

Radiation properties of a planar antenna on a photonic-crystal substrate

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The photonic crystal is investigated as a substrate material for planar antennas in the microwave and millimeter-wave bands. Experimental results are presented for a bow-tie antenna on a (111)-oriented face-centered-cubic photonic-crystal substrate with a band gap between approximately 13 and 16 GHz. When driven at 13.2 GHz, the antenna radiates predominantly into the air rather than into the substrate. This suggests that highly efficient planar antennas can be made on photonic-crystal regions fabricated in semiconductor substrates such as GaAs.

The photonic crystal is a periodic dielectric structure that can exhibit a forbidden band of frequencies, or a band gap, in its electromagnetic dispersion relation (ω versus k). The first realization of a band gap in a three-dimensional photonic crystal occurred in 1989.¹ This breakthrough brought considerable attention to earlier proposals for optical applications of these crystals.²⁻⁴ Most of these proposals were based on the fact that the photon density of states vanishes in the band gap. At the same time, fabrication techniques were being developed to synthesize photonic crystals on a size scale consistent with a band gap in the visible wavelength region.⁵

Recently the interest in photonic crystals has expanded to applications in the microwave and millimeter-wave bands. Much of this interest was initiated at a recent workshop in which several applications were proposed, such as⁶: (1) planar antennas, (2) delay lines, and (3) nonreciprocal devices. Each of these applications falls into the general class of signal propagation and control. The photonic crystal is well suited for this class of applications because of the absence of propagation in the band gap and because of the nature of the dispersion curves at frequencies above and below the band gap. The photonic crystal is also much easier to fabricate for these three applications, because the appropriate lattice constant is roughly four orders of magnitude larger than it is in optical applications.

This paper addresses the photonic crystal as a substrate material for planar antennas. The other two applications mentioned above are of technological interest but are excluded from the present discussion because of the preeminence of the planar antenna. The planar antenna is the first application to be demonstrated experimentally and has the distinction of being the only known microwave application that requires a three-dimensional photonic band gap for optimum performance. The other applications

can be carried out in two- or even one-dimensional photonic crystals.

In microwave and millimeter-wave integrated circuits planar antennas play the important role of radiating signals off the chip into free space. When fabricated monolithically on III-V semiconductor substrate materials such as GaAs or InP, such circuits greatly enhance the performance and functional density compared with those for the counterpart hybrid circuits. However, these III-V materials all have a high dielectric constant, which generally makes the performance of planar antennas inferior to that of metallic feedhorns. At present, feedhorns are used in the majority of applications at frequencies above 20 GHz.

The problems associated with planar antennas on semiconductor substrates originate in the fundamental electromagnetics of a conductor on a dielectric surface.⁷ Shown in Fig. 1(a) is the conductor-substrate interface for a generic planar antenna on a uniform substrate with a purely real dielectric function (i.e., no electromagnetic attenuation) represented by the dielectric constant ϵ . For example, if the planar antenna is an elementary dipole, the ratio of the power radiated into the substrate to the power radiated into the air is approximately $\epsilon^{3/2}$.⁷ Thus a dipole on a GaAs substrate ($\epsilon = 12.8$) radiates 46 times more power into the substrate. A second problem is that the power radiated into the substrate at angles greater than $\theta_c = \sin^{-1}\epsilon^{-1/2}$ is totally internally reflected at the top and the bottom substrate-air interfaces. For GaAs this occurs at $\theta_c = 16^\circ$, so that in many antenna structures the vast majority of the radiated power is trapped in the substrate, as shown in Fig. 1(a).

An intriguing concept for alleviating these problems is the use of a three-dimensional photonic crystal as the antenna substrate, as shown schematically in Fig. 1(b). If the driving frequency of the antenna lies within the band

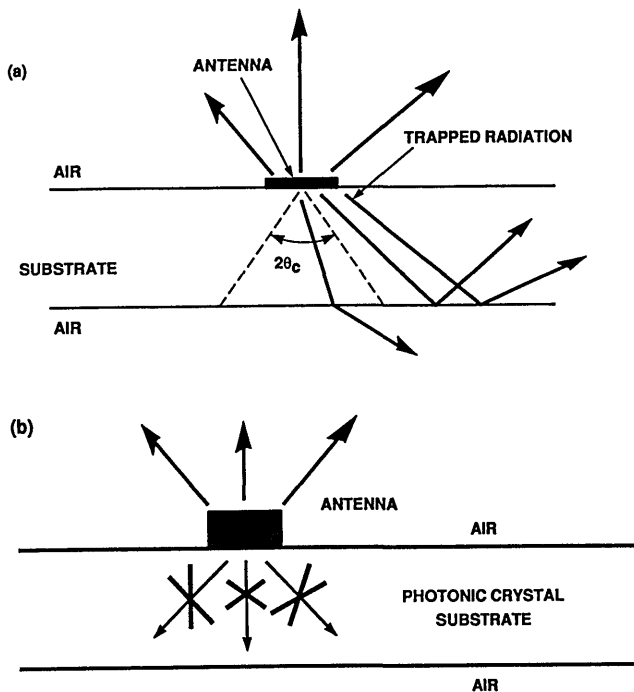


Fig. 1. (a) Cross-sectional view of generic planar antenna on uniform-dielectric substrate. (b) Cross-sectional view of generic planar antenna on a photonic-crystal substrate, showing expulsion of radiation at frequencies in the band gap.

gap, one expects that no power will be radiated into the substrate at any angle, since at every point along the conductor-substrate interface there is no propagation over the full hemisphere on the substrate side. However, it is not clear what fraction of the driving power will be radiated into the air side, since evanescent modes still exist at the air-substrate interface,⁸ and impedance mismatch can reflect power back to the generator.

To test this concept experimentally, we have fabricated a planar antenna on a photonic crystal substrate and have measured the antenna pattern by using the setup shown in Fig. 2. In this setup the photonic crystal was placed on a rotating table mounted inside an anechoic chamber. The antenna was driven by a microwave sweep oscillator with a coaxial output port. To drive the antenna in a balanced manner, the oscillator power was divided equally by a 3-dB hybrid coupler into two coaxial feed lines with phases 180° apart. The feed lines were routed to the planar antenna and connected to the driving points through their center conductors. The power radiating from the antenna was measured by a waveguide receiver consisting of a pyramidal feedhorn connected to standard-height Ku-band waveguide (cutoff frequency of 9.4 GHz for the fundamental TE₁₀ mode), a Ku-band waveguide-to-coaxial transition, and a microwave spectrum analyzer. This receiver measured power in only the TE₁₀ mode up to approximately 19 GHz. The *H* (magnetic) plane pattern of the antenna was measured by rotating the mounting table through 360° with the crystal and feedhorn configured as in Fig. 2, in which the side of the waveguide is shown. After the *H*-plane pattern was measured, the photonic crystal was turned 90° about the normal to the plane of the antenna to lie on an adjacent side, and the feedhorn was also turned 90° about the waveguide axis. The *E*

(electric) plane pattern was then measured by another 360° rotation of the table. The separation between the crystal and the feedhorn was approximately 60 cm.

The photonic crystal tested has a face-centered-cubic (fcc) crystal structure with a lattice constant of 7.8 mm. It was fabricated at Bellcore by drilling holes in an epoxy-based dielectric (Stycast) with $\epsilon \approx 13$ in the microwave band.⁹ The dimensions of the crystal are 15 cm × 15 cm wide and 8 cm thick. The planar antenna was mounted on the top surface of the crystal, which is (111) oriented and terminated halfway between two cubic-lattice planes. The band gap of this crystal lies between approximately 13 and 16 GHz as determined by previous transmission measurements.⁹ The planar antenna was made from copper tape that adhered to the top surface of the crystal. The antenna had a bow-tie geometry with an end-to-end length of 15 cm and a flare angle of 50°. A bow tie is preferable to a dipole in this experiment because it is non-resonant (i.e., the driving-point impedance is nearly real and frequency independent). Although the antenna pattern of the bow tie is less desirable, the division of power between the conductor and the dielectric is similar to that for the dipole or any other planar antenna.

The resulting *E*- and *H*-plane antenna patterns of the planar bow tie are shown in Figs. 3(a) and 3(b). At a driving frequency of 13.2 GHz, which is at the bottom edge of the band gap, the power in both planes is confined predominantly to the air side of the antenna. The pattern in the *H* plane is characterized by a strong lobe centered at the zenith and smaller sidelobes oriented at approximately ±70° from the zenith. The pattern in the *E* plane is more complex, consisting of a relatively small lobe at the zenith and three sidelobes oriented at approximately ±35°, ±70°, and ±85° from the zenith. The patterns are consistent qualitatively with previous results made on bow-tie antennas in which the measurements were made on the substrate side through a dielectrically matched lens.¹⁰ In the *H* plane the previous patterns had a major lobe at the zenith, and in the *E* plane they had major lobes oriented at an angle from the zenith that depended on the dielectric constant of the substrate and lens. The marked asymmetry of the photonic-crystal bow tie in the *E* plane is thought to arise from a slight imbalance in the drive

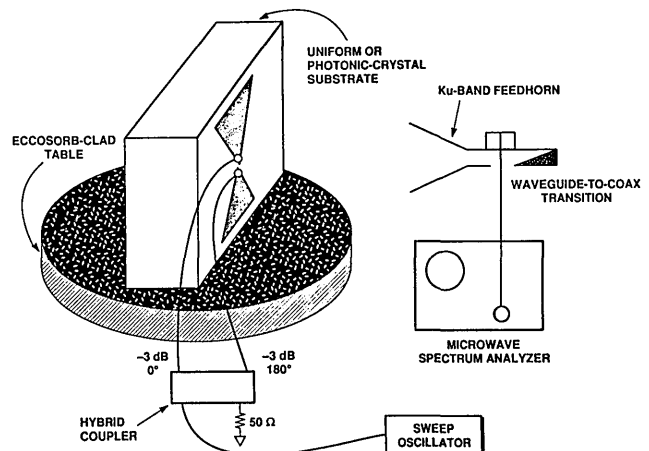


Fig. 2. Experimental setup for measuring radiation patterns from planar bow-tie antennas on photonic-crystal or uniform substrates.

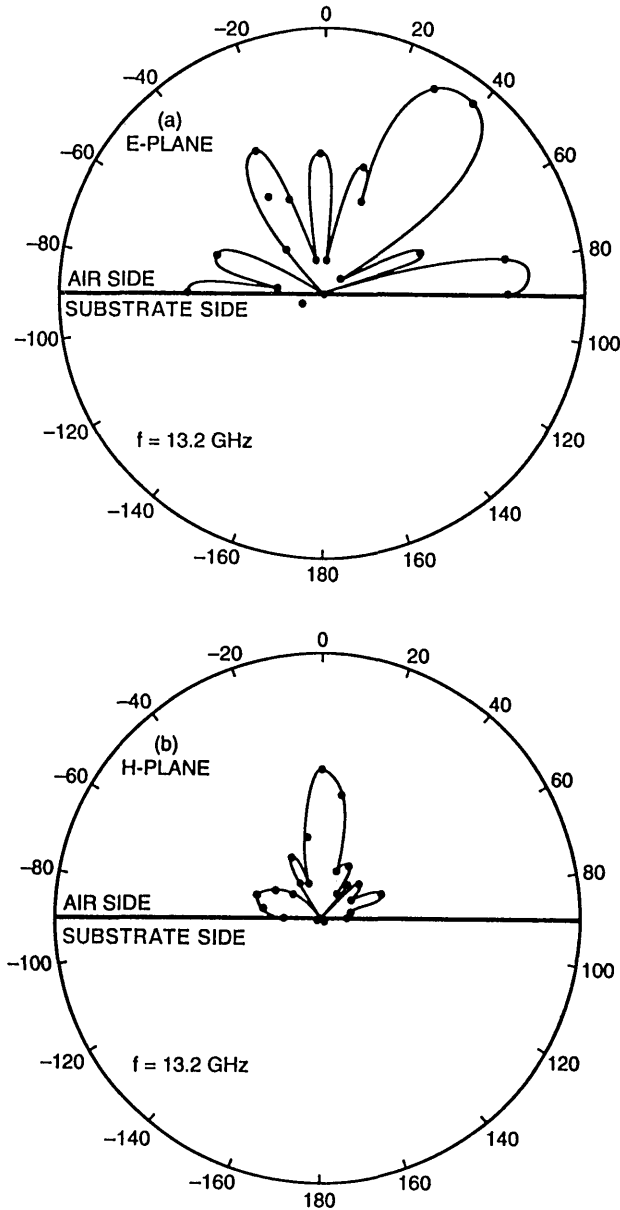


Fig. 3. (a) Radiation pattern at 13.2 GHz measured over 360° in the E plane for the bow-tie antenna on a photonic-crystal substrate (radial scale linear in power). (b) Radiation pattern measured in the H plane under the same conditions as in (a).

signal. The sharp minima in both patterns of Fig. 3 may represent nulls in the three-dimensional Bragg scattering profile from the substrate, but further study is needed to explain this complex behavior.

To emphasize the benefit of photonic crystals for planar antennas, we also measured the antenna pattern from an identical bow tie on a uniform Stycast substrate with the same dielectric constant as the solid portion of the photonic crystal and nearly the same thickness. The patterns for this antenna in the E and H planes at 13.2 GHz are shown in Figs. 4(a) and (b), respectively. In contrast to the photonic-crystal antenna patterns, the uniform-substrate antenna radiates little into the air side. As discussed above, the majority of the radiated power enters and is trapped within the substrate. This is why the total power on the substrate side, roughly averaged over

the E and H planes, is substantially less than the total power radiated by the antenna on the photonic crystal. We have verified that the difference in radiated power between the two substrates is not caused by a large difference in the power reflected back to the generator. Over the entire frequency range of the band gap we measured a reflection coefficient of $\sim 10\%$ for the bow tie on the photonic crystal and less than 10% for the bow tie on the uniform substrate.

One might think that the behavior of the planar antenna on the photonic crystal could be reproduced by simpler substrate structures, such as a uniform dielectric with a conducting bottom plane. This is precisely the structure of microstrip antennas, which are commonly used in the microwave band. The difference between the

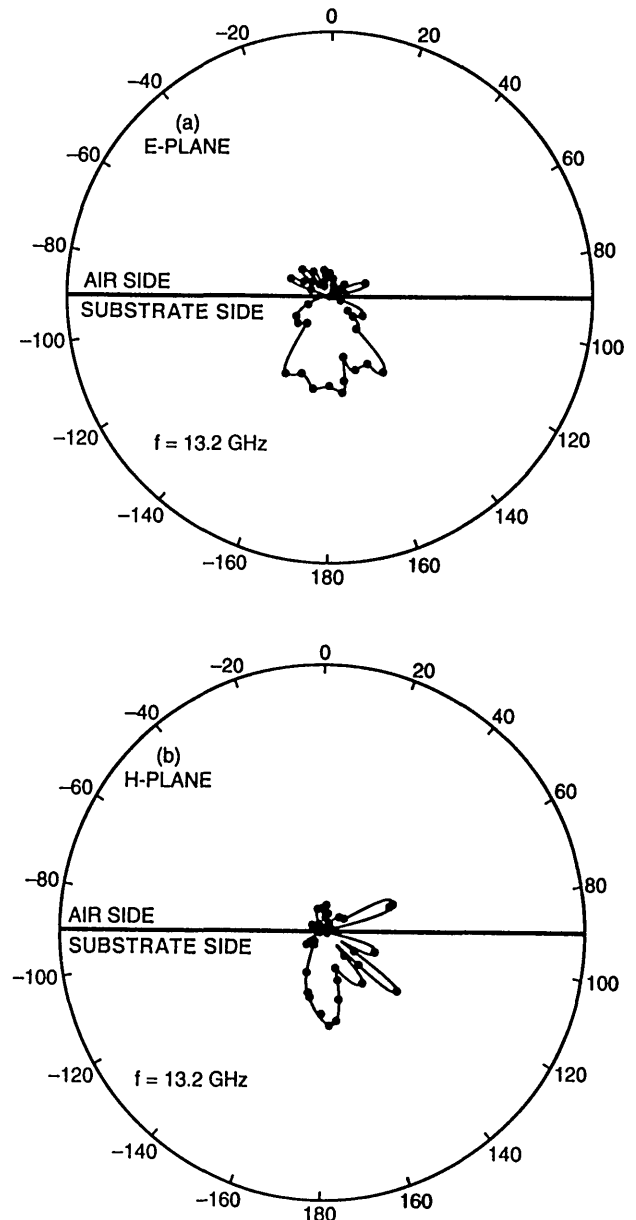


Fig. 4. (a) Radiation pattern at 13.2 GHz measured over 360° in the E plane for the bow-tie antenna on a uniform-dielectric substrate. The radial magnitude scale is kept the same as in Fig. 3. (b) Radiation pattern measured in the H plane under the same conditions as in (a).

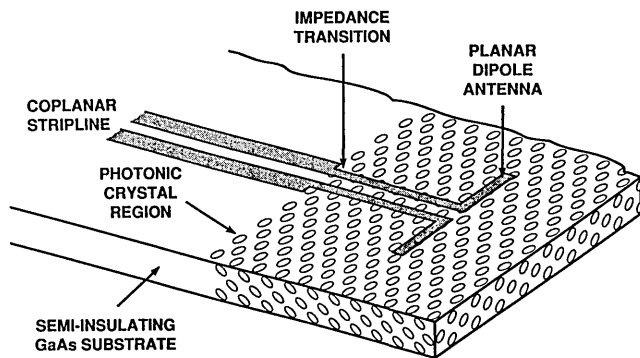


Fig. 5. Possible design of a planar dipole antenna lying over the photonic-crystal region of a semi-insulating GaAs substrate. The top surface and the two visible sides of the photonic-crystal region are assumed to be equivalent (100) facets of an fcc lattice.

two antenna configurations is in the way in which radiation is expelled from the substrate. The microstrip antenna does this by specular reflection from the bottom conducting plane. This process is hindered by two difficulties that have an opposite dependence on the substrate thickness. For thick substrates the microstrip antenna still radiates most of the power into the substrate, and all the substrate power that propagates at angles greater than θ_c is trapped in the substrate. For thin substrates the fraction of the total power that is radiated into the substrate is diminished, but the 180° phase shift that results from the reflection at the bottom conductor tends to cancel out the electric field at the driving point. This means that the driving-point resistance of the antenna approaches zero, and most of the driving power is reflected back to the generator. In contrast, the photonic crystal expels the radiation by Bragg scattering, which is highly nonspecular. Consequently radiation is neither trapped in the substrate nor reflected back at such a phase as to lower the resistance of the driving point. Judging from the low reflection coefficient of the bow tie on the photonic crystal, we have confirmed that the antenna does not have a low driving-point resistance.

To implement the planar-antenna concept in a monolithic integrated circuit, we envision a structure such as that shown in Fig. 5. It consists of a region of photonic crystal fabricated by etching sets of holes at different orientations in an otherwise uniform substrate of semi-

insulating GaAs. A dipole antenna is fabricated on the top surface of the photonic-crystal region and is driven by a coplanar stripline. A change in the dimensions of the coplanar stripline is made to transform the characteristic impedance between the uniform-dielectric and the photonic-crystal regions. This type of antenna design could be useful in the millimeter-wave band.

In summary, we have presented what are to our knowledge the first measurements of a planar antenna on a photonic-crystal substrate. When driven at a frequency lying within the band gap, the antenna radiates predominantly into the air rather than into the substrate. This is advantageous for the application of planar antennas in semiconductor integrated circuits.

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