Quadrupole radiation from terahertz dipole antennas

J. V. Rudd

Picometrix, Inc., P.O. Box 130243, Ann Arbor, Michigan 48113

Jon L. Johnson and Daniel M. Mittleman

Department of Electrical and Computer Engineering, MS-366, Rice University, P.O. Box 1892, Houston, Texas 77251-1892

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We report what is to our knowledge the first detailed investigation of the polarization state of radiation from lens-coupled terahertz dipole antennas. The radiation exhibits a weak but measurable component that is polarized orthogonally to the orientation of the emitter dipole. The angular radiation pattern of this cross-polarized emission reveals that it is quadrupolar, rather than dipolar, in nature. One can understand this result by taking into account the photocurrent flowing in the strip lines that feed the dipole antenna. A Fresnel–Kirchhoff scalar diffraction calculation is used for calculating the frequency-dependent angular distribution of the radiation pattern, providing satisfactory agreement with the measurements.

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The technique known as terahertz (THz) time-domain spectroscopy has become a popular tool for spectroscopy and imaging, and numerous sensing and monitoring applications have been proposed. As a result of the growing importance of this technique, much research has been devoted to characterizing the THz beam generated from a photoconductive switch coupled to a substrate lens.[1] The beam divergence, the spatial mode, and the frequency-dependent transverse profile have been discussed in several publications.[2–5] The polarization state of the radiation has received less attention. For several measurements the polarization properties of the THz radiation have been exploited,[6–8] and other authors have noted polarization-dependent properties of optical elements.[9,10] As THz time-domain spectroscopy becomes more widespread, it is becoming clear that the degree of polarization of the THz radiation is an important aspect of these systems.

In most cases, the emission from THz antennas has been described by use of the approximation of an ideal dipole linear.[4] Of course, the dipoles used in real THz systems are not ideal, so the polarization state of the radiation is not, in general, purely linear. The conventional wisdom is that the typical emitter generates a cross-polarized component that is of the order of a few percent as large as the component polarized along the dipole. Yet, to our knowledge, there are almost no reports in the literature that corroborate this statement. Cai *et al.* found that the cross-polarized radiation has an amplitude roughly 7% as large as the dominant polarization component,[11] although they provided no explanation for the origin of this small component. Garet *et al.*[10] reported a frequency-dependent variation in the linear polarization axis, which they attributed to substrate-lens misalignment. We are aware of no thorough characterization of the polarization of the THz beam.

Here we report measurements of the cross-polarized component of the field radiated from a lens-coupled THz antenna, similar to one of the antennas described in Ref. 11. The angular dependence of both the s-polarized and the p-polarized components of the E-plane emission has been measured. For the s-polarized emission, the largest peak-to-peak electric field amplitude is approximately 7% of the p-polarized emission, as was previously noted.[11] However, we have found that the maximum in the s-polarized emission occurs at an angle of approximately 6° away from the optical axis. These results indicate that the s-polarized component is quadrupolar, rather than dipolar, in character. These measurements represent what is to our knowledge the first detailed characterization of the orthogonally polarized component of the radiation from THz antennas.

For these measurements we have used a THz time-domain spectroscopy system in which the femtosecond optical pulses are delivered to the antennas via single-mode optical fiber. Without this advantage it would have been necessary to realign the optical beam onto the detector at each angular position to ensure that the detection efficiency was not compromised by misalignment.[12] An even more important advantage afforded by the fiber coupling is that one may mount the receiver antenna on the end of a rail that pivots about the position of the emitter, as in Fig. 1(a). This procedure guarantees that the receiver antenna is always oriented normally to the propagation direction of the emitted wave, which removes the issue of the angular sensitivity of the receiver from the analysis. As a result, the measurements reflect the angular distribution of the emitted radiation rather than a convolution of the emitter and receiver antenna patterns.

With the exception of the fiber coupling of the antennas, the system is a fairly conventional THz spectrometer. The structure of the emitter antenna [Fig. 1(b)] is equivalent to the structure labeled FTM in Ref. 11 with a dipole length $L = 60\ \mu$m. We chose this structure for our initial investigation because it has become quite popular recently, as a result of the enhanced

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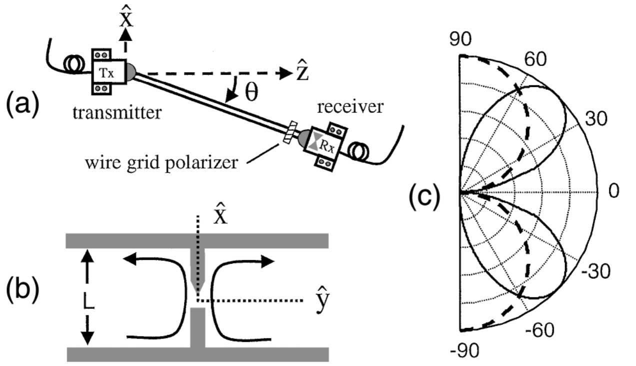

Fig. 1. (a) Schematic of the experimental arrangement. The receiver is mounted upon a rail that pivots under the transmitter. (b) Schematic of the emitter antenna. The dotted lines define the coordinate system used in the calculations; the z axis points into the substrate. The arrows show the flow of current from one strip line through the dipole to the other strip line, as described in the text. (c) Calculated angular field pattern for a quadrupole radiator of the type illustrated in (b). The dashed curve is the pattern for a radiator in free space; the solid curve shows the pattern modified by the presence of a high dielectric ($n = 3.42$) substrate.

THz field that it provides. For the detector, we use a 90° bow-tie antenna. A wire-grid polarizer is placed directly in front of the receiver [Fig. 1(a)], oriented to transmit only the radiation polarized parallel to the receiver dipole. Thus the measurements of the weak s-polarized radiation are not contaminated by cross talk from the much stronger p-polarized component. Both emitter and receiver are fabricated upon low-temperature-grown GaAs and coupled to silicon aplanatic hyperhemispherical substrate lenses[5] with radii of 4 mm. These lenses are aligned and attached to the antenna while the THz waveform is monitored in real time to minimize the effects of optical misalignment.[10] The emitter-to-detector distance of 21 cm is chosen to provide an angular resolution of ~2° for the measurements.

Figure 2 shows a series of waveforms measured at different angular positions of the receiver antenna relative to the optical axis ($\theta = 0°$). The emitter dipole is horizontal, so the E-plane of the antenna is parallel to the surface of the table. Negative angles correspond to the side of the dipole without the pointed tip. In contrast to that of the p-polarized emission [Fig. 2(b)], the amplitude of the s-polarized emission passes through a minimum at $\theta = 0°$, with symmetric maxima at $\theta = \pm 6°$. Also, the waveform at each positive θ is inverted relative to that at the corresponding negative θ. Both the null at $\theta = 0°$ and the symmetric lobes of opposite sign are reminiscent of a quadrupole radiation pattern. Figure 3 summarizes the results for the s-polarized case.

We propose the following mechanism for the generation of quadrupole radiation: The current flowing into the dipole is drawn from both ends of the strip line on one side and exits the dipole in both directions into the other strip line on the other side, as illustrated by the arrows in Fig. 1(b). For simplicity, we assume that the current does not vary with position along the dipole arms and that it drops to zero along the two strip lines with a linear dependence away from the dipole position. This current distribution is characterized by the length L of the dipole and by the distance d from the dipole to the point at which the current vanishes. This static current distribution possesses a zero dipole moment but a quadrupole tensor with two nonzero elements, $Q_{xy} = Q_{yx} \equiv Q_0$, where Q_0 is proportional to the product of d and L. In the coordinate system defined in Fig. 1, this quadrupole tensor gives rise to an electric field, which is given by

$$\mathbf{E}_Q \propto \sin\theta \cos\theta \sin 2\varphi\, \hat{\theta} + \sin\theta \cos 2\varphi\, \hat{\varphi}\,, \qquad (1)$$

where ϕ is measured from the x axis. For E-plane emission ($\phi = 0$), $\mathbf{E}_Q$ is an s-polarized wave with amplitude $\sin(\theta)$. We note that a linearly varying current is obviously not a realistic description of the current flow in this structure, but it does provide the appropriate symmetry and scaling and is thus a useful first approximation. One would obtain the same symmetry from an array of four point charges on the corners of a rectangle, for example.

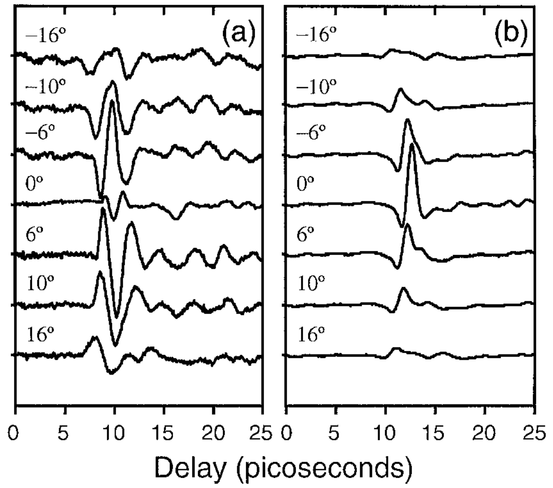

Fig. 2. Waveforms measured at the specified angles in the E-plane of the emitter antenna: (a) s-polarized emission (perpendicular to the emitter dipole), (b) p-polarized emission (parallel to the dipole). The vertical axis in (b) is reduced relative to that in (a) by a factor of 20, and all waveforms have been vertically displaced for clarity.

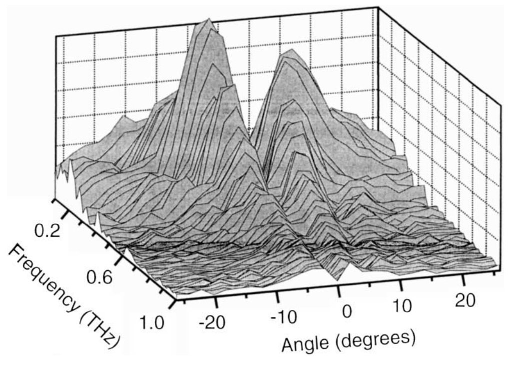

Fig. 3. Measured amplitude of the s-polarized radiation as a function of frequency and emission angle, showing a minimum at $\theta = 0°$ for all frequency components.

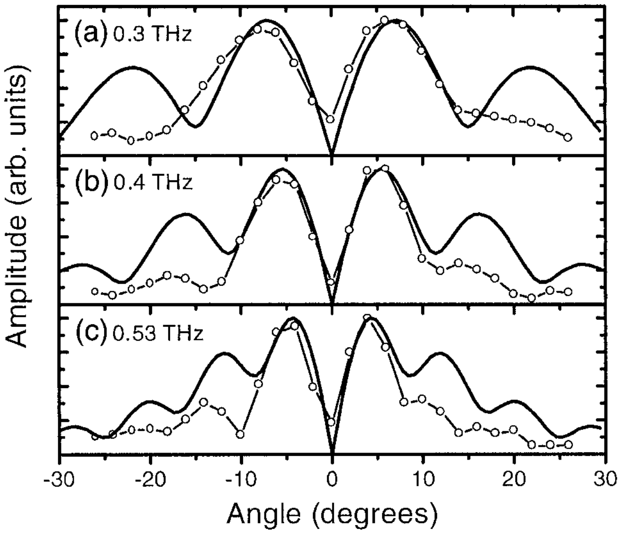

Fig. 4. Amplitude of the s-polarized radiation as a function of θ for three representative frequency components. Open circles are measured data; solid curves are calculated as described in the text. All the data and calculations have been normalized to unity amplitude.

This quadrupole pattern is distorted by the presence of the high dielectric substrate. The distortion of the field of a dipole at a dielectric interface has been treated extensively in the literature.[3,4,13,14] The quadrupole field of relation (1) may be treated in exactly the same way. Figure 1(c) shows the free-space emission pattern and the corresponding pattern for a quadrupole upon a silicon substrate. The modified pattern emits no radiation parallel to the interface and preserves the null at $\theta = 0°$, as expected. It also exhibits a small but discernable kink at $\theta = \pm 17°$, which is the angle for total internal reflection at the air–silicon interface.

This modified quadrupole pattern is strongest at angles of ±45° from the symmetry axis. So, to explain the much narrower angular distribution shown in Fig. 3, we must account for refraction effects at the output facet of the silicon substrate lens and for the diffraction that is due to the finite aperture presented by the lens. We employ a scalar Fresnel–Kirchhoff diffraction analysis to calculate the far-field pattern.[3,14] Figure 4 compares the measured and calculated angular patterns for three representative frequency components of the emitted pulse. The good agreement, particularly for the angles of the maximum signal and the widths of the primary diffraction lobes, is additional evidence that the measured patterns arise from the proposed quadrupole radiation mechanism.

The above argument is valid only if the length scale associated with the quadrupole charge distribution is small compared with the wavelength of the radiation. For the antenna shown in Fig. 1(b), length d, the decay length of the current along the strip line, is not known. However, any radiation that originates from a location that is displaced from the central axis of the substrate lens by more than ~100 μm cannot be efficiently coupled out into free space.[4] This stricture sets an effective upper limit on the size of the current distribution that can contribute to the radiated fields and ensures that the approximations inherent in the model are reasonable.

In conclusion, we have reported measurements of the angular emission patterns of cross-polarized radiation from a lens-coupled terahertz antenna. This radiation exhibits a quadrupole pattern, with a pronounced amplitude minimum on the optical axis and a 180° phase shift between the fields at positive and negative angles. One can explain this pattern by taking into account the photocurrent induced in the strip lines that feed the dipole antenna. These measurements represent the first quantitative description of the cross-polarized emission from THz antennas.

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