Study of single-cycle pulse propagation inside a terahertz near-field probe

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Propagation of 0.5 THz single cycle pulses inside an aperture-type near-field probe is studied. The E-field amplitude attenuation is experimentally measured at various distances from the aperture. Numerical simulations based on a two-dimensional model illustrate the pulse waveform transformation and the spectral blueshift, which is experimentally observed. The study shows that the sensitivity of such a near-field probe can be improved by more than a factor of 10 by decreasing the aperture-to-detector separation without reduction of the spatial resolution. © 2001 American Institute of Physics. [DOI: 10.1063/1.1338962]

The main limitation on spatial resolution in aperture-type pulsed THz near-field scanning microscopy is a strong attenuation of the pulse as it passes through the subwavelength aperture. Therefore, significant enhancement of the radiation intensity from THz sources and/or optimization of detecting techniques beyond what has previously been available is required to achieve a spatial resolution on the order of 10 μm (≈ λ/50) or better. Recently, we proposed a high sensitivity collection mode probe and used it to demonstrate <40 μm resolution. The probe locally detects the electric field in the near-field zone of an object by means of a subwavelength aperture in front of a photoconducting receiving antenna. High sensitivity is achieved because the field is measured immediately behind the aperture before the transmitted beam diverges and the electric field amplitude drops. Quantitative analysis of the radiation coupling into the probe is still required to optimize the design and to estimate the limit of the spatial resolution. Alternative methods for subwavelength resolution imaging at THz frequencies exist. Among these methods the best resolution of <50 μm was demonstrated using the dynamic aperture approach.

The propagation of electromagnetic waves through a subwavelength aperture in a metallic screen has been studied by many authors. The electric field in the near-field zone of an illuminated aperture decreases rapidly as the distance from the aperture increases. The decay occurs at a characteristic length equal to the aperture size and depends on the wavelength. In the far-field zone, the electric field amplitude must decrease as \( r^{-1} \) appropriate for a spherical wave.

In this letter we present a study of THz pulse propagation through the subwavelength aperture of our near-field probe. To observe the electric field decay close to the aperture, we fabricated near-field probes with various separations between the probe aperture and the photoconducting receiving antenna. In addition, a simple computational method, which provides a qualitative description of the process, is presented. This method, based on the 2D finite difference time domain (FDTD) algorithm, can be used to compare various designs of the near-field probe to optimize its performance. The time domain formulation allows the use of an experimentally measured waveform of the incident pulse as the initial condition. Subsequently, the simulation results are compared with experimental findings directly. This study shows that the sensitivity of a collection mode aperture-type probe based on a photoconducting antenna can be significantly improved if the THz electric field is detected in the immediate vicinity of the collection aperture. We find that the spatial resolution is determined solely by the aperture size and is not reduced as a result of the sensitivity optimization.

A schematic cross section of the probe is given in Fig. 1. The probe is based on a low temperature GaAs photoconducting switch (with a 10 μm gap and a 60 μm long dipole antenna), which is mounted on a transparent sapphire substrate.

FIG. 1. Schematic cross section of the near-field collection mode probe. L, thickness of the GaAs layer, sets the distance from the aperture to the dipole antenna.
substrate. A 600 nm thick gold film is deposited on the surface of the GaAs layer except for a \(30\times30 \mu m^2\) square-shaped aperture below the dipole. The GaAs layer thickness can be adjusted by mechanical polishing before depositing the metal. We prepared probes with five aperture-to-dipole separations: \(L=7, 16, 21, 47,\) and 110 \(\mu m\) (measured by a profilometer). A GaAs protrusion extends through the aperture by \(-3.5 \mu m\) to achieve more efficient coupling of the THz radiation into the aperture. An optical pulse from a Ti:sapphire laser gates the photoconducting antenna through the sapphire substrate. The THz beam generated by a separate photoconducting switch is focused to a \(-2 \text{ mm}\) diameter spot, and is normally incident on the probe. This arrangement corresponds to a near-field microscope in collection mode, where a uniformly illuminated sample is scanned in front of the probe.

The black circles in Fig. 2 indicate the measured peak electric field amplitude normalized to the peak amplitude of the incident pulse. Clearly, the detected field decreases rapidly as the aperture-to-dipole separation, \(L\), increases. The probe with the shortest \(L=7 \mu m\) senses an electric field that is \(-12\) times stronger, compared to the probe with \(L=110 \mu m\). It can be seen that the electric field amplitude drops approximately as \(L^{-1}\).

The spatial resolution of all the probes is solely defined by the aperture size. Figure 3 presents a scan of a metallic film edge across the \(L=7 \mu m\) probe. The result gives a resolution of \(-36 \mu m\) when a 10\%-90\% criterion is applied to the electric field amplitude of the pulse. The probe with \(L=110 \mu m\) gives a similar resolution of \(-39 \mu m\).

For our 2D FDTD simulations the near-field probe geometry is modeled as a perfectly conducting screen, which divides space into media with dielectric constants of \(\epsilon=1\) (air) and \(\epsilon=13\) (GaAs) (Fig. 4). The discontinuity of the screen models a 2D aperture (slit). The dielectric extends slightly into the air half-space for a precise modeling of the probe geometry. We used a uniform Cartesian 2D space lattice with a \(1 \mu m^2\) cell and a 4.7 fs time step. An incident plane wave is simulated using the temporal profile of the THz pulse measured experimentally with a regular photoconducting antenna, which replaces the near-field probe in the setup. The electric field is polarized parallel to the slit edge (x direction).

The simulation results are shown in Fig. 4. Propagation direction of the incident wave is along the \(z\) axis. The contour plot demonstrates that the electric field energy density of the pulse (time integrated \(E^2\)) behind the aperture screen (positive \(z\)) is concentrated only within a short distance from the aperture. The solid curve in Fig. 2 shows the calculated peak electric field amplitude on the \(z\) axis passing through the center of the aperture. The electric field is normalized to the peak amplitude of the incident pulse for direct comparison with the experimental results. As the pulse propagates inside the dielectric, the field amplitude drops rapidly. For distances greater than \(-80 \mu m\), the calculated amplitude approaches a decay rate of \(L^{-1/2}\), corresponding to propagation in 2D space. The decay rate is slower compared to the experimental findings \((L^{-1})\), because the model does not take into account the field divergence in the direction perpendicular to the \(yz\) plane. However, the field divergence is small for \(L\) smaller than the aperture size, and both the experiment and the simulations give comparable results for the electric field strength. The calculations also demonstrate the high-pass properties of the subwavelength aperture. Figure 5(a) shows the calculated field \(7 \mu m\) away from the plane of the aperture (solid curve) and as well as the waveform, experimentally measured using the probe with \(L=7 \mu m\) (dots).
The normalized incident pulse waveform is shifted upward for clarity and is shown in the dashed curve as a reference. The single-cycle waveform of the incident pulse transforms into the faster oscillating waveform as a result of the transmission through the aperture. The spectral content of the detected field shifts to higher frequencies compared to the spectrum of the incident pulse.

It should be mentioned that the measured THz pulse exhibits longer oscillations compared to the simulated waveform, though the initial temporal transformation of the pulse is in good agreement with the simulations. The blueshift of the spectrum is well modeled by the simulations, as can be seen in Fig. 5(b). The central frequency of the calculated spectrum matches the experimental findings, although the spectral width of the measured pulse is smaller. The reason for the spectral narrowing and the long-lasting oscillations is still under investigation.

We applied the computational method to estimate the effect of the protruding tip on the wave coupling. Experimental estimation is difficult since a slight variation in the thickness of the GaAs layer brings a relatively large change in the measured pulse amplitude. We compared three cases: the GaAs protrusion (Fig. 4), a full cone-shaped taper, and the aperture without GaAs protrusion. The results show that the radiation coupling improves and the electric field amplitude increases by ~25% for the full cone taper and by ~9% for 3.5 μm GaAs protrusion compared to the plain aperture.

In conclusion, we studied propagation of 0.5 THz single-cycle pulses inside the near-field probe. The results demonstrate that the sensitivity of the collection mode probe can be significantly improved. Our approach allows decreasing the aperture size, which results in a higher spatial resolution. Assuming the third power law of the transmitted E-field amplitude as a function of the aperture size, we expect that a ~10 μm aperture can be employed with a signal to noise ratio higher than 10. The proposed computational method models the pulse propagation inside the near-field probe. The waveform deformation and the spectral shift are in good agreement with the experiment, while the electric field decay can only be treated qualitatively.

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