Observation of surface photons on periodic dielectric arrays

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The first observation to the authors' knowledge of electromagnetic surface waves in a two-dimensional dielectric crystal is reported. By using the coherent microwave transient spectroscopy technique, surface waves are shown to exist at frequencies within the photonic band gap for certain lattice terminations. Energy at gigahertz frequencies is coupled into the surface mode using a prism coupling technique. The experimental results are in excellent agreement with theoretical predictions.

Many physical processes are profoundly modified in regions of space in which photon propagation is forbidden over a certain frequency range. The realization that such photonic band gaps can be formed in practice owing to the combined effects of scattering and interference in periodic dielectric arrays has led to much recent research in these systems[1–10] for both fundamental[11,12] and practical reasons.[13] A less-studied aspect of the subject is that, at frequencies within the band gap, these structures can support surface electromagnetic waves.[14] Understanding the surface modes is vital in practical applications because they provide a radiative channel that must be accounted for. We demonstrate here the existence of surface waves on two-dimensional dielectric arrays at gigahertz frequencies and show that the surface mode dispersion is a sensitive function of the termination of the dielectric lattice.

In this Letter our interest lies in the nonradiative surface modes, i.e., those that have fields which decay exponentially on both sides of the boundary between the photonic crystal and the air. To determine the dispersion relation of the surface modes in the two-dimensional dielectric system, calculations were performed using the plane-wave expansion technique that has been described previously by a number of authors.[1–6] This method provides a means for solving problems in electrodynamics that takes full account of the vector nature of the electromagnetic radiation. To investigate the surface states, a supercell method was used in which layers of photonic crystal were alternated with layers of vacuum. A supercell with eight lattice constants of photonic crystal and four lattice constants of vacuum was employed; 27,648 plane waves were used in the supercell, and convergence of better than 1% was achieved. Previous calculations[14] in three-dimensional photonic systems demonstrated that the existence of surface modes depends strongly on the termination of the photonic crystal. Similarly, in the two-dimensional dielectric array, surface modes are only found to exist if the lattice is suitably terminated.

Figure 1 shows the band structure of the (10) surface of a square lattice of dielectric columns. As described in Ref. 14, the states at the interface can be catalogued as four separate types: EE, which is extended (i.e., propagating) on both sides of the interface; DE, which is decaying in the air region but extended in the photonic crystal; ED, which is extended in air but decaying in the crystal; and DD, which is fully localized at the surface. As Fig. 1 demonstrates, the crystal terminated with cylinders has no modes localized at the surface, whereas the surface terminated with hemicylinders does have a surface mode. Although no simple rules govern which terminations of the crystal will have surface modes, there will always exist some termination that has such a mode.[14] It is clear that the surface mode is unable to radiate into the air because it cannot

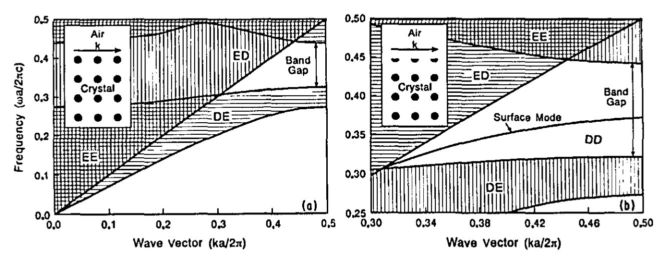

Fig. 1. Surface band structure of the (10) surface, shown in the ⟨01⟩ direction of the Brillouin zone. Shading indicates regions in which radiation can propagate in both the air and the photonic crystal (EE), exponentially decaying in the air and propagating in the crystal (DE), and decaying in the crystal and propagating in the air (ED). (a) Band structure terminated with cylinders, (b) band structure terminated with hemicylinders. The curve that lies in the band gap in (b) shows the localized surface mode (DD).

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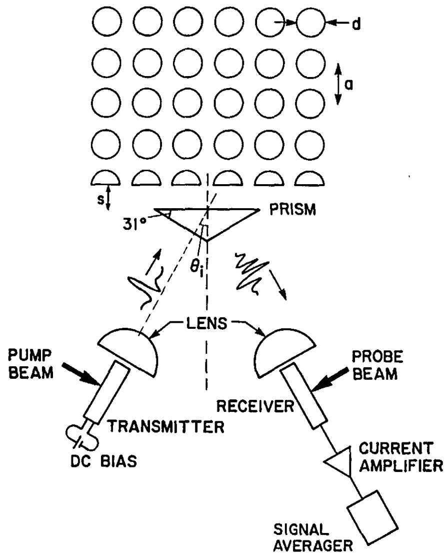

Fig. 2. Experimental configuration for COMITS experiments in TIR. The E field is parallel to the rod axes, i.e., perpendicular to the figure, where $d = 0.74 \pm 0.03$ mm, $a = 1.87$ mm, and S is varied from 0 to 5 mm. The figure is not to scale; the rods are drawn much larger than their relative size. In fact, ~30 columns of rods overlap the reflecting face of the prism.

satisfy wave vector and frequency conservation (i.e., it lies to the right of the light line), nor can it radiate into the photonic crystal because the mode exists at frequencies within the forbidden gap.

In the experiment described here, coupling to the surface electromagnetic wave is accomplished using attenuated total internal reflection (TIR) with a fused-silica prism to phase match the incident radiation to the surface excitation.[15] The experimental configuration for attenuated TIR experiments using the coherent microwave transient spectroscopy (COMITS) technique is shown in Fig. 2. COMITS is based on the radiation and detection of picosecond-duration electromagnetic transients by optoelectronically pulsed antennas.[16,17] The transmitting and detecting elements are exponentially taped coplanar strip lines fabricated photolithographically on silicon on sapphire.[16] The silicon is ion implanted to reduce the carrier lifetime to less than 1 ps. Optical pulses (1.5-ps duration at 527 nm) from a mode-locked, pulse-compressed, and frequency-doubled Nd:YLF laser are arranged in a conventional pump–probe configuration. A short current transient is generated when the pump pulse is focused onto the silicon between the coplanar strip lines of the dc-biased transmitter. The transient propagates down the strip line and is radiated in the exponentially tapered flare. The radiated transient contains frequency components in the range 15–140 GHz and is strongly polarized with its E field parallel to the plane of the antennas. Hemispherical fused-silica lenses collimate the radiation from the transmitter and focus the total internally reflected signal from the prism onto the receiving antenna. The voltage signal at the receiver is detected, as a function of time delay between the pump and probe pulses, by photoconductive sampling with the variably delayed probe beam. A complete description of the COMITS technique is given in Ref. 17.

The prism is made of fused silica with a dielectric constant $\epsilon = 3.78$ and negligible loss over the frequency range of interest.[16] The prism angles (shown in Fig. 2) were chosen so that, with the transient from the transmitter incident normally upon the input face, the angle of incidence on the reflecting face is just above the critical angle for TIR ($\theta_i = 31°$). The setup is arranged such that the E field is s polarized (parallel to the rod axes, perpendicular to the page in Fig. 2). The wave vector of the evanescent field parallel to the reflecting face is given by

$$k_p = n\frac{2\pi}{\lambda}\sin\ \theta_i\,, \tag{1}$$

where n is the refractive index of the prism and λ is the wavelength of the radiation. For θ_i greater than the critical angle, k_p is larger than the wave vector of light in air. This increase in wave vector permits coupling to the nonradiative modes at the surface of the photonic crystal. This technique, known as the Otto configuration,[15] is a well-known method for coupling to nonradiative excitations.

The photonic crystal used in these experiments consists of 0.74 ± 0.03 mm diameter, 100-mm-long alumina ceramic cylinders arranged in a square array of lattice constant 1.87 mm and held in a machined aluminum holder. The photonic band structure of the square lattice, well known from previous measurements,[10] exhibits a band gap between 45 and 70 GHz for radiation polarized with the E field parallel to the rod axes. Enough rods to complete a single row were ground to half their diameter (0.37 ± 0.02 mm) with a diamond wheel, i.e., they were made into hemicylinders. TIR experiments were conducted both with full rod and with hemicylindrical termination. The terminating row was closest to the reflecting face of the prism, and enough rows were used behind that row for the sample to be essentially a semi-infinite photonic crystal. A translation stage was used to position the sample at accurately known distances from the reflecting face of the prism.

Time-domain data were acquired first with no sample in the vicinity of the reflecting face of the prism and then with the photonic crystal of one termination or the other at various distances between 0 and 5 mm. The time-domain data for the two configurations at the same distance from the prism face were only slightly different. However, when the temporal data are numerically Fourier transformed, striking differences appear. Figure 3 shows the amplitude spectra for no sample [Fig. 3(a)], as well as for three different spacings with full rod termination [Figs. 3(b)–3(d)] and with hemicylindrical termination [Figs. 3(e)–3(g)]. There is a clear dip in the reflected spectrum in the latter case, which is absent in the former. This dip corresponds to the excitation of a surface mode on the hemicylindrically terminated surface. The frequency of the dip occurs at 48.8 GHz, which is at the bottom of the band

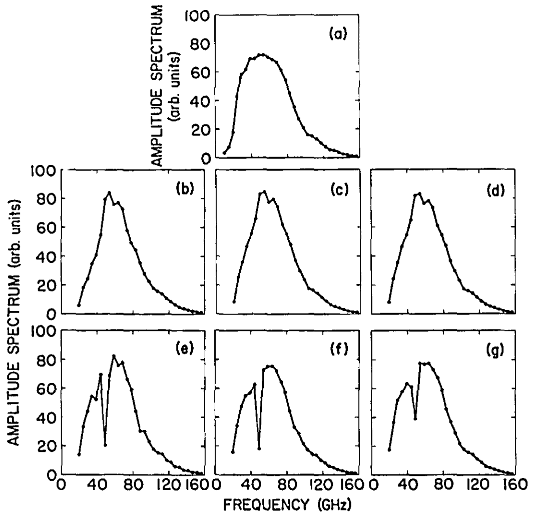

Fig. 3. Amplitude spectra obtained by numerically Fourier transforming the time-domain data. (a) TIR from prism alone; (b)–(d) cylindrical rod termination with prism–photonic crystal spacings of 1.7, 2.2, and 2.7 mm, respectively; (e)–(g) hemicylindrical rod termination with prism–photonic crystal spacings of 1.7, 2.2, and 2.7 mm, respectively.

gap and just below the light line. This is in good agreement with our theoretical predictions, which show that the surface mode punctures the light line at the bottom of the band gap [see Fig. 1(b)]. By changing to greater angles of incidence, larger wave vectors can be probed and the full dispersion relation of the surface mode plotted out.

The coupling efficiency of the incident radiation to the surface mode is clearly sensitive to the spacing between the prism face and the photonic crystal. For small spacings, the coupling is strong and much of the incident radiation is channeled to the surface mode. However, because of the strong coupling the surface mode can also efficiently radiate back into the prism, and hence the dip in reflected amplitude is not very deep. Conversely, if the spacing is large, there is little coupling and most of the radiation is internally reflected. Clearly, there is some intermediate spacing between these values at which the coupling is optimum.

Accurate determination of the linewidth of the frequency dip is not possible because of the limited frequency resolution of the experiment. The resolution of COMITS is limited by the temporal span of the time-domain data, which in these experiments is 200 ps. The corresponding frequency resolution is 5 GHz.[17] The dip is so narrow that it only affects the single amplitude point at 48.8 GHz and not the neighboring points. It is not surprising that the linewidth is so narrow. Because the two media making up the boundary consist of real dielectrics there is essentially no dielectric loss for propagation of surface waves on a photonic crystal. The only loss results from imperfections in the dielectric lattice and, in these experiments, because of radiative damping by the prism. This situation is different from surface-wave generation of metals and semiconductors for which dielectric losses strongly attenuate the propagating surface wave. As Ref. 14 indicates, the surface waves on a photonic crystal are similar to the propagation of Bloch waves on layered dielectric media.[18]

The amplitude spectra due to the photonic crystal with cylindrical termination [Figs. 3(b)–3(d)] are different from the reference spectrum. This feature is expected because the TIR at the prism is affected by the proximity of the dielectric array, particularly at low frequencies where the evanescent field extends into the crystal. At these frequencies the TIR process may become frustrated, i.e., some of the evanescent field will become radiative in the array.

In summary, the excitation of surface electromagnetic waves on a two-dimensional photonic crystal has been observed using the technique of attenuated TIR. In agreement with theoretical calculations we find that the existence of surface waves is sensitive to the specific termination of the dielectric lattice. No evidence of surface-wave generation is observed on the lattice terminated by full cylindrical rods, whereas for the surface terminated with hemicylinders there is strong coupling to the surface mode.

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