Plasmonic focusing on metal and semiconductor disks under radially polarized terahertz illumination

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***Abstract*—Optimal focusing of surface plasmon polaritons in the center of a metal disc illuminated by radially polarized terahertz pulses is demonstrated. Due to the cylinder symmetrical structure surface plasmons can be excited along the entire circumference, which interfere constructively in the center of the disk forming a sharp frequency-depended focal spot. We map the field distribution on the disk by THz near-field microscopy and compare our result to numerical simulations. For comparison, behavior under linearly polarized THz illumination is characterized. Furthermore, first results of semiconducting plasmonic lenses are presented.**

I. Introduction And Background

Surface plasmon polaritons (SPP) enable focusing into highly confined spots with sizes significantly beyond the diffraction limit. Depending on the material and frequency range SPPs possess much shorter effective wavelengths and their fields are strongly confined to the surface rather than being focused in free-space. By structuring a conductive surface on which the SPPs are generated their propagation can be efficiently manipulated, enabling guiding or lensing functionality. Upon illumination of slits or grooves by TM polarized light the incident light field is converted into surface plasmon waves propagating along the metal surface. Circular geometries allow focusing the plasmonic field in the center of the structure, where they form a sharp frequency-dependent focal spot well described by a zero-order Bessel function ([1], [2]). Naturally, radially polarized light is a better choice than linearly polarized light for the illumination of such a circular plasmonic lens, since it is always TM polarized with respect to the annular grooves or slits. In this case SPPs are launched in-phase forming a homogeneous plasmon focus through constructive interference of the counter propagating surface plasmon waves. As a result radially polarized illumination gives rise to orders of magnitude larger enhancements of the field at the focus of the plasmonic lens compared to illumination by conventional linearly polarized light. More interestingly, the plasmonic focus generated this way forms an evanescent non-spreading Bessel beam [3]. In the THz frequency range metals represent nearly perfect conductors. Hence, metal surfaces cannot provide plasmonic lensing with sub-wavelength focusing. Nevertheless, the low losses of SPPs propagating along metal surfaces make THz plasmonics an attractive concept. It is worth mentioning that by using certain semiconductors sub-wavelength focusing can be achieved.

II. Experimental Details

Here, we demonstrate optimal THz plasmonic focusing by a simple circular metallic disc illuminated by a radially polarized field. The THz electric field associated with the focused SPP waves is experimentally mapped by THz near-field microscopy. Our experiments are complemented by numerical simulations.

In order to experimentally demonstrate plasmonic focusing under radially and linearly polarized THz illumination it is important to generate THz radiation with a controllable polarization state. Whereas most conventional THz emitters readily produce linearly polarized fields, the generation of cylindrical vector beams, e.g. radially polarized beams, requires more sophisticated concepts ([4], [5], [6], [7]). In order to generate single-cycle THz pulses with radial polarization we developed a photo-conductive emitter consisting of concentric ring electrodes on a semi-insulating GaAs substrate (Fig. 1).

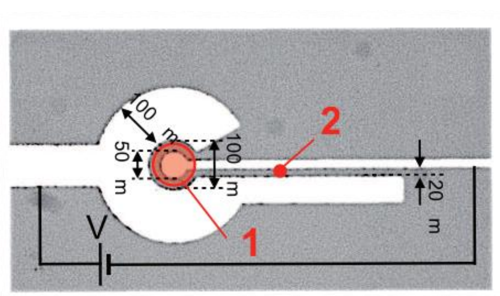

Figure 1 Electrode structure of the photoconductive antenna capable of emitting radially as well as linearly polarized THz pulses when illuminated at region 1 and 2, respectively.

The emitted THz pulses are coupled out of the emitter substrate by a hemispherical silicon lens and re-focused by a pair of off-axis paraboloidal mirrors to a frequency-dependent spot. Here, the sample under investigation is mounted. A photoconductive receiver antenna acts as polarization sensitive near-field probe, which can be moved together with the gating laser beam in x-, y- and z-directions. Scanning the detector in the x-y-plane allows mapping the electric field profile for a fixed z-position, either in free-space, or close to a sample. A detailed description of the photo-conductive receiver-based THz near-field setup has been given elsewhere [8] .

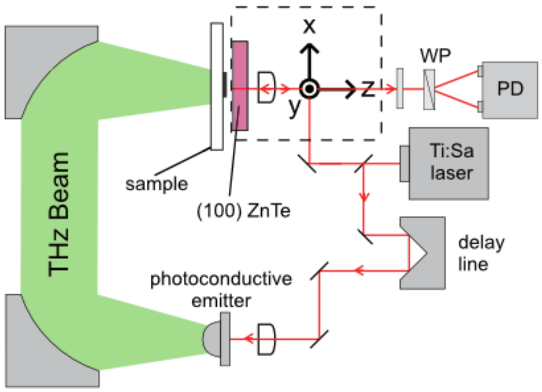

Figure 2: Experimental setup for measuring the z-component of the THz electric field distributions close to a sample by electro-optical sampling in a (100) ZnTe crystal.

The planar receiver antenna is not able to detect the z-component of the electric near-field. For this purpose the photoconductive receiver chip was replaced by a 500 µm-thick ZnTe crystal. The polarization of the fs-laser beam back reflected by the crystal's front surface is analyzed by balanced photo-detection (Fig. 2). By using a (100)-cut ZnTe crystal, the photodiode signal is directly proportional to the electric field z-component.

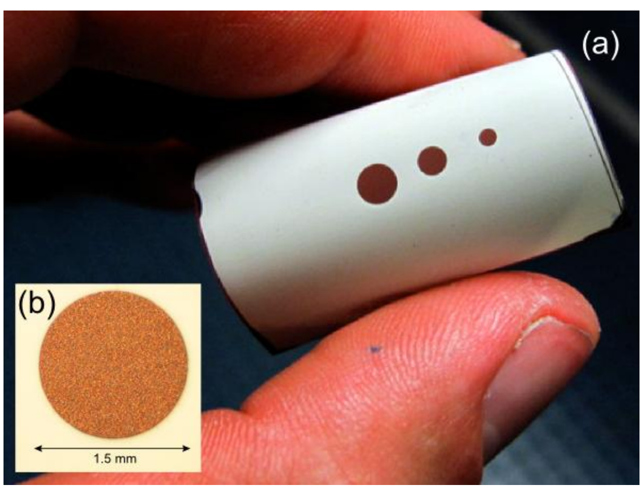

Figure 3 (a) Plasmonic copper lenses with different diameter on top of a thin flexible teflon substrate. (b) The plasmonic lens used for our study.

For our investigations we produced metal discs on a dielectric substrate as shown in Fig. 3. The discs have been fabricated by conventional photolithography and wet-etching from 9 µm thick copper on a 120 µm thick polytetraflouroethene (PTFE) substrate from Rogers (RT/duroid 5880). Various disk diameters have been fabricated and investigated. Due to the limited waist size of the THz beam at the position of the sample we found that a disc diameter of 1.5 mm was most suitable for the frequency range of 0.1 THz to 0.5 THz. The corresponding sample investigated in this study is shown in Fig. 3 (b).

III. Results And Discussion

When the sample is illuminated through the substrate by a linearly polarized THz field an anti-symmetric two-lobe pattern with a zero along the y-axis is observed with additional extrema appearing with increasing frequency (Fig. 4 & Fig. 5 left). All features observed in the measurement are well reproduced by the simulation, which have been performed based on finite element method modeling (Comsol Multiphysics).

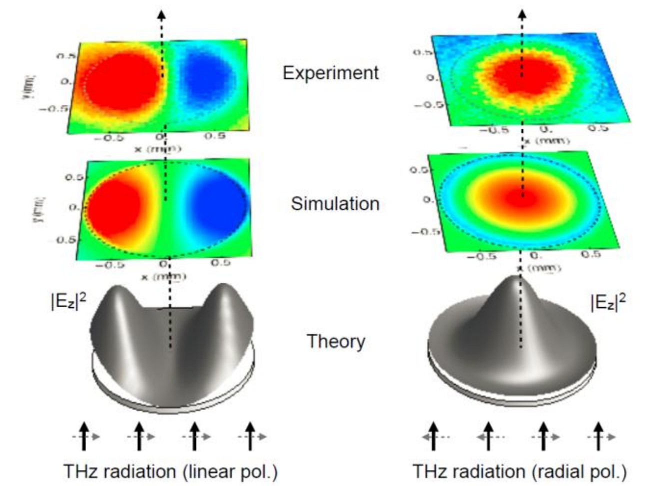

Figure 4 Experimental (top) and simulated (middle) distribution of the out-of-plane electric field component Ez close to the metal disc illuminated by linearly (left) and radially (right) polarized THz radiation at 0.20 THz.

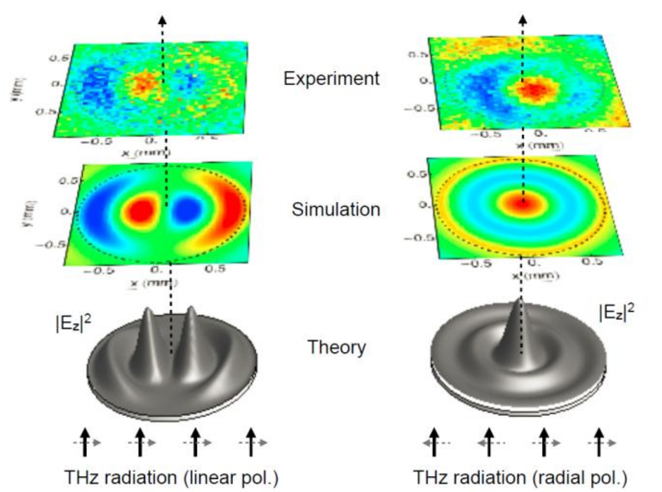

Figure 5 Experimental (top) and simulated (middel) distribution of the out-of-plane electric field component Ez close to the metal disc illuminated by linearly (left) and radially (right) polarized THz radiation at 0.43 THz.

The situation changes dramatically when the disc is illuminated by radially polarized THz radiation. As shown in Fig. 4 and Fig. 5 on the right hand side the measured and simulated field intensity distributions become cylindrically symmetric, reflecting the matched symmetry of the circular metal structure and the radially polarized excitation field. As a consequence, a single focal spot is formed in the center if the disc with decreasing spot size as the frequency increases. The experimentally observed spot sizes at different frequencies yield a universal spot size of 0.36 λ, which represents a canonical full width half-maximum (FWHM) of the zero order Bessel function.

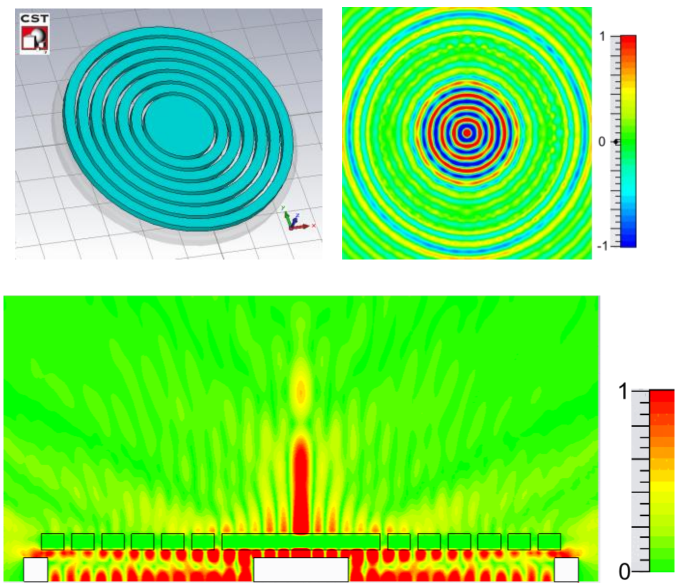

Figure 6 Center cross section and top view of the distribution of the out-of-plane electric field component E_z at 0.83 THz.

Using materials with plasmon frequencies in the THz regime (e.g. doped semiconductors) instead of metals will effectively shorten the SPP wavelength and further decrease achievable spot sizes. Figure 6 shows the simulated field distribution of an annular ring structure to support efficient coupling of SPPs on a plasmonic silicon lens. The simulation was performed with CST MW Studio. By adding concentric rings around the center disc that satisfy the circular Bragg condition for the plasmonic wavelength more radiation can be caught by the lens structure. Thus, the peak intensity of the plasmonic focus gets much stronger for certain frequencies.

IV. Conclusion

In summary, using THz near-field microscopy and numerical simulations we the demonstrated plasmonic focusing of THz SPP waves on top of a circular metal disc illuminated by radially polarized light. The results show that radial polarization of the THz illumination is crucial for achieving a radially symmetric focal spot as the result of constructive interference of the SPP fields in the center of the disc. For linearly polarized illumination a distinct two-lobe pattern is produced close to the center with both lobes oscillating out-of-phase.

In addition, we investigate a concept of a plasmonic silicon lens in order to increase the performance of plasmonic focusing by enhancing the coupling efficiency and decreasing the achievable spot size paving the way for true sub-wavelength THz focusing.

The remarkable focusing capabilities together with the simplicity of the structure offers considerable potential for the implementation of such plasmonic lenses for sensing or imaging in the THz regime.

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