Terahertz Wave Focusing at Localized Surface Plasmon Resonance

M. A. Seo[a], A. J. L. Adam[b], J. H. Kang[c], K. J. Ahn[a], J.W. Lee,[a] Q. H. Park[c], P. C. M. Planken[b], and D. S. Kim[a]
[a]Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea

[b]Faculty of Applied Sciences, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands

[c]Department of Physics, Korea University, Seoul 136-701, Korea

***Abstract* — We report on the enhanced terahertz transmission at the fundamental shape resonance of the rectangular holes. The funneling of energy at the fundamental resonance is also confirmed at the near-field.**

I. Introduction And Background

RECENTLY, it has been predicted[1] that a rectangular aperture with a large aspect ratio at its fundamental resonance focuses the incoming wave onto its small area through an enormous field enhancement. Here, we performed terahertz near-field experiments on single rectangular holes grown on an electro-optic crystal substrate. We find that the near-field amplitude becomes proportionally larger as the rectangle becomes narrower, strongly suggesting that a constant energy passes through even for a very narrow slit. We expect that the enormous field enhancement will have wide ranging implications in many areas where strong terahertz fields are much desired.

II. Results

We have demonstrated, using terahertz Fourier-transform near-field imaging technique[2] with λ/100 resolution, the occurrence of a large field enhancement at the fundamental localized surface plasmon resonance. The focusing effect of the rectangular hole is highlighted in the cross sectional view displayed in Fig. 1. Using an FDTD (Finite Differential Time Domain) simulation, we plot the *x*-component of the terahertz electric field amplitude, $|E_x(x, 0, z)|$ where *y*=0 is chosen to be the middle of the long-axis, for a rectangle with the width a_x =10 *um* and the length a_y =300 *um*. The frequency is chosen to be the fundamental shape resonance of the crystal side of the rectangle; occurring at approximately $c/2na_y \sim 0.2$ THz where *n* is the index of refraction of the crystal. The image reveals the field into the slit being focused by the rectangle at this resonance frequency, and being released immediately into the far-field.

Our sample consists of rectangular holes made in a metallic sheet deposited on a (110) oriented GaP crystal, which acts both as a dielectric support and as the field-detecting electro-optic crystal.

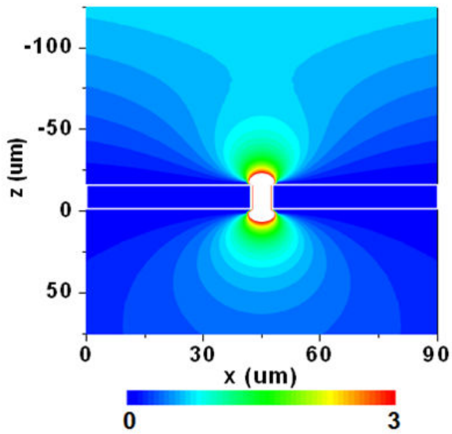

Fig. 1: FDTD simulated image. A side view of an FDTD simulated image describing energy focusing onto the single slit of 10 *um* width and 300 *um* length at the fundamental resonance of 0.2 THz.

In this orientation of the crystal, with the probing light polarization along the *x*-axis, we detect the horizontal component of the terahertz electric field along the *x*-axis[3], while the long axis of the rectangle is along the *y*-axis (Fig. 2(a)). The measured signal through the rectangular hole is normalized with the incident wave (Fig. 2(b) and (c)).

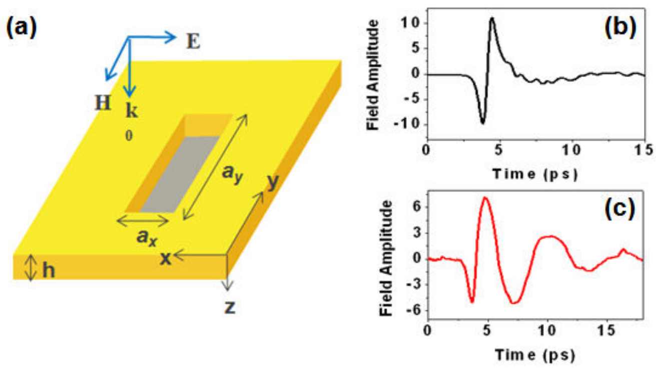

Fig. 2: (a) Terahertz near-field measurement of a single rectangular hole of sides a_x and a_y perforated on a gold metal film deposited on a piece of electro-optic crystal GaP. (b) The measured time trace without any structure on the crystal GaP, as an incident wave. (c) The resonant signal is measured through the rectangular hole.

978-1-4244-2120-6/08/$25.00 ©IEEE.

We measure the x-component electric field around a rectangle of $a_x = 10$ *um* and $a_y = 300$ *um* with a scan area of 200 *um* × 400 *um*. At each pixel, time-domain THz signal is acquired. Fast Fourier Transforming (FFT) the time traces at each position results in the frequency-domain images, containing both amplitudes and phases:

$$E_x(x, y, \omega) = \frac{1}{2\pi} \int E_x(x, y, t) e^{i\omega t} dt \qquad (1)$$

The experimental image reconstruction based on equation (1), with proper normalization against the incoming terahertz spectrum, can plot the steady-state images at each frequency component from the time-domain signal. Figures 3 (a), (b), and (c) show the field amplitude images at 0.1 THz, 0.2 THz, and 0.6 THz, respectively. The brightest image occurs at around 0.2 THz, which is close to the predicted fundamental localized surface plasmon resonance on the crystal side.

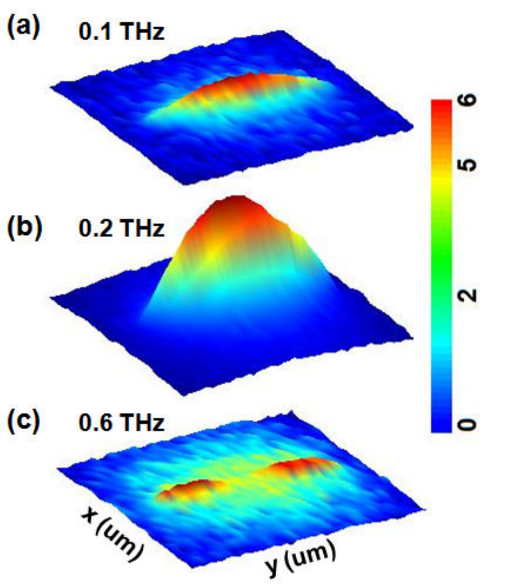

Fig. 3: Fourier-transformed images of E_x component at a rectangle of 10 *um* width and 300 *um* length. The E_x images are shown at (a) 0.1 THz, (b) the resonance frequency of 0.2 THz, and (c) 0.6 THz, respectively.

Remarkably, the field enhancement increases with increasing a_y/a_x ratio and therefore with decreasing slit width (Fig. 4). For each sample, the near-field amplitude is normalized against the high-frequency plateau at the frequency range of 0.7-1.2 THz, taken at the center pixel (Fig. 3). This normalization process allows us to estimate the actual field enhancement relative to the incident field amplitude, since we expect that the near-field amplitude far above the cut-off would simply be equal to that of the incident wave. In Fig. 3, with narrowing slit widths, the normalized near-field amplitude at resonance keeps increasing. At the narrowest slit shown in Fig. 4, the near-field enhancement factor reaches six.

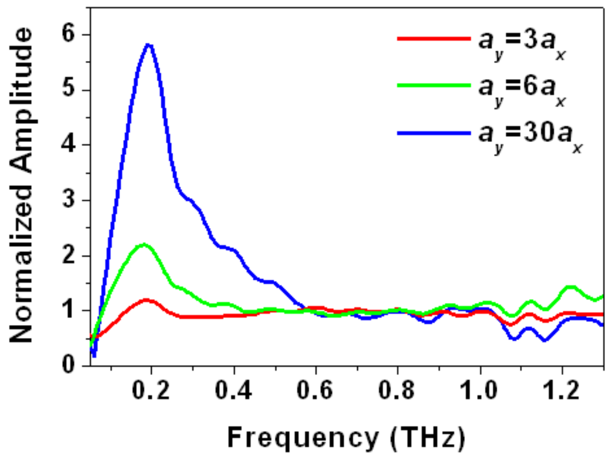

Fig. 4: The spectra at the center of the slits for various slit aspect ratios are shown. These spectra are normalized against the high frequency plateaus.

III. Summary

We touch upon the interesting issue of translating the observed large electric-field amplitude to the Poynting vector and thus energy flow through the slit. While the horizontal electric field greatly depends on frequency and slit width, the magnetic field variation is in general much less. This is because in a perfect conductor, the horizontal magnetic field is perturbed little by the presence of an aperture, whereas the horizontal electric field in the aperture is much larger or smaller than the incident field critically depending on the aperture geometry. To achieve the highest field enhancement at a given frequency then, one needs to design the slit length to be half the wavelength and the slit length to be as narrow as possible. The extremely large aspect ratio rectangular slits would find immediate application in physics, engineering and biology where large and controllable terahertz field enhancement is much desired.

References

[1] Garcia-Vidal, F. J., Moreno, E., Porto, J. A., and Martin-Moreno, L., "Transmission of light through a single rectangular hole," Phys. Rev. Lett. 95 (10), 103901 (2005).

[2] M. A. Seo, A. J. L. Adam, J. H. Kang, J. W. Lee, S. C. Jeoung, Q. H. Park, P. C. M. Planken, and D. S. Kim, "Fourier-transform terahertz near-field imaging of one-dimensional slit arrays: mapping of electric-field-, magnetic-field-, and Poynting vectors," Opt. Express 15, 11781 (2007).

[3] Van der Valk, N. C. J., Wenckebach, T., and Planken, P. C. M., "Full mathematical description of electro-optic detection in optically isotropic crystals" Journal of the Optical Society of America B: Optical Physics 21 (3), 622 (2004)

978-1-4244-2120-6/08/$25.00 ©IEEE.