Measurement of THz Spot Sizes with a $\lambda/200$ Diameter in the Near-Field of a Metal Tip

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Abstract. We report on a method to obtain a sub-wavelength resolution in terahertz time-domain imaging. In our method, a sharp copper tip is used to locally distort and concentrate the THz electric field. The distorted electric field, present mainly in the near field of the tip, is electro-optically measured in an (100) oriented GaP crystal. By raster scanning the tip along the surface of the crystal we find a smallest THz spot size of $10\ \mu\text{m}$ for frequencies from 0.1 to 2.5 THz. For our peak frequency of 0.15 THz this corresponds to a resolution of $\lambda/200$. Our setup has the potential to reach a resolution down to a few μm , and is a promising candidate to study single, living cells in the THz frequency range.

Key words: Microscopy, near-field, spectroscopy, terahertz

In recent years, terahertz time domain spectroscopy (TDS) has become a popular method to obtain information on the far-infrared properties of molecules, semiconductors, and other materials [1–4] and has shown to be a promising technique to image objects [5–7]. Unfortunately, diffraction, which limits the resolution to about a wavelength, is an obstacle for a number of interesting new THz applications. Breaking the diffraction limit would, for instance, make it possible to perform THz spectroscopy on extremely small volumes, and, ultimately on single cells. Work on the label free probing of DNA [8], shows that THz radiation can be used to distinguish between different biomolecules. Work on skin-tumor recognition [9] shows that terahertz radiation can be used to image skin-tumors with sufficient contrast to distinguish between healthy tissue and cancer tissue. However, the contrast mechanisms remain somewhat uncertain. A terahertz imaging setup capable of studying single cells could possibly clarify these mechanisms.

One way to overcome the diffraction limit is to limit the detection area with an aperture. For example, Mitrofanov et al. [10] have shown that, using a detector with an integrated aperture, near field images can be made with a spatial resolution determined by the aperture size, and not by the THz wavelength. Unfortunately, this method relies on extensive micro-fabrication and requires two parallel plates, namely one carrying the object and the other the detector, to be scanned along each other at close distance, which is difficult to do in practice. Also, since the aperture has a finite thickness, waveguide effects strongly attenuate long wavelength com-

ponents [11], which makes their detection difficult. Another approach to obtain sub-wavelength resolution [12] uses a laser to modulate the THz transmission of a small area on a semiconductor surface near the object. The modulation on the THz beam is measured in the far field, and an improved spatial resolution, down to 50 μm is observed. In this method, however, signals are small and superimposed on a large background, complicating the detection.

Here, we present a method to create and detect a local THz source with a sub-wavelength resolution, which has the potential to image a microscopic object by raster-scanning it between the source and the detector. In our method, THz pulses are incident on a sharp metal tip, having sub-wavelength dimensions, which is held in close proximity to an (100) oriented GaP crystal. A synchronized probe pulse is tightly focused into the crystal close to the tip and, using the electro-optic effect in the same crystal, only detects the THz polarization component that is perpendicular to the (100) surface. As the incident THz polarization is parallel to the crystal surface, the perpendicular component is present only near the tip, which functions as a lightning rod where field lines are bent and concentrated. We find that, directly under the tip, the measured THz spot size has a diameter of only 10 μm , corresponding to $\lambda/200$ for a wavelength of 2 mm. Our method to obtain a sub-wavelength resolution has four advantages. (i) The resolution is determined by the spot diameter of our probe laser, not by the incident THz beam size. (ii) Our measurements are background free, as we only detect the component near the tip that is perpendicularly polarized to the crystal surface. (iii) Our detection setup measures in the near field, where the electric field can be strong. This provides sufficiently large signals and thus reduces the measurement time. (iv) Our method has the more practical requirement of scanning a tip along a surface, instead of two surfaces parallel to each other.

Our setup to generate THz pulses, is described elsewhere [13]. As we show in Figure 1, the THz pulses, which have an average power of 40 μW , are focussed onto a copper tip, which has been sharpened in a FeCl etch bath. A 300 μm thick, (100) oriented GaP detection crystal is placed within a distance of several microns of the tip. The crystal surface closest to the tip is coated with a 300 nm thick Ge layer on top off a 133 nm thick SiO_2 layer. A synchronized, 800 nm probe pulse, derived from the same laser that generates the THz pulse, is focussed to about a 10 μm spot size on the coating, initially counter propagating with respect to the THz pulse. The coating, which has a negligible effect on the THz beam, absorbs any probe light before it reaches the tip. This eliminates any measurement errors that would have been caused by probe light scattered off the tip. After the reflection at the coating the probe pulse is sent through a $\lambda/4$ plate, and a Wollaston prism to a differential detector. When a THz electric field is present in the crystal, the electro-optic effect changes the probe polarization from linear to elliptical. The amount of ellipticity is proportional to the instantaneous THz electric field, and is measured by the differential detector setup. We emphasize that in an (110) oriented crystal, which is the conventionally used orientation in electro-optic detection, the probe polarization is

Figure 1. Schematic picture of the setup used. The THz radiation comes in from above, and scatters at the tip. The probe beam comes in from below, and is focussed on the crystal-air interface of an (100) GaP crystal. At this interface the probe beam polarization is changed by the THz electric field near the tip. The probe beam reflects back at the crystal interface, and is sent to the differential detection setup (not shown).

only affected by electric fields parallel to the crystal surface [14]. Here, however, using an (100) oriented crystal, the probe polarization is only changed by electric fields perpendicular to the crystal surface [15] making the probe 'blind' to the parallel polarized electric field of the incident THz pulse. Near the tip, the THz near field must have a component perpendicular to the crystal surface, since the electric field near a metal, in this case the tip, has to be perpendicular to the metal surface.

The inset of Figure 2 shows the THz electric field as a function of the delay between probe and THz pulse, measured directly under the copper tip, which is pressed against the crystal. The power spectrum of this pulse is plotted in Figure 2. It contains frequencies from 0.1 THz to 2.5 THz and peaks around 0.15 THz. Although this measurement was obtained in less than a minute, we note that, in our

Figure 2. THz power spectrum, calculated from the THz electric field as a function of delay shown in the inset. The measurement was performed with the tip pressed against the crystal, directly above the probe beam. This measurement was obtained in less than a minute.

setup, a measurement of a 25 ps long THz electric field pulse is obtained in 20 ms with a dynamic range of 50.

Figure 3 shows the measured peak THz electric field as a function of the tip-crystal separation. The measurement covers a total distance of about 30 μm . The

Figure 3. Measured peak THz electric field as a function of the tip-crystal distance. The inset shows a separate measurement of the region close to the crystal.

Figure 4. THz intensity as a function of the xy position of the tip along the crystal. The scan is a 50×50 pixel image with a $1 \times 1 \mu\text{m}^2$ pixel size. For this measurement the tip was at zero distance from the crystal. The scale is shown at the top and runs from zero (light gray) to maximum intensity (black). The black, dashed line is the FWHM of the spot.

inset shows an additional measurement, which zooms in on the region close to the crystal. We have chosen the $0 \mu\text{m}$ position arbitrarily as the position where the signal reaches its maximum. The figure shows that the THz electric field decreases to 30% of its maximum value, when the tip-crystal distance increases to $6.5 \mu\text{m}$, which clearly indicates near field behavior. When the tip is close to the crystal ($\sim 1 \mu\text{m}$), it is abruptly attracted to the crystal, presumably by electrostatic forces, which gives rise to a sudden increase in the signal at $0 \mu\text{m}$. The sharp, but smooth, decrease of the THz electric field when the distance to the crystal is increased only a few μm , is related to results obtained by Knoll et al. [16] at the much shorter wavelength of $10 \mu\text{m}$. They found that the scattering cross-section of a tip close to a dielectric half-space is strongly increased due to an image charge induced in the dielectric medium. It is likely, that these results also apply in our case, and that an increase of the scattering cross-section is related to the strong enhancement of the local THz electric field when the tip approaches the crystal.

In Figure 4, we plot the integrated power of the THz pulses, measured while raster-scanning the tip across the crystal surface with the tip in contact with the crystal. The observed spot diameter is $10 \mu\text{m}$. A spectral analysis (not shown here) clearly proves that the spot diameter is independent of frequency, with a spot corresponding to a maximum resolution of $\lambda/200$ at 0.15 THz .

In earlier measurements [17], we showed that the size of our spot size is limited by the size of our probe beam and size of the apex of the metal tip. It should be possible to reduce both, leading to an even smaller THz spot size. The physical limit on the size of the probe focus and thus on the THz spot, is given by the wavelength of the probe beam. In our setup this leads to a minimum THz spot size of about $1\ \mu\text{m}$, which is comparable to the resolution of a conventional optical microscope. Ultimately, we envisage an experiment in which a thin sample is placed on the crystal underneath the tip. When the crystal is raster-scanned underneath the tip, a two-dimensional THz image of the sample is obtained. In this way, we hope to make images of microscopic objects, such as living cells. As microscope cover-glasses are incompatible with this near-field technique, we intend to use $0.9\ \mu\text{m}$ Mylar film to prevent samples from drying out. Such a Mylar film has an optical thickness that is negligible compared to terahertz wavelengths, so we do not expect that multiple reflections in the film will cause any problems.

The advantages of our method to use THz TDS to produce near field images are that it is coherent, intrinsically broadband, and uses only $40\ \mu\text{W}$ of input power. Coherent detection offers the advantage of measuring both amplitude and phase, while broadband detection allows us to obtain information on a wide range of frequencies in one measurement. The chance that a sample is heated significantly or even damaged is negligible in our setup, since we use low input powers. We note that the time-dependent nature of THz pulses makes it possible to use our setup for visible pump-THz probe measurements on biological systems.

In conclusion, we have presented a method to obtain a sub-wavelength resolution in THz imaging by electro-optically measuring the THz electric field close to a sharp copper tip in a (100) oriented GaP crystal. We demonstrate a THz spot size of $10\ \mu\text{m}$, determined by the probe beam diameter, and argue that our method should be able to reach a resolution of about $1\ \mu\text{m}$, limited by the focal diameter of the probe beam.

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References

1. Grischkowsky, D., Keiding, S., van Exter, M. and Fattinger, C.: Far-infrared Time-Domain Spectroscopy with Terahertz Beams of Dielectrics and Semiconductors, *J. Opt. Soc. Am. B* **7** (1990), 2006–2015.
2. Cheville, R.A. and Grischkowsky, D.: Time Domain Terahertz Impulse ranging Studies, *Appl. Phys. Lett.* **67** (1995), 1960–1962.

3. Jiang, Z., Li, M. and Zhang, X.-C.: Dielectric Constant Measurement of Thin Films by Differential Time-Domain Spectroscopy, *Appl. Phys. Lett.* **76** (2000), 3221–3223.
4. Walther, M., Fischer, B., Schall, M., Helm, H. and Jepsen, P. Uhd: Far-infrared Vibrational Spectra of All-trans, 9-cis and 13-cis Retinal measured by THz Time-Domain Spectroscopy, *Chem. Phys. Lett.* **332** (2000), 389–395.
5. Mittleman, D.M., Jacobsen, R.H. and Nuss, M.C.: T-Ray Imaging, *IEEE J. Select. Topics Quantum Electron.* **2** (1996), 679–692.
6. Jiang, Z., Xu, X.G. and Zhang, X.-C.: Improvement of Terahertz Imaging with a Dynamic Subtraction Technique, *Appl. Opt. IP* **39** (2000), 2982–2987.
7. Mickan, S., Abbott, D., Munch, J., Zhang, X.-C. and Van Doorn, T.: Analysis of System Trade-offs for Terahertz Imaging, *Microelectron. J.* **31** (2000), 503–514.
8. Brucherseifer, M., Nagel, M., Haring Bolivar, P., Kurz, H., Bosserhoft, A. and Büttner, R.: Label-Free Probing of the Binding State of DNA by Time-Domain Terahertz Sensing, *Appl. Phys. Lett.* **77** (2000), 4049–4051.
9. Woodward, R.M., Cole, B.E., Wallace V.P., Pye, R.J., Arnone, D.D., Linfield, E.H. and Pepper, M.: Terahertz Pulse Imaging in Reflection Geometry of Human Skin Cancer and Skin Tissue, *Phys. Med. Biol.* **47** (2002), 3853–3864.
10. Mitrofanov, O., Brener, I., Harel, R., Wynn, J.D., Pfeiffer, L.N., West, K.W. and Federici, J.: Terahertz Near-Field Microscopy based on a Collection Mode Detector, *Appl. Phys. Lett.* **77** (2000), 3496–3498.
11. Wynne, K., Carey, J.J., Zawadzka, J. and Jaroszynski, D.A.: Tunneling of Single-Cycle Terahertz Pulses through Waveguides, *Opt. Comm.* **176** (2000), 429–435.
12. Chen, Q. and Zhang, X.-C.: Semiconductor Dynamic Aperture for Near-Field Terahertz Wave Imaging, *IEEE J. Select. Topics Quantum Electron.* **7** (2001), 608–614.
13. Zhao, G., Schouten, R.N., Van der Valk, N., Wenckebach, W.Th. and Planken, P.C.M.: Design and Performance of a THz Emission and Detection Setup based on a Semi-Insulating GaAs Emitter, *Rev. Scient. Instr.* **73** (2002), 1715–1719.
14. Planken, P.C.M., Nienhuys, H.-K., Bakker, H.J. and Wenckebach, W.Th.: Measurement and Calculation of the Orientation Dependence of Terahertz Pulse Detection in ZnTe, *J. Opt. Soc. Am. B* **18** (2001), 313–317.
15. Kütt, W.A., Albrecht, W. and Kurz, H.: Generation of Coherent Phonons in Condensed Media, *IEEE J. Quantum Electron.* **28** (1992), 2434–2444.
16. Knoll, B. and Keilmann, F.: Electromagnetic Fields in the Cutoff Regime of Tapered Metallic Waveguides, *Opt. Comm.* **182** (2000), 321–328.
17. Van der Valk, N.C.J. and Planken, P.C.M.: Electro-optic Detection of Sub-wavelength Terahertz Spot Sizes in the Near Field of a Metal Tip, *Appl. Phys. Lett.* **81** (2002), 1558–1560.