Near-Field THz Imaging and Characterization of an Array of Sub-Wavelength Circular Apertures

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***Abstract*—An array of sub-wavelength circular apertures (d=60 µm), periodically distributed in a square lattice, was studied in the near field using Terahertz Time-Domain Spectroscopy (THz-TDS). Images of the complete electric field distribution ($\vec{E}_x$, $\vec{E}_y$, $\vec{E}_z$) were recorded over a subsection of the array, as well as the corresponding spectral information, with a spatial resolution <10 µm.**

I. Introduction And Background

The optical properties of subwavelength apertures and aperture arrays have been the subject of many studies over the past several years[1-3]. Much work has been done in the visible regime and also at THz frequencies. Working at THz frequencies has the advantage that the structures can be larger and that the electric field, rather than intensity, can be measured. Most of these studies have been conducted in the far field. To understand how light emerges from arrays, *near-field* measurements are essential. This is because near-field information, such as the presence of evanescent waves or the spatial distribution of the surface charge density, is inevitably lost in the far-field.

Here, we show near-field measurements of the complete THz electric field, E_x E_y and E_z, for sub-wavelength diameter, metallic hole arrays. The arrays consist of holes in a 200 nm thick gold layer, deposited directly onto a GaP electro-optic detection crystal. THz light is focused onto the arrays and the electric near-field below the apertures is electro-optically detected close to the metal layer with a counter -propagating probe beam. GaP detection crystals with different crystal orientation are chosen such that we can measure all three electric-field components.

II. RESULTS

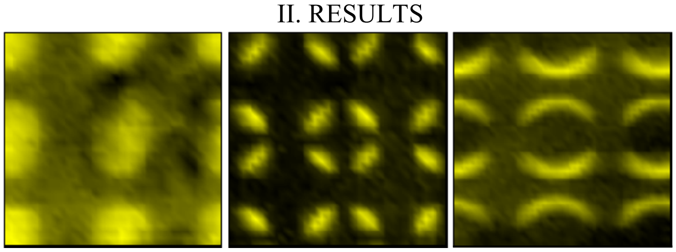

Figure 1 From left to right: E_x, E_y and E_z amplitude images measured in the near field of an aperture array. Aperture diameter = 60 µm. Scan dimensions ~200 µm x 200 µm. Period=90 µm.

Near-field measurements of the peak amplitudes, E_x, E_y and E_z, of a subsection of an aperture array are shown in Fig. 1. The scan length is approximately 200 µm per side. The aperture diameter is 60 µm and the periodicity is 90 µm. The x-component of the transmitted field, corresponding to the polarization of the incident field, passes directly through and is diffracted by the aperture, with the highest amplitude at the center. The y- and z-components of the diffracted beam are concentrated around the aperture edges. Together, they completely characterize the field in a plane just below the array. Note that the usable bandwidth of these measurements extends from ~0.2 to 1.5 THz, corresponding to wavelengths of 1.5 mm down to 200 µm. We are thus able to resolve an aperture that has spatial dimensions 25x smaller than the largest incident wavelength, with a spatial resolution < 10 µm.

Fig. 2 shows the spectral transmission of the x-component of the field, normalized to that of the incoming light spectrum, for a single pixel taken within one of the array apertures (black curve). Also shown is the normalized field of a single, isolated aperture (red curve).

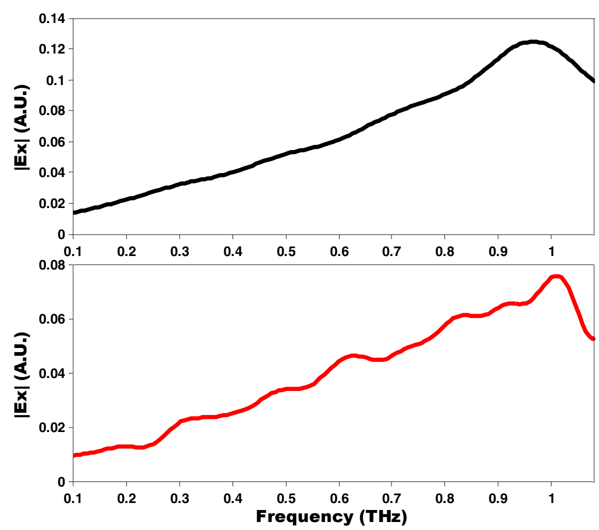

Figure 2 Normalized transmission of E_x field component taken from a single pixel within an aperture in the array (black) and a single, isolated aperture (red).

The transmission through the array aperture increases linearly until it reaches the cutoff for a 60 µm waveguide, at which point a peak emerges. The cutoff frequency is ~0.89 THz, assuming that the apertures behave as if they are filled with their dielectric substrate (GaP, n=3.3). Comparisons between these data and comparable data from a single 60 µm aperture can highlight the contribution of the array to the observed transmission. As seen in Fig. 2, initial measurements for a single, isolated aperture also show a linearly increasing

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frequency dependence. There is, however, no indication of a peak in transmission around the cutoff frequency. This may serve to illustrate the importance of diffracted light contributions in the array, coming from increased diffraction in the neighboring holes as the frequency decreases toward the cutoff. Another possible origin of this peak could be surface wave contributions. In this case, the location of the transmission peak is approximately given by[2]

$$\lambda_{\text{Resonance}} = \frac{P}{\sqrt{i^2 + j^2}} \sqrt{\varepsilon} \qquad (1)$$

Here, P is the periodicity of the array, i and j are integers corresponding to the resonance order, and ε is the real part of the dielectric constant for the interfacial material. In our case, the lowest-order resonant peak should occur at 1.01 THz, corresponding to a surface wave contribution at the metal-GaP interface.

Since we are directly measuring the fields, we may further distinguish and highlight contributions to the transmission from surface waves and/or diffraction by using data for a single, isolated aperture to construct an 'artificial' array. Data from a measurement of the x-component of the field for a single aperture can be used as a single array element; multiple elements may be added together to construct an array with arbitrary size and periodicity. This is possible because we measure the electric field, and fields can be added together as long as we assume electromagnetically decoupled structures.

In Fig. 3, an amplitude image of the x-component of the field for a 60 µm aperture is shown on the left.

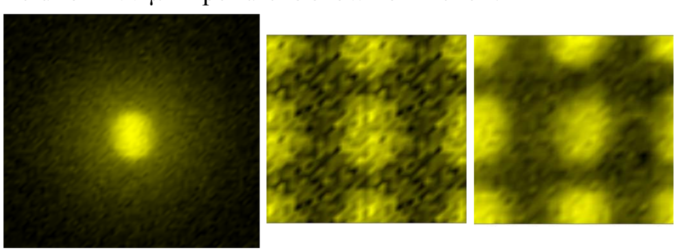

Figure 3 From left to right: Amplitude image (0.48 THz) of E_x for a single, isolated aperture (d=60 µm, image dimensions = 350 µm^2); 'artificial' array, constructed using single aperture data shown to the left (P=90 µm, image dimensions = 180 µm^2); measured E_x for P=90 µm array (image dimensions = 198 µm^2).

Note that the dimensions for this image are fairly large (350 µm x 350 µm). These data were used to construct an 'artificial' array (middle image) with the same periodicity (P=90 µm) as the measured real array (image on the far right). The dimensions for the constructed array image are 180 µm x 180 µm and for the real array image, 198 µm x 198 µm. All data shown in Fig. 3 are for a frequency of 0.48 THz. Adding array elements together in this fashion allows us to simulate the influence of diffracted light from surrounding apertures on a single aperture within an array. This is true so long as the scan area of the single aperture measurement is large enough that the fields measured at the periphery of the scan are negligible and the area is larger than at least twice the array periodicity. In the constructed array shown in Fig. 3, field contributions come not only from the nine apertures shown in the image, but also from apertures that are not shown, one row above and below, and one column to the right and to the left. Fig. 3 shows very good qualitative agreement between the constructed array and the measured array at this frequency.

For each pixel of a constructed array image we also have complete spectral information. This allows us to directly compare the spectral responses of the real and 'artificial' arrays at all points in an array image. Fig. 4 shows a comparison of the normalized transmission for a single pixel taken from the central aperture in the array image shown in Fig. 3, and its counterpart, taken from the constructed image (also shown in Fig. 3). Note that the constructed array data have been rescaled in order to display them more clearly.

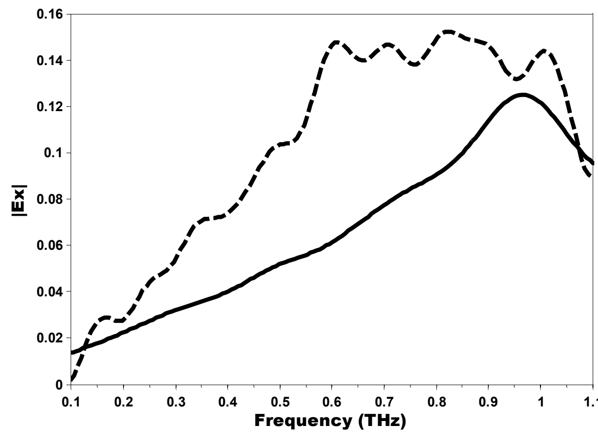

Figure 4 Normalized transmission of E_x field component taken from a single pixel within the central aperture of the array in Fig. 3 (black-solid) and from a pixel within the central aperture of the constructed array (black-dash).

The constructed array data are very different from the measured data. The data increase to a frequency ~0.6 THz after which the normalized transmission levels off. It is unexpected that the transmitted field reaches a maximum value below the cutoff frequency and this is also not what we observe in the actual measurement. Nor can we reproduce the peak we observe at ~1.0 THz by reconstructing the array in this manner. This preliminary analysis indicates that one cannot simply reconstruct an array using single aperture data. It is therefore not sufficient to include diffraction alone to explain the observed spectrum; one must also account for the interaction of the holes.

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