Vector Field Mapping of THz-Electromagnetic Wave Transmitted through Quadruple Square Holes

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***Abstract*—By using terahertz (THz) time-domain spectroscopy we measured THz-electromagnetic pulse passing through a two-by -two subwavelength hole matrix in near-field regime. Our Fourier analysis of measured data shows detection position dependent transmission maxima with respect to the polarization direction of the incident field. By comparing with numerical simulations based on finite element method, we found that the frequency dependent coupling between the transmitted waves through individual holes leads to different transmission maxima directly above and between holes.**

I. Introduction And Background

Transmission of the electromagnetic (EM) wave through holes smaller than the wavelength of the incident wave [1,2] has continuously been investigated by many engineers and scientists from the mid 20th century up to now, due to its diverse applications as well as importance in fundamental optics. Enhanced transmission of light through holes drilled in metal film [3] triggered many theoretical and experimental studies in optical frequency region, but there are still open questions: the role of the coupling between the transmitted waves through individual holes in near- and far-field measurement is not clearly explained. In this sense, experiments in THz range provide ideal test-beds to investigate pure coupling of the transmitted waves, since metal in this frequency region can be considered as perfectly conducting, thus, the influence of the surface plasmon polariton playing an important role on the transmission of light in optical frequency region can be neglected.

In this contribution, we present a near-field measurement of a short THz-pulse passing through a two by two sub-wavelength square hole matrix drilled in Al-film by using THz time-domain spectroscopy [4]. This technique makes it possible to discriminate each field component with high temporal and spatial resolution. By comparing Fourier-transformed signals in frequency domain to numerical simulations using finite element method (FEM) above and around holes we discuss how the local near-field transmittance spectra are changed. In addition, we study the effect of the asymmetric dielectric environments on the field distribution at the aperture plane.

II. RESULTS AND DISCUSSION

Four square holes with the same width and height of 200 μm are punctured in Al-film with a thickness of 80 μm. The distance between two adjacent holes is 400 μm (see figure 1 (c) and inset in figure 2). A single-cycle broadband THz pulse containing frequency components of 50 GHz - 3 THz and polarized in x direction is incident on the sample. The electric field transmitted through the holes is electro-optically measured by scanning a GaP electro-optical crystal adjacent to the sample with synchronized femtosecond probe laser pulse focused onto a 5 μm spot size (Figure 1 (a)). The spatial distribution of the electric field in time domain is Fourier- transformed into frequency domain (Figure 1 (b)) [5].

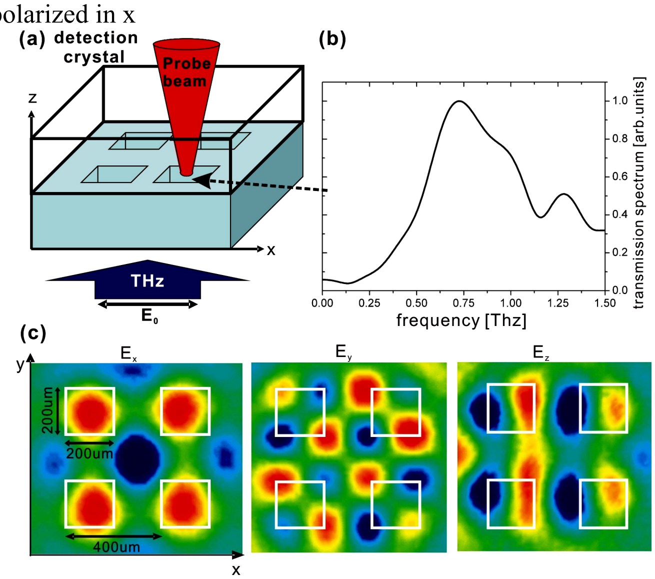

Figure 1: (a) Schematically depicted experimental setup. (b) The local transmission spectrum of the E_x field component, measured above the center of an aperture plane and transformed into frequency domain. (c) Near-field distributions of E_x, E_y, and E_z electric field components at the frequency of 0.66 THz. The field amplitude is normalized by the maximum in each figure, and the white squares indicate the boundaries of the holes.

In Figure 1 (c), as an example, the near-field distributions of three electric field components at frequency of 0.66 THz are presented, which qualitatively agree with the previous theoretical work [6] and our FEM simulations (not shown).

With these data we investigate the shift of local transmission spectrum depending on the detection position. In Figure 2 the frequency shifts of transmission maxima measured for the parallel and the perpendicular direction to the incident field polarization direction are plotted by black circles and red diamonds, respectively. While the transmittance maxima on y-axis (perpendicular to the polarization direction) show blue-shifts, those on x-axis (parallel) displays red-shifts. The transmission spectrum in the near-field is strongly related to the field distribution induced at the aperture plane, because it is the

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source of the transmitted wave according to the equivalence principle [7]. Therefore, we compare the experimental results to a half analytical model:

$$E_x(x,y)=\sum_{i=1}^{4}\int_{S_i}(ikR-1/R)e^{ikR}/R^2(z-z')E(x',y')dx'dy', \quad (1)$$

where k is the wave number in the considered region, R the distance between the source point (x', y', z') and the detection position (x, y, z). For the electric field distribution at the aperture plane *E(x', y')* the well-known eigenmode field distribution of the square wave guide [7], multiplied by the transmittance coefficient at the center of an aperture $\tau(\omega)$ (Figure 1 (b)), is used. While the calculated frequency shifts on x-axis match relatively well to the experimental result, the theoretical results on y-axis show a completely different tendency (red-shifts) from the experimental ones (blue-shifts). In parallel to these results, we have obtained the same red-shifts for both directions in FEM calculations.

The contrary frequency shifts of the experiment on y-axis are likely to result from the following reasons: the slightly asymmetrical field distribution and the relatively strong field intensity of the E_x component at the central position surrounded by the holes are caused by the misalignment of the sample, multiple reflections of the transmitted wave in the detection crystal, and the waves leaked out of the interface between the crystal and the sample. In addition, the detection height where the probe beam is focused must precisely be known, since the near-field distribution above the aperture plane changes itself very differently, depending on the distance from the aperture plane.

In order to study the influence of the detection crystal on the transmitted near-field distribution, we calculated with FEM the E_x field distributions at 50 µm from an aperture plane on y-axis for two different dielectric constants of the electro-optic crystal.

When all media except for metal are vacuum, the field distributions hardly change as the frequency varies (Figure 3, right).

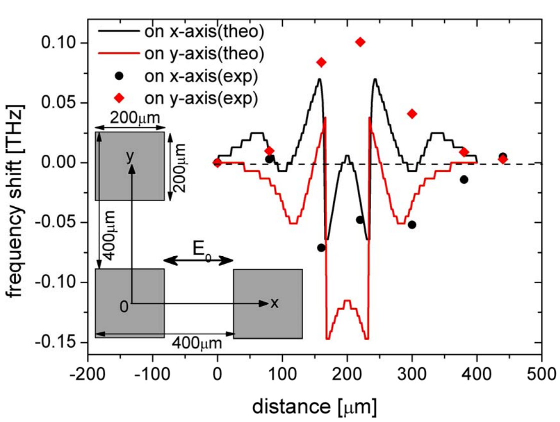

Figure 2: The frequency shifts of transmittance maxima as a function of the detection position for field directions parallel and perpendicular to the polarization direction of the incident field (x direction). The experimental results marked by the black circles and red diamonds are compared to the theoretical calculations with (1).

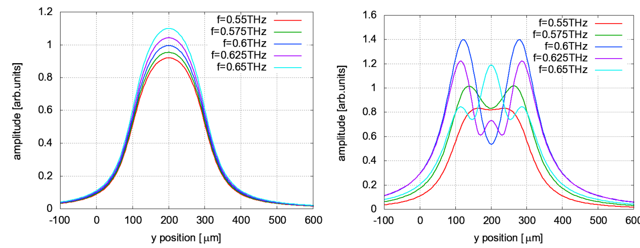

Figure 3: The near-field distributions calculated at 50 µm from an aperture as a function of the incident field frequency. In figures the dielectric constant of output space is considered as ε=1 (left) and ε=9.61 (right), respectively.

When the dielectric constant of GaP (ε=9.61, right) is considered, the field distribution and, in turn, the frequency shift of local transmission spectrum maxima change drastically, depending on the frequency. Due to the increased impedance mismatching at the output aperture plane, especially, around the cut-off wavelength, higher modes of the electric field are induced at the aperture plane, and which results in qualitatively different field distributions. Higher order modes generation at the junction of two waveguides filled with different media have already been discussed in microwave frequency regime [8, 9].

In summary, we presented near-field measurements of a short THz-pulse passing through a two by two sub-wavelength square aperture matrix drilled in Al-film by using THz time-domain spectroscopy, and discussed the frequency shift of local trans- mission spectrum maxima measured with respect to the incident field polarization direction. While the theory predicts red-shifts for both directions, the experiment shows red-shifts for the parallel and blue-shifts for the perpendicular direction. The discrepancy between the theory and the experiment can be caused by the measured asymmetrical field distribution.

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