Poynting Vector Mapping of Terahertz Wave Transmission through Metallic Grating

D. S. Kim,[a] M. A. Seo,[a] A. J. L. Adam,[b] J. H. Kang,[c] H. R. Park,[a] Q. H. Park,[c] and P. C. M. Planken[b]

[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 experimentally visualize Poynting vector of transmitted terahertz wave through a multiple slit array. This new method provides direct mapping of energy flow and helps distinguishing different diffraction orders in the near-field.**

I. Introduction And Background

UNDERSTANDING how light propagates around or through structures of sub-wavelength dimensions is essential for a broad range of scientific and engineering applications. Increasingly, methods developed in the terahertz (THz) frequency range of the electromagnetic spectrum are applied to the study of, for example, the extraordinary transmission[1] of light through sub-wavelength apertures in metal film.

II. Results

Here, we show that, using a near-field imaging technique based on THz time-domain spectroscopy (THz-TDS),[2] it is possible to measure the full vectorial, time-dependent electric field with a sub-wavelength spatial and a sub-cycle temporal resolution. The field $\vec{E}(x, 0, z, t) = [E_x(x, 0, z, t), 0, E_z(x, 0, z, t)]$ is detected through an electro-optic sampling technique using two GaP crystals. The vertical electric-field component E_z is detected using a (001) oriented GaP crystal, while E_x is detected using a (110) GaP crystal. Fourier transforming the time dependent images allows us to obtain time images at each frequency component. As an example, we show measurements of the near field of slit arrays (500 *um* of period and 100 *um* of slit width) in thin metal foils, illuminated with THz pulses having a broad spectral bandwidth.

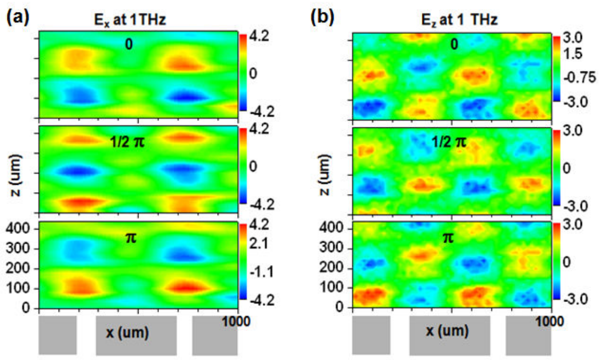

Fig. 1: The horizontal (a) and the vertical (b) electric field distributions behind the multiple slit at 1 THz.

The Fourier-transformed images are dominated by the interference between the 0th and 1st order diffractions, as can be explicitly visualized in Fig. 1(a) and (b). We now show that we can use this information to construct vectorial images of electromagnetic waves through the multiple slit structures (Fig. 2(a)).

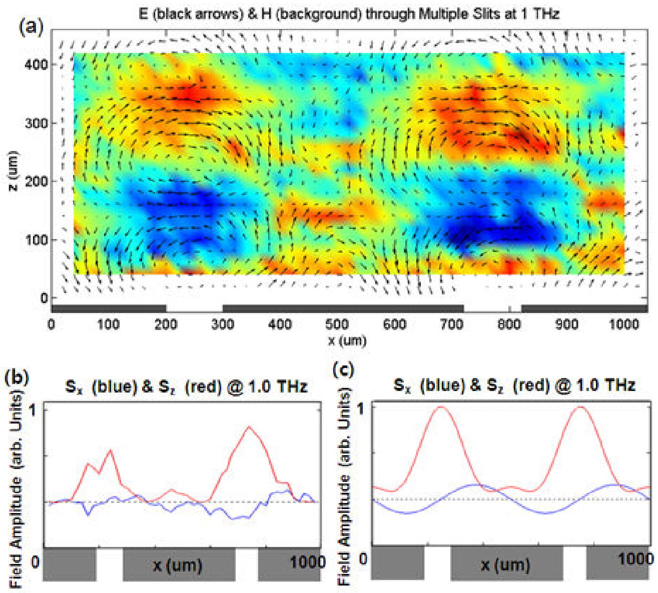

Fig. 2: (a) Electric field vector behind the multiple slit at 1 THz, measured in the x-z plane behind the slit. The background color map represents the corresponding magnetic field vectors calculated by curling of the electric field data. (b) The cross-sectional views of the Poynting vectors at a 100 um height. The blue line denotes the x-component of the Poynting vector and the red line represents the z-component. (c) Poynting vector calculation assuming the relative magnetic field amplitudes of the 0th, 1st, and -1st order diffractions are to be 2: 1: 1.

We can understand the saddle point and the vortex point in the following way. Around the null electric field point located at $(x_0, 0, z_0)$, both the vortex and the saddle point, with the forms $\vec{E}(x, 0, z, \omega, t) \propto (z - z_0, 0, -(x - x_0), \omega)e^{i\omega t}$ and $\vec{E}(x, 0, z, \omega, t) \propto (x - x_0, 0, -z + z_0, \omega)e^{i\omega t}$, respectively, satisfy the divergence equation $\nabla \cdot \vec{E} = 0$. However, these regions are obviously the regions with non-zero curl. Since we measure the field, rather than intensity, we can directly apply the Maxwell-Faraday equation to identify these regions as

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ones having a time-dependent magnetic field according to: $\frac{\partial \vec{H}(x, 0, z, \omega, t)}{\partial t} = -c \cdot \vec{\nabla} \times \vec{E}(x, 0, z, \omega, t)$.

Taking the curl to access the magnetic field is possible because our THz-TDS setup provides information on both the amplitude and the phase of each electric field component. We note that direct measurements of the magnetic field are usually extremely difficult, but our measurements of the *full time-dependent electric field* make such measurements superfluous (Fig. 2(a)). Now that we have the electric and magnetic field vectors at each position and in time, we can experimentally obtain the Poynting vector $\vec{S} = \vec{E} \times \vec{H}$. Our method provides a more straightforward method for power flow at each position at a time than the single component measurement.

In Fig. 2(b), time dependent Poynting vectors at 1 THz are plotted. The Poynting vectors are mostly concentrated around the slit axes. Essentially, the *z*-component of the Poynting vector S_z at 1 THz, which is above the Rayleigh frequency, is a linear combination of a constant background and two additional terms proportional to $\cos\frac{2\pi x}{d}$ and $\cos^2\frac{2\pi x}{d}$ where d is the period of the multiple slit. All the three terms make constructive interference at the slit positions, while $\cos\frac{2\pi x}{d}$ and $\cos^2\frac{2\pi x}{d}$ terms interfere destructively in the middle regions.

Our vector microscope accesses $\vec{E}(\vec{x},t)$, $\vec{H}(\vec{x},t)$, $\vec{S}(\vec{x},t)$, and finally time-averaged Poynting vector $<\vec{S}(\vec{x})>$ (see Fig. 3) experimentally in the broad frequency range between 0.32 and 1.5 THz. Having thus obtained knowledge of the complete knowledge of the electric and magnetic field components, we then experimentally calculate the Poynting vector to determine the flow of light in the near-field zone of the slits.

III. Summary

Poynting vector distribution which is determined by the measured electric field and obtained magnetic field proves a powerful method to show electromagnetic energy flows in the near-field zone, including the energies contained in each diffraction orders. The results of our measurements are directly relevant to other frequency domains, such as the visible and microwave regimes[3, 4].

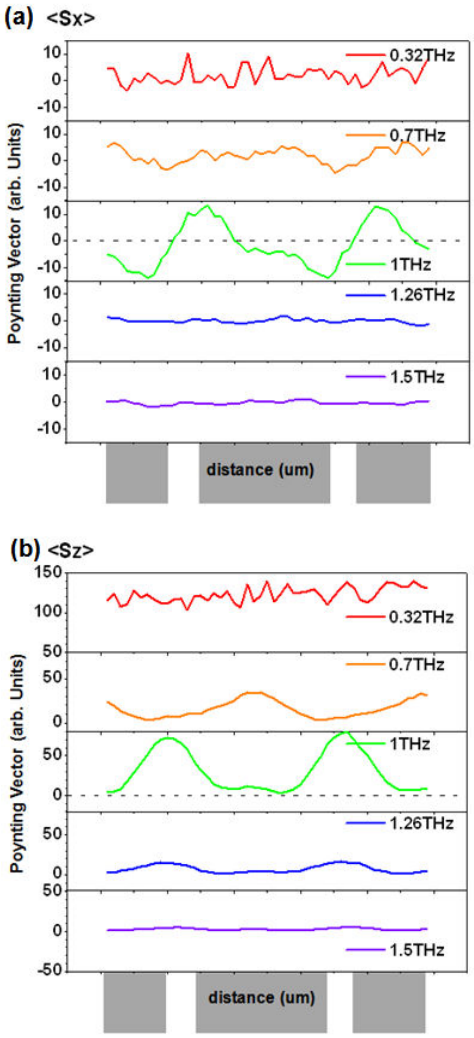

Fig. 3: (a) The horizontal component of the time-averaged Poynting vector behind the multiple slit at 0.32 THz, 0.7 THz, 1 THz, 1.26 THz, and 1.5 THz, respectively. (b) The vertical component of the time-averaged Poynting vector behind the multiple slit at 0.32 THz, 0.7 THz, 1 THz, 1.26 THz, and 1.5 THz, respectively.

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