Optimal plasmonic focusing on a metal disc under radially polarized terahertz illumination

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New Journal of Physics 15 (2013) 075005 (13pp)
Received 7 March 2013
Published 3 July 2013
Online at http://www.njp.org/
doi:10.1088/1367-2630/15/7/075005

Abstract. Optimal focusing of surface plasmon polaritons in the center of a metal disc illuminated by radially polarized terahertz pulses is demonstrated. By matching the cylindrical symmetry of the metal structure with the radially polarized terahertz field, surface plasmons are excited along its entire circumference. Constructive interference in the disc center produces a sharp frequency-dependent focal spot well described by a zero-order Bessel function. We map the field distributions on the disc by terahertz (THz) near-field microscopy and compare our results with numerical simulations. For comparison, the behavior of the plasmonic lens under linearly polarized THz illumination is also characterized. The remarkable focusing capabilities of such a plasmonic lens together with its simple structure offer considerable potential for THz sensing and imaging applications.

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New Journal of Physics 15 (2013) 075005
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1. Introduction

Guiding and focusing surface plasmon polaritons (SPPs) instead of light waves can be advantageous for many potential applications. Their shorter effective wavelength, particularly in the visible and infrared regimes, enables focusing into highly confined spots with sizes significantly beyond the diffraction limit, paving the way for applications in high-resolution imaging, nano-lithography, waveguiding and sensing. Furthermore, their field is strongly confined to surfaces rather than being focused in free space which may add further benefits. By structuring the metal surface on which the SPPs are generated, their propagation can be efficiently manipulated, enabling guiding or lensing functionality. Following this strategy various plasmonic lenses have been proposed and implemented, generally consisting of a geometric arrangement of subwavelength grooves or slits in a metal surface [1–7]. Upon illumination by TM polarized light, the slits convert the incident light field into surface plasmon waves propagating along the metal surface. Circular geometries allow focusing of the plasmonic field in the center of the structure, where they form a sharp focal spot. 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 allowing surface plasmon waves to be launched along the whole circumference. Moreover, 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 than when illuminated by conventional linearly polarized light [2]. More interestingly, the plasmonic focus generated this way forms an evanescent non-spreading Bessel beam [8].

In the terahertz (THz) frequency range metals typically represent nearly perfect conductors. As a result a surface plasmon’s wave vector is close to the light line with its wavelength being similar to a free-space wave. Hence, metal surfaces cannot provide plasmonic lensing with subwavelength focusing at THz frequencies. Nevertheless, the incredibly low losses of SPPs propagating along metal surfaces make THz plasmonics an attractive concept. As an example, the nearly lossless and dispersion-free guiding of THz waves along bare metal wires has been demonstrated [9, 10] with potential applications for endoscopy [11] or chemical sensing [12]. Furthermore, planar THz plasmonics [13–15] may hold promise for information transmission at ultrahigh bandwidths.
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.

2. Experimental details

In many cases controlling the polarization state of light is of great importance. In particular, beams with axial symmetry such as radially polarized beams are of interest due to their unique properties, in particular enabling enhanced focusing [16, 17]. In order to experimentally demonstrate plasmonic focusing under radially and linearly polarized THz illumination, we had to be able 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. Different schemes for generating THz radiation with radial polarization have been demonstrated, either by passively converting linear into radial polarization [18], or by active generation of radially polarized THz transients via velocity-mismatched optical rectification [19] or emitted from photo-conductive antennas with radial electrode geometry [20, 21]. Here we adopt the latter approach based on generating single-cycle THz pulses with radial polarization by photo-excitation of a photo-conductive emitter consisting of concentric ring electrodes.

2.1. Experimental setup

Our photo-conductive THz emitter antenna featuring co-axial electrodes is shown in figure 1(a). The electrodes were structured by photolithography and subsequent gold deposition onto a semi-insulating GaAs substrate. On the antenna a 50 µm-diameter center electrode is coaxially surrounded by a 100 µm wide outer electrode separated by a gap of 25 µm. The electrodes are contacted from opposite sides and were biased by 40 V. By slightly focusing the output of a Ti:Sa laser (wavelength 800 nm, 80 MHz repetition rate, 20 fs duration, 5 nJ pulse energy) to a ∼100 µm spot centered on the concentric electrodes (area 1), THz pulses with radial polarization are emitted. Part of the outer ring has been elongated along the contact of the inner electrode. By moving the emitter with respect to the stationary laser beam and re-focusing the laser spot so that the 20 µm gap between the two linear parts of the electrodes is illuminated (area 2), linearly polarized THz pulses can be emitted by the same chip.

As shown in figure 1(b), 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 us to map the electric field profile for a fixed z-position, either in free space or close to a sample. By rotating the detector around the laser beam axis, x- and y-components of the electric field can be measured separately, allowing reconstruction of the projection of the electric field vectors onto the x–y plane ($\vec{E}_{xy}$). A detailed description of the photo-conductive receiver-based THz near-field setup and field vector retrieval has been given elsewhere [22, 23].

Since the planar receiver antenna is not able to detect the z-component of the electric near field, an alternative detection scheme has also been applied as depicted in figure 1(c),
Figure 1. (a) Electrode structure of the photoconductive antenna capable of emitting radially as well as linearly polarized THz pulses when illuminated at regions 1 and 2, respectively. Experimental setup for measuring THz electric field distributions close to a sample: (b) $E_x$ and $E_y$ are measured by a photoconductive near-field receiver and (c) $E_z$ by electro-optic sampling in a (100) ZnTe crystal.

based on electro-optic sampling in a nonlinear optical crystal [24, 25]. For this purpose the photoconductive receiver chip was replaced by a 500 $\mu$m-thick ZnTe crystal. The polarization of the fs-laser beam back-reflected by the crystal’s front surface is analyzed by balanced photodetection. By using a (100)-cut ZnTe crystal, the photodiode signal is directly proportional to the electric field $z$-component.

2.2. Characterization of radially polarized terahertz pulses

Figure 2 shows the result of spatially mapping the electric field of the radially polarized THz pulses in the focal plane of the second paraboloidal mirror in our setup. In two consecutive spatial scans, the distributions of the two orthogonal components of the electric field, $E_x$ and $E_y$, have been measured separately. Figure 2(a) shows the $x$-polarized THz transients, $E_x(t)$, recorded at
two spots left and right of the beam axis, as indicated in figure 2(c). As expected for a radially polarized beam, the electric fields have opposite polarity. Fourier transforming the waveforms yields their spectra shown in figure 2(b).

From the two electric field components $E_x(\omega)$ and $E_y(\omega)$ the corresponding vector fields in the $x$–$y$ plane have been reconstructed and are shown in figures 2(c)–(e) for three different frequencies. We observe radially polarized THz beams with frequency-dependent spot sizes, ranging from approximately 3 mm at 0.3 THz to approximately 1 mm at 0.6 THz. We note that the linearly polarized THz pulses generated when the photo-conductive THz emitter is moved with respect to the laser beam path as described in the previous subsection, have similar dimensions as the radially polarized fields shown in figure 2.

3. Plasmonic focusing on a metal disc

Previous studies have demonstrated plasmonic focusing on metallic structures with circular symmetry [1, 2, 4]. The underlying concept is based on the excitation of surface plasmons in the outer region of the concentric structure, which propagate toward the center where they are
focused. At visible and infrared wavelengths coupling to SPPs can be achieved by using a single annular subwavelength slit milled into a metal layer. The SPPs excited in the slit couple to SPPs that propagate along the metal surface toward the focus. Circular gratings may be used instead of a slit to improve coupling of free-space radiation to surface waves and thereby enhance the efficiency of such a plasmonic lens [1]. For THz radiation with correspondingly small wave vectors the SPP propagation constant is close to the wave vector of freely propagating light and SPPs therefore acquire the nature of a grazing-incidence light field (also known as Sommerfeld–Zenneck waves [26]). In this regime, coupling between a light field and SPPs can easily be achieved, e.g. through diffraction on a sharp edge. Hence, for a plasmonic lens operating at THz frequencies slits or gratings are not crucially required. A simple structure with an edge such as a metallic disc is already sufficient to provide (broadband) THz coupling to SPPs.

Generally, the polarization of the incident light with respect to the edge determines the phase of the excited SPPs. This strongly impacts the field distribution in the focus of a plasmonic lens, where all surface waves interfere. In figure 3 the focusing mechanism on top of a simple metal disc is schematically illustrated for two situations, an incident field of linear (a), and radial polarization (b). The black arrows indicate the wave propagation direction and the dashed arrows correspond to the electric field polarization. In figure 3(a) x-polarized light is normally incident from the bottom side of the disc. On the edges the light is diffractively coupled into SPPs, which counter-propagate toward the center of the disc. As a consequence they interfere destructively in the disc center (as indicated by the opposite directions of the dashed arrows) leading to an electric field node ($E_z = 0$) at the center. Due to cylindrical symmetry of the structure interference leads to

**Figure 3.** Schematic illustration of plasmonic focusing on a metal disc for normally incident light of (a) linear $x$-polarization and (b) radial polarization. Black arrows indicate the propagation direction of light and SPP waves, and dashed arrows the polarization of the electric field. Top images show the electric field intensity distribution $|E_z|^2$ on top of the disc according to equations (1) and (2).
the dominant electric field $z$-component of the SPPs being proportional to the first-order Bessel function as \[ E_z(r) \propto J_1(k_{\text{SPP}} r) \cos(\theta), \] where $k_{\text{SPP}} = 2\pi/\lambda_{\text{SPP}}$ is the wave vector of the surface plasmons and $\theta$ is the angle between the polarization direction and the normal to the edge of the disc. The angular-dependent term originates from the fact that TM-polarization is required for SPP excitation and for linearly polarized light the TM-component drops as $\cos(\theta)$. In figure 3 (top) the resulting electric field intensity distribution $|E_z|^2$ on top of the circular metal disc is plotted according to equation (1) for $\lambda_{\text{SPP}} = 3d$, where $d$ is the diameter of the disc. In contrast to linearly polarized illumination, for incident light of radial polarization the SPPs launched from two opposite points along the circumference of the disc are in phase as shown in figure 3(b) and the $E_z$-components interfere constructively. In addition, the incident field is TM-polarized along the entire circumference of the disc providing much stronger coupling of light into SPPs and therefore a strong enhancement of the field at the focus. In this case the out-of-plane component of the electric field is simply proportional to the zero-order Bessel function as \[ E_z(r) \propto J_0(k_{\text{SPP}} r). \] As a result, under radial polarization illumination the electric energy density is sharply focused at the center, in contrast to illumination by linearly polarized light, where the energy density distribution is dominated by a two-lobe pattern with a zero along the axis of symmetry.

4. Experimental investigation

As mentioned above, in the THz regime the edge of a metallic structure is sufficient for coupling to SPPs. In combination with a circular shape, ensuring SPP propagation toward a common focus, such a simple structure already enables plasmonic lensing of the incident radiation. For our investigation, we produced metal discs on a dielectric substrate as shown in figure 4. The discs have been fabricated by conventional photolithography and wet etching from 9 $\mu$m
Figure 5. Experimental (left column) and simulated (right column) distributions of the out-of-plane electric field component $E_z$ close to the metal disc (50 µm distance) illuminated by linearly polarized THz radiation.

thick copper on a 120 µm thick polytetrafluoroethylene substrate from Rogers (RT/duroid 5880). First, a layer of photoresist was spin coated on the surface. After UV-light exposure through a photomask, the photoresist was subjected to development which destroys unwanted areas of the protective layer, exposing the corresponding areas of the copper. Subsequent chemical etching removes the exposed metal from the substrate. The flexible substrate in principle allows bending of the structures which, however, was not relevant for this study. Various disc diameters have been fabricated and investigated. Due to the limited waist size of the THz beam at the position of the sample (see figures 2(c)–(e)), we found that a disc diameter of 1.5 mm was most suitable for a wide range of THz frequencies (0.1–0.5 THz). The corresponding sample investigated in this study is shown in figure 4(b). We note that our fabrication method produced metal discs with notable surface roughness, however, on length scales well below the THz wavelengths. Thus, severe effects on SPP propagation are not expected.

First, we consider the electric near-field distribution on the disc when illuminated through the substrate by a linearly polarized THz field. Figure 5 (left column) shows the out-of-plane electric field component $E_z$ measured in a plane ~50 µm (~$\lambda$/20 at 0.3 THz) above the disc for three different frequencies. Numerical simulations have been performed based on finite
Figure 6. Experimental (left column) and simulated (right column) distributions of the out-of-plane electric field component $E_z$ close to the metal disc (at $50 \mu m$ distance) illuminated by radially polarized THz radiation.

element method modeling using the commercial program package COMSOL Multiphysics. In the simulation the metal disc has been placed inside a three-dimensional simulation volume with a linearly polarized field being incident from its back side and the electric field $z$-component was sampled in a plane $50 \mu m$ above the metal surface. For comparison the simulation result is also shown in figure 5 (right column).

As expected from equation (1) an anti-symmetric two-lobe pattern with a zero along the $y$-axis is observed with additional extrema appearing with increasing frequency (i.e. increasing wave number $k_{SPP}$). All features observed in the measurement are well reproduced by the simulation. Note that the experimental field patterns are slightly asymmetric with the left lobes being more pronounced and the node along the disc center being slightly shifted to the right, likely due to asymmetric alignment. For example, a tilt of the incident wavefronts can account for asymmetries, such as a displacement of the plasmonic focus [27]. At frequencies above 0.5 THz the measured signal disappears due to the fact that the frequency-dependent THz beam waist decreases below the disc diameter.

The situation changes dramatically when the disc is illuminated by radially polarized THz radiation. As shown in figure 6 the measured and simulated field intensity distributions become cylindrically symmetric, reflecting the matched symmetry of the circular metal structure and

New Journal of Physics 15 (2013) 075005 (http://www.njp.org/)
Figure 7. (a)–(c) Experimental (red, dot markers) electric field intensities along a line through the center of the disc for THz illumination with linear polarization and theoretical fit (black, dashed lines) according to equation (1) for three frequencies. (d)–(f) Simulated field intensities (blue, solid lines) and theoretical curves (black, dashed lines) for the same frequencies.

the radially polarized excitation field. As a consequence, a single focal spot is formed in the center of the disc with decreasing spot size as the frequency increases (i.e. with increasing wave number \( k_{SPP} \)). In the experiment, we observe a (frequency-dependent) displacement of the focus from the disc center, again most likely due to asymmetric alignment, such as a tilt of the incident wavefronts.

We wish to point out that in spite of a much lower incident field amplitude for radial polarization provided by our antenna, we experimentally observe slightly stronger \( E_z \) fields near the center of the disc than for linear polarized illumination. This is consistent with the fact that for radially polarized illumination a strong field enhancement in the focus is expected. On the basis of equations (1) and (2) and assuming uniform illumination along the entire disc circumference, an increase in electric field peak amplitude of a factor of \( \sim 10 \) is theoretically expected.

Horizontal cross sections through the electric field distributions in figures 5 and 6 are presented in figures 7 and 8 in terms of the electric field intensities \( |E_z|^2 \). In both figures the
Figure 8. (a)–(c) Experimental (red, dot markers) electric field intensities along a line through the center of the disc for THz illumination with radial polarization and theoretical fit (black, dashed lines) according to equation (2) for three frequencies. (d)–(f) Simulated field intensities (blue, solid lines) and theoretical curves (black, dashed lines) for the same frequencies.

Left column (a)–(c) shows the measured field intensities together with a corresponding Bessel fit according to equation (1) (for $\theta = 0$) and equation (2), respectively. In order to account for the effect of an asymmetric alignment which resulted in slightly stronger signals at negative $x$-values a linearly sloped background has been subtracted from each experimental dataset. Cross-sections through the simulated field distributions are plotted in the right column (d)–(f) of both figures together with the theoretical curves. All measured and simulated field distributions match well with the theoretical curves. In particular the width and shape of the central lobes fully reproduce the predictions from the Bessel distributions. Only at the disc edges are deviations from the Bessel distributions observed, in particular in the simulations. These edge effects are due to superimposed residual field contributions diffracted off the edges, an effect not accounted for in the theoretical model.

For radially polarized illumination, we experimentally observe at the three selected frequencies 0.20, 0.30 and 0.43 THz spot sizes of 540, 360 and 250 $\mu$m full-width at half-maximum (FWHM), respectively. This corresponds to a universal subwavelength spot size of

[New Journal of Physics 15 (2013) 075005 (http://www.njp.org/)]
0.36\(\lambda_{SPP}\) (with the surface plasmon wavelength \(\lambda_{SPP} \approx \lambda\) for metals at THz frequencies), which represents the canonical FWHM of the zero-order Bessel function. Hence, the plasmonic focus is only determined by the Bessel function and the surface plasmon wavelength. In contrast to focusing by conventional optical components such as lenses or mirrors, the Bessel-focus produced by plasmonic lensing is not limited by a numerical aperture.

5. Conclusion

In conclusion, using THz near-field microscopy and numerical simulations, we demonstrate plasmonic focusing of THz SPP waves on top of a circular metal disc illuminated by radially polarized light. The observed field pattern of the dominant out-of-plane electric field component corresponds to the zero-order Bessel function yielding a spot size at the plasmonic focus of 0.36\(\lambda\) (FWHM). As we have shown, 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.

Since the lensing mechanism is based on focusing SPPs, the associated fields are mainly \(z\)-polarized and localized to the metal surface. 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 applications at giga-to-terahertz frequencies. Using corrugated metals such as bull’s eye structures could further improve efficiency of plasmonic focusing of radially polarized THz radiation owing to coupling to surface modes on multiple slits or edges instead of only a single edge; however, at the expense of being operable only within a narrow frequency band due to the frequency selectivity of the grating. Furthermore, implementing materials with plasmon frequencies in the THz regime (e.g. doped semiconductors) instead of metals will effectively shorten SPP wavelengths and therefore further decrease achievable spot sizes paving the way for true subwavelength THz focusing.

Acknowledgments

We acknowledge financial support by the DFG through grant WA 2641/5. We are grateful to Alex Fauler and Sultan Coban for aid in sample preparation.

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