[11] Radiations with frequencies near the dip position are all directive. We choose this frequency for an easy comparison with the FDTD results.
[12] We have no information on the lateral size of the system adopted in Ref. 3.
[13] Simulations were performed using the package CONCERTO 3.1, developed by Vector Fields Limited, England, 2002.
[14] The resonance wavelengths are obtained by the dips in the return loss spectra in our experiments and FDTD simulations.
[15] The measured radiation patterns are not completely symmetrical, caused by some uncontrollable factors (including antenna quality, feeding method, etc.) in realistic situations. It is particularly difficult to keep the two reflectors *perfectly* parallel, especially for thicker cavities, so that the asymmetry in radiation pattern is more conspicuous in this situation.