Terahertz Transmission through Nanogaps Using both Pulsed and CW Sources

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***Abstract*— We measure field enhancement through nanogap by using both terahertz time domain spectroscopy (TDS) and terahertz imaging technique with continuous wave (CW) radiation source. Far-field amplitude is connected to the near-field enhancement through the Kirchhoff formalism [1, 2, 3]. With TDS, we found that a field enhancement of 200 at 0.1 THz for the 500 nm slit. To confirm our TDS results, we also perform the transmission experiment with 70 nm width nanogap structure perforated in thin gold films on Si substrates by using 0.2 THz CW source.**

I. Introduction and Background

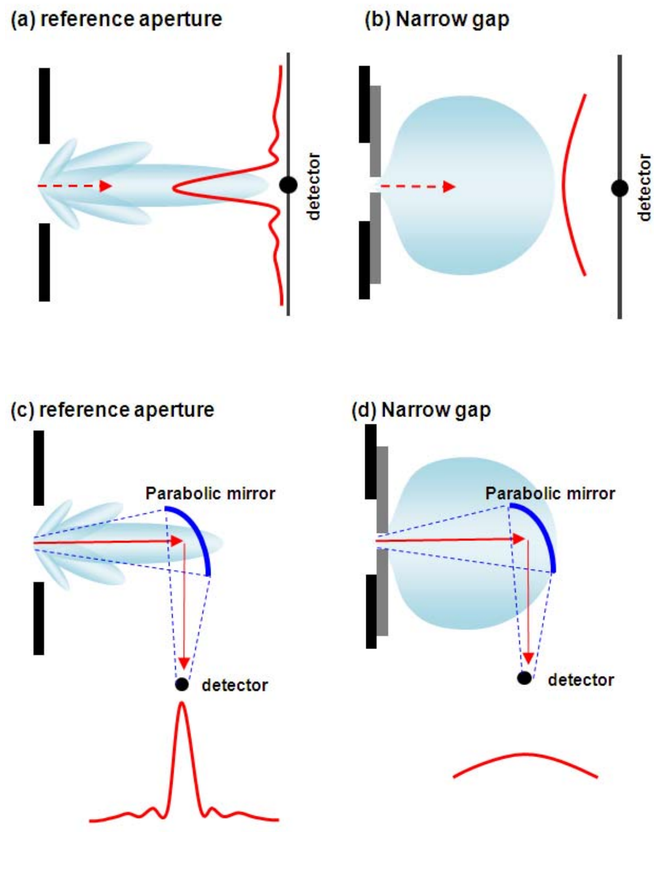
Understanding how light propagates through sub-wavelength apertures is essential for broad ranges of scientific and engineering applications. Periodic arrays in metal have attracted considerable interests in the aspect of the enhanced transmission [4]. Recent papers show that each rectangle plays a key role in the enhanced transmission of the rectangular periodic arrays [3, 5].

In our experiment, we study the optical feature of a single slit to examine the role of the shape of a single aperture in the enhanced transmission. Here, we report on terahertz funneling through a single nanogap, using terahertz time-domain spectroscopy in the far-field and discuss the Kirchhoff integral formalism [1, 2, 3] to obtain the field enhancement at the near-field. In addition, we measure the THz transmission through a 70 nm width nanogap with CW THz radiation source.

II. Results

We perform THz-TDS experiment with various single slits of widths from 450 μm all the way down to 500 nm. Our μm – size single slit samples are made in a 17 μm thick Al film using laser machining. For the 500nm sample, we first prepared a nearly free standing 60-nm-thick gold film. The gold is deposited onto a 1.2 μm -thick layer of SiO_2 followed by a 0.5- μm -thick SiN. Then, a nanogap is fabricated on the gold film using Focused Ion Beam (FIB) apparatus.

A 2mm by 2mm size aperture is used as the reference area, and the field enhancement is calculated by using the Kirchhoff formalism [2, 3]. At first we consider the Kirchhoff integral formula to calculate the field enhancement in our system. Supposing that there were only a amplitude-detector at the center of the diffraction pattern, as illustrated in *Fig*. 1 (a) and (b), the incident THz beam through the aperture without the sample is used as the reference signal for the normalization of the transmitted THz wave through the nanogap. The near-field enhancement factor is defined as α/β, where α is the normalized transmitted amplitude through slits and β the ratio of the gap size to the aperture size. After measuring the transmitted electric field $E_{far}^{aperture}$ only through the reference aperture at the detector, we next perform the same experiment with narrow gaps and obtain the transmitted electric fields E_{far}^{gap}.



Figures1: Diffraction pattern (a) Wide slit with a point detector (b) Narrow slit with a point detector (c) Wide slit with collection optical elements (d) Narrow slit with collection optical elements

We define the normalized amplitude α as the ratio between the two measured values: $\alpha(\omega) = \left| E_{far}^{gap}(\omega) / E_{far}^{aperture}(\omega) \right|$. We assume that the reference aperture is large enough so that the

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electric field at the aperture is almost same as the incident one E_{inc} . According to the Kirchhoff integral formalism, the far field amplitude transmitted through the aperture at the normal incidence is proportional to the near-field amplitude via the following relation:

$$E_{far}^{aperture} = \frac{e^{ikR}}{i\lambda R}\int_0^{b_1}\int_0^{b_2} E_{inc}\, dxdy = \frac{e^{ikR}}{i\lambda R} E_{inc} b_1 b_2,$$

where $b_1 \times b_2$ is the cross section of the reference aperture and R the distance from the scattering center to the detector. Likewise, we can express the E_{far}^{gap} with a nanogap as:

$$E_{far}^{gap} = \frac{e^{ikR}}{i\lambda R}\int_0^{b_2}\int_0^{a} E_{near}\, dxdy = \frac{e^{ikR}}{i\lambda R} E_{near} a b_2,$$

where a is the gap width. Dividing the two relations, we obtain $\frac{E_{near}}{E_{inc}}\frac{a}{b_1} = \alpha \Rightarrow E_{near} = \frac{\alpha}{\beta}\cdot E_{inc}$. This is the basic method which we have used to calculate the field enhancement.

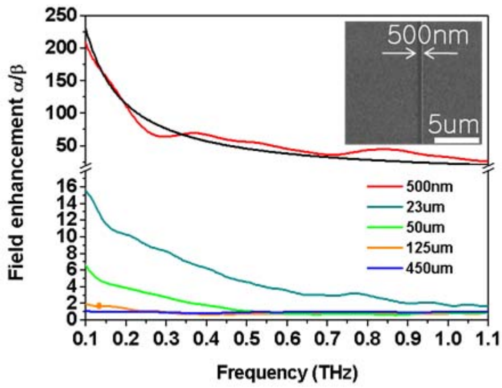
Shown *Fig*. 1 (c) and (d) are collection optical elements such as a parabolic mirror in our experimental setup. It is straightforward to include this effect by integrating the signal over the surface of the used parabolic mirror. We compare two cases by using rigorous diffraction formalism and find that the correction is less than 1%.

The field enhancement through a slit increases as the width of the slit decrease. For 500nm width of the nanogap the field enhancement reaches 200 at 0.1 THz (*Fig*2. (a)).

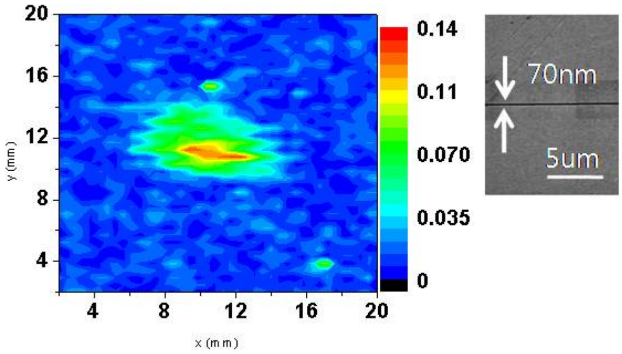
From our results, we expect that the field enhancement can be still more enhanced for a smaller size slit, and the huge near field enhancement inside the nanogap can contribute to the extraordinary far field transmission. To experimentally confirm our idea, we choose a single frequency of 0.2 THz and a 70nm slit. A nanogap with 70nm width and 3mm length is perforated on a gold thin film on a Si substrate using FIB machine. We raster scann the nano gap structures and detect the transmitted THz signal at the opposite side of the sample. By using the relation derived above, we measure a huge field enhancement over 800 for the 70nm slit. This enhancement factor is consistent with the results by pulsed TDS measurements.

In conclusion, we showed that huge THz far field enhancements can be obtained with metallic slits whose width are in hundred nanometer scales. In addition, we presented a connection between the far field transmission and near field enhancement using the Kirchhoff formalism. Huge enhanced THz field can be used for various researches such as THz-nonlinear measurements or single molecule detection.

(a)



(b)



Figures2: (a) Field enhancement with various slits. (Inset: 500nm slit SEM image) (b) 70nm width nanogap experimental result. 0.2THz CW radiation source is used. (Inset: 70nm gap SEM image)

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