SAND2014-0463C

Transmission of THz pulses through 3μm apertures: applications for near-field microscopy

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Abstract: We demonstrate that THz pulses transmitted through small apertures (~λ/100) exhibit strong evanescent components in the near-field zone of the aperture. Using this effect, we developed sub-wavelength aperture THz near-field probes that provide 3μm resolution.
OCIS codes: (110.6795) Terahertz imaging; (240.6680) Spectroscopy, terahertz.

Introduction: limited transmission through sub-wavelength apertures

Terahertz (THz) imaging with spatial resolution beyond the diffraction limit is achieved using near-field probes.[1] For sub-wavelength aperture probes, the resolution in principle is limited by the size of the aperture, independent of the wavelength.[2] However, for the apertures substantially smaller than the wavelength λ, the aperture transmission coefficient exhibits a prohibitive behavior. Bethe's theory of transmission through a sub-wavelength aperture of size a predicts that the transmitted electric field decrease with the aperture size as $E \propto a^3$ (for the intensity: $I \propto a^6$). The Bethe's dependence was confirmed experimentally.[2]

However, numerical simulations showed recently that the Bethe's dependence changes for the evanescent field components in very close proximity to the aperture (~1µm for THz waves).[1,4] Here, we investigate the transmission of THz pulses in the near-field zone ($z < a$) for apertures as small as 3µm. The experimental results show the transmitted field amplitude does not follow the a^3 dependence. This effect is attributed to the evanescent components.

The effect allows us to enable higher spatial resolution in THz near-field imaging. We developed integrated THz near-field probes where a THz detector is integrated within ~1µm from the aperture. The near-field probes show enhanced sensitivity and allow us to demonstrate a spatial resolution of 3µm for THz time-domain imaging.

Experimental results

To detect the evanescent field components for small apertures, the entire THz detector must be sufficiently small to be accommodated within a short range (~1µm) of the aperture. This is accomplished in samples shown schematically in Fig 1(a). A THz detector made on 500nm-thick layer of low-temperate grown (LT) GaAs is located ~500nm or ~1000nm from the aperture. Using this design, we tested transmission of THz pulse through apertures of 3, 5, and 10µm (Fig. 2). The dependence of the transmitted THz pulse amplitude is summarized in Fig. 1(c).

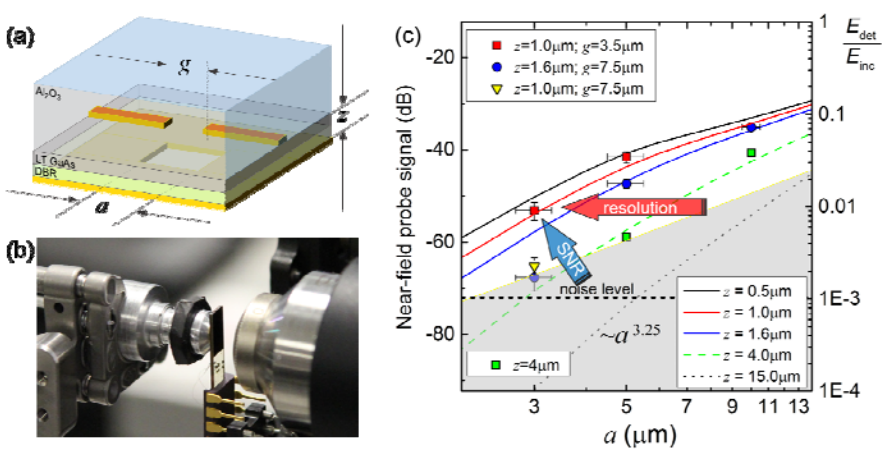

Fig. 1. Schematic diagram of the aperture samples with the integrated THz detector. (b) experimental system for characterization of aperture transmission. (c) Amplitude of THz pulses transmitted through sub-wavelength apertures.

The results show that by moving the LT GaAs detector within 1 μm form the aperture the amplitude of the THz pulse is increased substantially.

To exploit this effect in a THz near-field probe, we developed a photoconductive THz near-field detector structure, which incorporates the thinned photo-conductive LT GaAs detector region and the distributed Bragg reflector between the detector and the aperture plane. Detection of the evanescent waves in such a probe enables us to improve sensitivity and, as a result, resolution of sub-wavelength aperture THz near-field microscopy.

Spatial resolution capabilities of the integrated near-field probes are evaluated by scanning an edge of a metallic strip deposited on GaAs in front of the 3μm aperture probe. For this experiment we used an unfocused THz beam generated using the ZnTe crystal positioned approximately 5mm away from the test sample. The metallic edge is oriented parallel to the beam polarization. The THz pulse waveform is shown in Fig. 2(a). The amplitude of the THz pulse changes between the metallic and dielectric regions (Fig. 2(b), red line) with the transition region length of 3.3±0.5μm using the 10-90% criterion or 2.5μm using the 20-80% criterion. The test confirms that the probe spatial resolution is determined by the aperture size.

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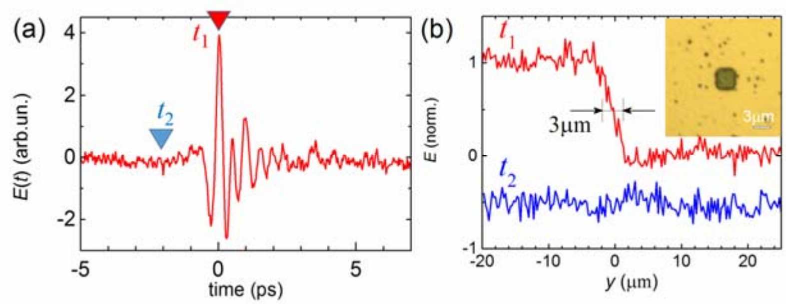

Fig. 2. (a) THz pulse transmitted through a 3μm aperture in the near-field zone. (b) Spatial resolution test for the 3μm aperture near-field probe: the red trace shows the amplitude of the THz detected pulse (at $t = t_1$) as a metallic edge is scanned across the aperture; the blue trace shows the same line scan 2ps prior the arrival of the pulse (at $t = t_2$).

Conclusions

We investigate the transmission of THz pulses in the near-field zone (z < a) for apertures as small as 3μm. The experimental results show the transmitted field amplitude does not follow the a^3 dependence. This effect is attributed to the evanescent field components. We exploit this effect for improving sensitivity and spatial resolution of the sub-wavelength aperture near-field probes. We present the highest spatial resolution (3μm) achieved to date with an aperture-type near-field probe for THz time-domain microscopy.

Acknowledgement

This work is supported by the Royal Society [Grant No. UF080745] and was performed at UCL and at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.

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