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COMMUNICATIONS

Photonic crystal-based resonant antenna with a very high directivity

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We investigate the radiation properties of an antenna that was formed by a hybrid combination of a monopole radiation source and a cavity built around a dielectric layer-by-layer three-dimensional photonic crystal. We measured a maximum directivity of 310, and a power enhancement of 180 at the resonant frequency of the cavity. We observed that the antenna has a narrow bandwidth determined by the cavity, where the resonant frequency can be tuned within the band gap of the photonic crystal. The measured radiation patterns agree well with our theoretical results. © *2000 American Institute of Physics.* [S0021-8979(00)03601-X]

Photonic crystals, in which electromagnetic (EM) wave propagation is forbidden in all directions for a certain range of frequencies, have a wide range of applications extending from microwave to optical frequencies.[1–3] However, the fabrication of photonic crystals at optical frequencies was a major challenge since the invention of these materials nearly a decade ago. Recently, a photonic crystal with a full three-dimensional (3D) band gap at 1.55 μm wavelength was reported by Fleming and Lin.[4] In addition to this major breakthrough, the same structure was previously fabricated at millimeter wave and microwave frequencies,[5,6] where a number of photonic crystal based applications were demonstrated.[7] Among these applications, there is a great deal of growing interest for photonic crystal-based antennas.[8,9] The reported experimental and theoretical studies on the antenna applications mostly made use of the total reflection property of photonic crystals. The antennas mounted on photonic crystal substrate surfaces exhibited high efficiency and directivity compared to conventional antennas on dielectric substrates.[10] Although high directivities which could be achieved using array antennas on photonic crystals were suggested,[11] the maximum directivity that was demonstrated by Brown and McMahon using a photonic crystal-based single dipole antenna was 10, along with a radiative gain of 8.[10]

One other important property of photonic crystals is that by breaking the periodicity of the crystal, one can create resonant cavities. Resonant cavity enhanced detectors[12] and waveguide applications[13] were recently demonstrated using localized modes of the cavities built around photonic crystals. In this letter, we report a photonic crystal-based resonant antenna with a very high directivity and gain. The antenna was formed by a hybrid combination of a monopole radiation source and a cavity built around a dielectric 3D layer-by-layer photonic crystal.

The layer-by-layer dielectric photonic crystal we used in our experiments was designed to have a three-dimensional band gap with a midgap frequency around 12 GHz.[13] We used the output port of a microwave network analyzer and a monopole antenna to obtain EM waves. The monopole antenna was constructed by removing the shield around one end of a microwave coaxial cable. The cleaved center conductor, which also acted as the radiation source, was 6 mm long. The chosen length of the monopole antenna corresponds to a quarter wavelength of EM wave at a frequency of 12.5 GHz, which is close to the adjusted resonance frequency of the cavity. Input port of the network analyzer and a standard gain horn antenna were used to receive the radiated EM field from the monopole antenna. The receiver was kept free to rotate around the antenna as shown in Fig. 1.

We investigated the radiation characteristics of this monopole antenna, which was inserted into the planar defect structures built around a photonic crystal that consisted of 20 layers. The planar defect was formed by separating the 8th and 9th layers of the structure. In order to suppress the radiation in the backward direction, we intentionally chose one of the crystals of the cavity to have a higher reflectivity than the front crystal. This resulted in an asymmetric planar cavity with a two unit cell (8 layers) front crystal, and a three unit cell (12 layers) back crystal. The intensity through the back crystal is ~18–20 dB lower than the front crystal in the 0° direction. If a symmetric cavity was used, two directional beams would emerge in both directions.

In the *H*-plane measurements, the antenna and the polarization axis of the receiver horn antenna was kept vertical, and were parallel to each other at all incidence angles. We then rotated the antenna, photonic crystals, and the horn antenna 90° (so that the monopole antenna and the polarization

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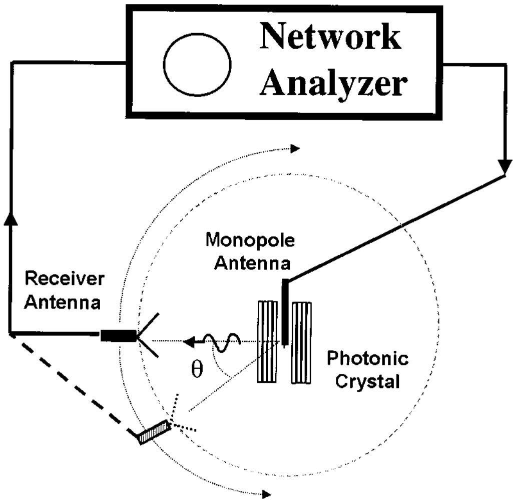

FIG. 1. Experimental setup for measuring the radiation patterns of the monopole antenna at various angles.

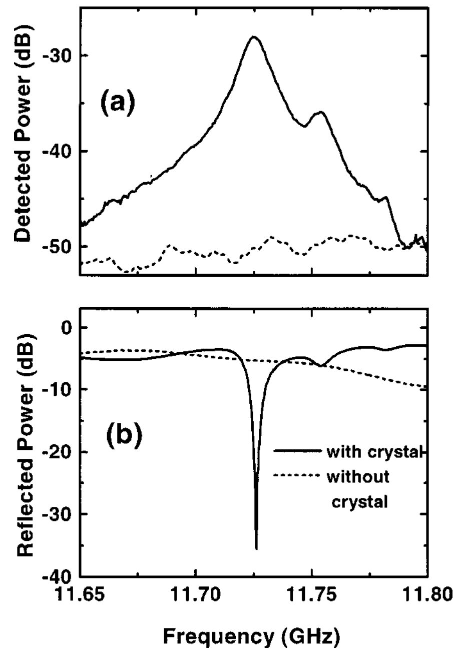

FIG. 3. (a) Detected power of the monopole antenna with (solid line) and without (dashed line) photonic crystal around resonance frequency at $\theta = 0°$. (b) The reflection power coefficient (S_{11}) measured with (solid line) and without (dashed line) photonic crystal.

axis of the horn were horizontal) to measure the radiation pattern in the perpendicular plane (*E* plane). In all these measurements, the monopole antenna was kept close to the back crystal of the cavity. The antenna was parallel to the surface rods of the back crystal to maximize the directivity and the detected power.

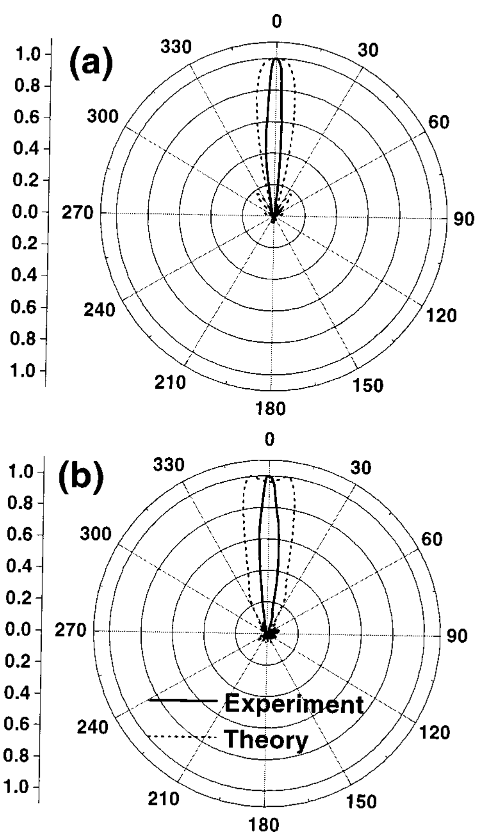

FIG. 2. The measured (solid lines) and calculated (dotted lines) radiation patterns of the monopole antenna inside the cavity of the photonic crystal for (a) *H* and (b) *E* field. The measurements and simulations were made at the resonance frequency of 11.7 GHz.

Antenna radiation patterns were simulated with the widely used finite-difference-time-domain (FDTD) technique.[9] To reduce the FDTD computational space, a short dipole antenna was used in the simulations which should approximate well the monopole antenna. The time dependent Maxwell's equations were numerically integrated with the fixed frequency dipole source inside the defect volume of the photonic crystal, to obtain the far-field radiation pattern. The calculations were repeated at different frequencies of the dipole source.

We first measured the detected power at the resonance frequency of the cavity as a function of angle. Figure 2(a) (solid line) shows the normalized radiation pattern in *H* plane, which was measured at the resonance frequency of the cavity. We observed a strong radiation around $\theta = 0°$, where the radiation along other directions is highly suppressed. The measurements performed in the other plane [*E* plane, Fig. 2(b), solid line] also resulted in a similar radiation pattern. The measured (solid lines) and calculated (dotted lines) radiation patterns for both planes agree qualitatively well. The simulations also predict a directed radiation pattern that displays the same trends but is somewhat broader than experiment. The broader pattern in the simulations may be due to the finite time of the simulations not allowing the system to fully reach a steady state.

For antennas with one narrow major lobe and very negligible minor lobes in the radiation pattern, the maximum directivity is approximately equal to[14]

$$D_0 \cong \frac{4\pi}{\Theta_1 \Theta_2}. \tag{1}$$

where Θ_1 is the half-power beamwidth in one plane and Θ_2 in the perpendicular plane to the first, in radians. The measured half-power beamwidth along the *H* plane [Fig. 2(a)] was 11°, and was 12° along the *E* plane [Fig. 2(b)]. These values lead to a directivity value around 310.

Figure 3(a) (solid line) shows the detected power as a function of frequency at $\theta=0°$. The dotted line displays the detected power at the same angle in the absence of the photonic crystal. At resonance frequency, we observed a power enhancement factor of 180 (22.6 dB) at a defect frequency of 11.725 GHz. The radiated EM field from the monopole antenna has also frequency selectivity introduced by the cavity. The *Q* factor (quality factor), defined as the center frequency divided by the full width at half maximum, was measured to be 895.

In order to understand the effect of the resonator to the efficiency of the monopole antenna, we also measured the *S* parameters of our antenna structure. Figure 3(b) shows the reflection power coefficient (S_{11}) which is 30% (−5 dB) for the monopole antenna standing alone in air. This implies that the antenna radiates only 70% of the incoming power. When the antenna was inserted inside the cavity, we observed a very sharp drop (−35 dB) at resonance frequency in the reflection spectra [Fig. 3(b), solid line]. This drop indicates that most of the power (99.97%) is radiated out in the presence of the cavity. The maximum radiation gain for our antenna is related to the maximum directivity by $G_0=(1-R)\times(1-A)D_0$, where *R* is the reflected power and *A* is the absorptivity of the antenna. In our case, the reflectivity at the resonance frequency is very small (0.0003). Assuming that the absorption in the antenna has a negligible value, the maximum gain has a value $\sim$300.

Such a planar cavity built around a 3D photonic crystal should not be confused with the Fabry–Perot type of resonators that are constructed by using distributed Bragg reflectors [which are known as one-dimensional (1D) photonic crystals]. In the former structure, the EM field is always coupled to the evanescent defect mode within the band gap irrespective of the incidence angle. However, the resonant frequency shifts as the angle of incidence of the EM wave changes in the latter case.[15,16] It is obvious that for planar waves, 3D and 1D resonant structures will result in similar enhancements and directivities. In our case, the monopole antenna radiates in all directions, and all the power radiated is coupled to the evanescent mode of the defect, regardless of the direction. This is the reason we have an antenna with a very high efficiency [see Fig. 3(b)]. However, for a 1D structure, the radiated EM field, except a certain direction, will not be coupled to the corresponding resonant mode of the cavity.

Although our structure is suitable for narrow bandwidth applications, one can tune the defect frequency to any desired value by adjusting the width of the cavity. We observed that the resonance frequency could be tuned within a frequency range extending from 10.6 to 12.8 GHz, which corresponds to the full band gap of our photonic crystal. The directivity drops to values around 100 at the band edges, and reaches a peak value of 310 at 11.7 GHz.

In conclusion, we have investigated the radiation characteristics of a photonic crystal-based antenna. The maximum directivity we have measured, which is around 310, is very high when compared to the previously reported directivities of photonic crystal based antennas. There's a good agreement between the measurements and the FDTD calculations.

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