Spot-size reduction in terahertz apertureless near-field imaging

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We show measurements and calculations of the terahertz (THz) near field of a metal tip with a specially formed, semicircular apex that allows us to identify the separate contributions of the tip apex and shaft to the measured signal. We find that when the tip–crystal distance is modulated, the measured near-field signal is overwhelmed by contributions from the tip shaft, resulting in a relatively large THz spot size. When the tip–crystal distance is modulated, with subsequent lock-in detection at the modulation frequency, only the near-field distribution of the semicircular apex is observed, resulting in a much smaller THz spot size and thus improved spatial resolution.

The setup used to measure the THz near field has been described in more detail elsewhere. A metal tip with a semicircular apex of subwavelength dimensions (Fig. 1) is held close to the surface of a GaP electro-optic crystal. The tip is illuminated with THz pulses generated in a photoconductive switch. The THz pulses are polarized parallel to the crystal surface with a component along the length of the tip shaft. From the back of the crystal, a probe laser pulse is tightly focused to a 4-μm spot size underneath the metal tip. Because of the electro-optic effect in the GaP crystal, the THz electric field elliptically polarizes the probe beam. The degree of ellipticity is measured in a standard differential detector setup and is directly proportional to the THz electric field. The (100) orientation of the GaP crystal ensures that only THz field components polarized perpendicularly to the crystal surface, present in the vicinity of the tip, are observed. The tip is glued to a piezo and can be vibrated at a frequency of 30 kHz. The tip–piezo combination is raster scanned parallel to the crystal surface with computer-controlled x–y translation stages. At each

Recently, apertureless near-field scanning optical microscopy (ANSOM) techniques emerged that have the ability to provide subwavelength resolution at terahertz (THz) frequencies. In most of these techniques THz light is incident upon a metal tip with an apex of subwavelength dimensions, which is held close to a sample. To extract near-field information from the vicinity of the tip, one measures the near field either directly or indirectly, by measuring light scattered into the far field. In contrast to ANSOM experiments reported at visible or mid-IR wavelengths, THz ANSOM is unique in that it directly measures the electric field and thus gives phase and amplitude information in a broad frequency interval up to several THz. In spite of this, little is known about the exact nature of the THz electric field in the near field of the metal tip. In particular, the spatial extent of the THz near field and the relative contributions of the tip apex and the tip shaft to the measured signal in THz ANSOM experiments are not well known. Obtaining this information has acquired a sense of urgency, as recent reports suggest that the metal tips used in THz ANSOM experiments are not well described by small metal spheres but should instead be treated as real antennas. This information would also be useful in determining the effect of modulating the tip–sample distance, with subsequent lock-in detection of the far-field signal at the modulation frequency, which has been shown to improve the spatial resolution in visible–mid-IR ANSOM experiments.

Here we present measurements of the THz electric field directly obtained in the near field of a long metal tip with a specially formed, semicircular tip apex. We find that, in spite of the close proximity of the semicircular apex, the THz near-field spatial distribution, measured in a plane underneath the metal tip, is generally dominated by contributions from the tip shaft. In addition, we observe that the area underneath the tip in which a near-field signal is observed is much larger than the typical dimensions of the tip apex. However, when the tip–crystal distance is modulated, with subsequent lock-in detection of the signal at the modulation frequency, we find that the observed spatial distribution of the near field changes dramatically in shape and is strongly reduced in size, now corresponding to a field distribution originating from the semicircular apex alone. Our results show the importance of antenna effects in THz ANSOM experiments and prove that modulation of the tip–sample separation can improve the spatial resolution.

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Fig. 1. Schematic of the experimental setup: A copper tip (right) is held close to a (100)-oriented GaP crystal. The tip is mounted on a piezo to allow modulation of the tip–crystal separation.
(x, y) position, a full THz electric field of 25-ps duration is obtained in a total measurement time of 20 ms.

In Fig. 2(a) we plot a 30 × 30 pixel image of the frequency-integrated intensity of the measured THz near field. For this measurement the tip–crystal distance is not modulated. A THz spot size with a FWHM diameter of ~20 μm is clearly observed, orders of magnitude smaller than the peak wavelength of 3 mm. Remarkably, the measurement does not show any evidence of the influence of the semicircularly shaped apex, which should give rise to a differently shaped THz near-field spot, as we show below. This is a strong indication that the measured near-field signal originates largely from tip regions above the apex at distances >5 μm. When we repeat the experiment, while modulating the tip–crystal distance at 30 kHz (<1-μm amplitude) in conjunction with lock-in detection at the modulation frequency, the measured near-field spatial distribution underneath the tip looks dramatically different [Fig. 2(b)]. Now, two maxima in the near-field intensity are observed when the tip is raster scanned across the surface. Between the two maxima, the intensity is zero. In Figs. 2(c) and 2(d) we plot the electric field versus time for two different positions on either side of the zero intensity line, showing that the phases of the electric fields differ by π. We emphasize that similar phase shifts were not observed in the measurements shown in Fig. 2(a). Figure 2(b) also clearly demonstrates that the area over which a measurable near field is observed is strongly reduced. This shows that modulation of the tip–sample separation can give rise to improved spatial resolution in THz ANSOM experiments. To our knowledge this is the first time that this effect has been observed directly in the near field of a metal tip.

We can qualitatively understand our measurements by realizing that the metal tip used in the experiments functions as a real antenna. Above the apex the shaft resembles a linear wire antenna.7 We note that our measurement method is sensitive only to the z component of the near field in the crystal, integrated over the probe–near-field interaction length l. For the measured signal we thus have $S_{EO} \propto \int I_{z} dz$. In the quasi-static approximation, the z component of the electric field inside the crystal is given by
\[
E_z \propto \frac{1}{4\pi\varepsilon_0(1 + \varepsilon_r)} \left( \frac{1}{R_a} + \frac{1}{R_b} - \frac{2}{R} \right), \quad z < 0, \quad (1)
\]
where $\varepsilon_r$ is the relative permittivity of the crystal and where $R_a$, $R_b$, and $R$ have the geometrical interpretation indicated in Fig. 3(a). A comparison of the calculated signal $|S_{EO}|^2$ as a function of the in-plane separation $x$ (see Fig. 3) between the tip and the probe, with a cross section taken through the data of Fig. 2(a), is plotted in Fig. 4(a), showing excellent agreement between the two. We emphasize that treating the tip as a small metal sphere cannot explain the measurements plotted in Fig. 4(a). This is because the near field of a small metal sphere falls off more rapidly according to $E_z \propto 1/R^3$, where $R$ is the distance to the center of the sphere. Our measurements thus prove that the antenna properties have to be taken into account to understand our results.

We now concentrate on the results obtained when the tip–crystal separation is modulated. The π phase shift...
shift observed in Fig. 2(b) cannot be caused by the $z$ component of the near field of a vertical wire antenna [Eq. (1)], which has cylinder symmetry around the $z$ axis. This strongly suggests that the semicircular apex alone must be responsible for the observed antisymmetric behavior of the field. As a crude approximation we therefore treat the apex as a short horizontal wire antenna.$^7$ It can be shown that in a dielectric medium the $z$ component of the near field in the $x'-z$ plane of a horizontal wire antenna of length $2a$ [see Fig. 3(b)], oriented along the $x'$ axis, at $z = z_0$, is given by$^7\,$\,$^8$

$$E_z \propto -\frac{2}{4\pi \varepsilon_0 (1 + \varepsilon_r) (z - z_0)} \times \left( \frac{x' + a}{R - a} + \frac{x' - a}{R_a} - \frac{2x'}{R} \right), \quad z < 0. \quad (2)$$

$R_{-a}$, $R_a$, and $R$ have the geometrical interpretation indicated in Fig. 3(b).

In the unmodulated case the electro-optic signal would again be proportional to $S_{\text{EO}} \propto \int f(E_z) \, dz$. When the tip–crystal distance is modulated, however, the measured signal is proportional to the spatial derivative of $S_{\text{EO}}$ with respect to the modulation coordinate. It can be shown$^7$ that, to a good approximation, the measured signal is then proportional to the electric field $E_z$ itself, given by expression (2), evaluated at $z = 0$. In Fig. 4(b) we therefore plot $E_z$ for a 10-$\mu$m-long wire as a function of $x'$ for $z = 0$ $\mu$m, at $z_0 = 2$ $\mu$m. The calculation shows that the electric field amplitude is antisymmetric with respect to the variable $x'$, similar to what is observed in the measurement plotted in Fig. 2(b). We thus conclude that when the tip–crystal separation is modulated the measured electric field originates predominantly from a horizontal component of the current in the semicircular apex. The physical explanation for the $\pi$ phase shift is that the full-field lines of a horizontal wire antenna point downward for $x' > 0$, are exactly horizontal for $x' = 0$, and point upward for $x' < 0$, implying that $E_z < 0$, $E_z = 0$, and $E_z > 0$, respectively.

In this Letter the main reason for using a tip with a semicircular apex is that it allows us to identify and quantify which part of the tip contributes to the near field when the tip–sample separation is modulated. To understand why the field emitted by regions above the apex is not observed when the tip–crystal distance is modulated, we point out that it is the change in the signal $\delta S_{\text{EO}}$ caused by the modulation that is measured, rather than the signal $S_{\text{EO}}$ itself. Physically, we can think of the wire antenna as consisting of a series of infinitesimal oscillating dipoles. When the tip–crystal distance is modulated, only the fields from the dipoles closest to the crystal are strongly modulated. Contributions to the signal from dipoles in parts of the tip that are further from the crystal (the shaft) are thus strongly suppressed. The result is a smaller THz spot size and thus an improved spatial resolution in THz near-field microscopy.

We have performed measurements and calculations of the THz near field of a metal tip with a specially formed semicircular apex. Our results prove the existence of antenna effects in THz ANSOM and provide the first measurements obtained directly in the near field of the tip that show that tip–sample distance modulation suppresses the contributions to the signal from the tip shaft and improves the spatial resolution.

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References

8. P. C. M. Planken and N. C. J. van der Valk are preparing a manuscript called “Measurement and calculation of the near field of a terahertz apertureless scanning optical microscope” for submission to J. Opt. Soc. Am. B.