

# Resonant terahertz probes for near-field scattering microscopy

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**Abstract:** We propose and characterize a scattering probe for terahertz (THz) near-field microscopy, fabricated from indium, where the scattering efficiency is enhanced by the dipolar resonance supported by the indium probe. The scattering properties of the probe were evaluated experimentally using THz time-domain spectroscopy (TDS), and numerically using the finite-difference time-domain (FDTD) method in order to identify resonant enhancement. Numerical measurements show that the indium probes exhibit enhanced scattering across the THz frequency range due to dipolar resonance, with a fractional bandwidth of 0.65 at 1.24 THz. We experimentally observe the resonant enhancement of the scattered field with a peak at 0.3 THz. To enable practical THz microscopy applications of these resonant probes, we also demonstrate a simple excitation scheme utilizing a THz source with radial polarization, which excites a radial mode along the length of the tip. Strong field confinement at the apex of the tip, as required for THz near-field microscopy, was observed experimentally.

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OCIS codes: (180.4243) Near-field microscopy; (320.7100) Ultrafast measurements; (110.6795) Terahertz imaging.

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#### 1. Introduction

Terahertz (THz) near-field microscopy has proved invaluable in the study of electromagnetic phenomena within subwavelength resonators [1,2], of surface waves [3], and graphene

plasmons [4–6], as it enables spatial resolution far better than the diffraction limit ( $\sim\lambda/2$ ). There are two fundamentally different approaches to near-field microscopy in the THz range: The first is direct detection in the near-field [7–11], where the highest spatial resolution (2  $\mu$ m) was recently achieved using aperture-type near-field probes [1]. Further improvements in spatial resolution with this approach are hampered by the strong Bethe dependence of aperture transmission properties [12]. The second approach is known as scattering probe microscopy. This uses a sharp and usually metallic tip, designed to couple the near-field interaction at the tip apex into propagating THz radiation, which is detected in the far-field. The latter approach is not limited by the Bethe dependence, as spatial resolution is dependent primarily on the radius of the tip apex [13]. Both atomic force microscope (AFM) cantilevers and sharp metallic needles have been used as scattering probes [6,13–18], and have demonstrated nanoscale resolution in the THz range.

The efficiency in coupling the near-field interaction at the tip apex into the far-field (hereafter called the *scattering efficiency*) limits the sensitivity of the scattering probe approach [13]. Studies in the infra-red (IR) have shown that the scattering efficiency can be improved if the tip behaves as a resonant dipole antenna [19]. This occurs when the length of the tip is comparable to the wavelength of the light being scattered. Presently, most THz scattering probe microscopy systems use tips significantly longer (e.g. a sharp needle) or shorter (AFM cantilever) than the THz wavelength, necessitating a new tip design, with length ~50-500  $\mu$ m to take advantage of the increased scattering efficiency provided by resonant scattering tips.

The excitation scheme can also limit the sensitivity of scattering probe microscopy through inefficient coupling of THz fields to the tip. The vast majority of scattering probe implementations utilize a linearly-polarized THz source located in the far-field of the scattering tip. This contributes to large background signals, a characteristic trait of the technique [13]. Alternatively, a plasmonic surface mode can be excited along the length of a conical tip. This mode travels down the length of the cone to the apex, where the field is confined by the apex dimensions, acting as a local light source [20]. Practical excitation of this mode has been demonstrated using a grating coupler [21] or a photonic crystal [22,23]. In the THz range, tapered wire waveguides have been excited with plane wave [24] or radial THz sources [17,25–27] However, the precise alignment requirements have limited their application to scattering probe microscopy. It has recently been shown that optical excitation of semiconductor surfaces by short (<100 fs) IR pulses results in radially-polarized THz fields of substantial amplitude [28]. This process enables direct excitation at the base of a scattering tip.

In this paper, we demonstrate a resonant scattering probe, fabricated directly to the surface of a radial THz source. We quantify the field enhancement at the apex using an aperture-type near-field microscopy technique integrated into a THz time-domain spectroscopy system (THz-TDS). We also evaluate the far-field performance of the probe in the context of scattering probe microscopy.

#### 2. Resonant THz probes made of indium

Scattering indium tips are fabricated directly to the surface of a semiconductor wafer using a small drop of liquid indium at the end of a soldering iron. This is touched onto the surface and the tip of the iron is quickly retracted. Figures 1(a)-1(d) show scanning electron microscope (SEM) images of several fabricated tips. These are generally conical in shape with length L ~50  $\mu$ m to 1 mm, cone angle  $\theta$  from ~5 to 20°, and apex diameter  $r_a$  between ~50 and 150 nm. These parameters are shown schematically in Fig. 1(e).

The ideal half wave dipole model provides an approximate relationship between the length of the tip and the wavelength of its fundamental dipolar resonance: A thin wire with length *L* will resonate if the excitation wavelength  $\lambda = 2L$  in free space. If we apply this model to the indium tips (*L*~50  $\mu$ m - 1 mm), we expect they will resonate in the range  $\lambda = 100 \ \mu$ m to

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 $\lambda = 2000 \,\mu\text{m}$  (0.15-3 THz). However, the ideal dipole model does not account for a number of factors, which can influence the resonance of the indium tips: the tip geometry, excitation configuration and local environment. These must be accounted for numerically.

Using FDTD in cylindrical coordinates [29], we simulate a perfect electrically conducting (PEC) [30] cone of length  $L = 100 \ \mu$ m, with a base radius of  $r_b = 10 \ \mu$ m, and a hemispherical apex with radius  $r_a = 500 \ nm$ , as shown in Fig. 1(e). This apex radius is larger than that of the indium tips to reduce simulation time. We found that reducing the apex radius below  $\leq 1 \ \mu$ m in the simulations had a negligible effect on the spectrum of the scattered field. The cone is excited at the base with a broadband radially polarized THz pulse (adapted from [31]) with a center wavelength of 190  $\mu$ m and full width half maximum (FWHM) bandwidth of 1.2 THz.



Fig. 1. (a-d) Scanning electron microscope (SEM) images of a selection of indium probes. Inset in each is a high-resolution SEM at the apex of the probe. (e) Schematic showing Indium tip and simulation parameters. *L* is the length of the tip,  $r_a$  is the radius of the cone apex,  $r_b$  is the radius of the cone base,  $\theta$  is the full cone angle and *a* represents the distance to the detector. (f) Scattering spectrum from a 100  $\mu$ m long PEC cone with increasing base radius  $r_b$  in a radial excitation configuration. (g) Scattering spectrum maxima for increasing cone length with (red symbols) and without (black symbols) the GaAs substrate. (h) Magnitude of the electric field at the cone apex.

To determine how the scattering efficiency of the metal cone varies with frequency, and to align the simulations with experimental measurements, a scattering spectrum is evaluated as follows: the vertical ( $E_z$ ) component of the electromagnetic field is measured for frequencies 1 to 2.5 THz at a point positioned at distance a = 1 mm away from the tip axis (see Fig. 1(e)). This is then normalized to the incident THz pulse. As a = 1 mm is many times the length of the tip, we assume the spectrum measured at a corresponds to the far-field spectrum. We also make the assumption that the horizontal plane indicated in Fig. 1(e) by the dashed line is where the field scattered by the tip is strongest, in accordance with the half-wave dipole model [32].

The scattering spectrum  $(E_s/E_{inc})$  for the cone with geometry outlined above is shown in Fig. 1(f). It includes a clear broad peak with a maximum  $f_c = 1.24$  THz (241  $\mu$ m), and fractional bandwidth (FWHM/ $f_c$ ) of 0.65. This is a departure from the prediction of the half-wave dipole model for a dipole of this length (1.5 THz). However, we can approach the prediction of the ideal dipole by reducing the base diameter of the cone. Cones where  $r_b = 5$  and 0.5  $\mu$ m are shown in the figure, with the maxima in the scattering spectrum at 1.28 THz (234  $\mu$ m) and 1.36 THz (220  $\mu$ m), and fractional bandwidths of 0.50 and 0.33 THz, respectively. This reduction in bandwidth, and increase in resonant frequency with reducing base radius is common in thick dipole antennas [32]. We suggest the same principle applies to the indium tips.

In order to make approximate predictions about the resonant wavelength of the indium tips, we simulate cones of varying length, while keeping the base diameter  $r_b$  constant  $(10 \,\mu\text{m})$ . We expect the effect of increasing base diameter  $r_b$  on the scattering spectrum follows a similar pattern to that shown in Fig. 1(f) for each cone length L. As mentioned above, the effect of the apex radius  $r_a$  is minimal when the apex is small in comparison to the 150 and 200  $\mu$ m. We see the resonant wavelength is a linear function of the cone length. When a 20  $\mu$ m thick GaAs ( $\varepsilon_r$  = 12.96 [33]) substrate is included in the simulation at the base of the cone, the resonant wavelength again remains linear. We maintain a = 1 mm and measure the field on the horizontal plane shown in Fig. 1(e) when the substrate is added in order to simplify the presentation of the results. However, we expect that introducing the GaAs substrate will perturb the distribution of the scattered field in a similar manner to that predicted by Luan et al. [34]. We note that the bottom of the GaAs substrate terminates at an absorbing boundary, meaning it has effectively infinite thickness. Comparing these results to the ideal half-wave dipole, we suggest a simple empirical adjustment to this model, incorporating a factor  $\gamma$ , such that  $\lambda_{res} = 2\gamma L$ . From Fig. 1(g), we see  $\gamma = 2.1$  when the substrate (GaAs) is incorporated into the model. This formula can be used to predict the resonant wavelength of indium tips fabricated on a semiconductor surface, such as the probes discussed in this work.

We note that over the frequency range of the FDTD simulations, we observe no difference in the peak location and bandwidth when cones are excited by plane wave or radial excitation. Figure 1(h) shows the magnitude and the spatial distribution of the electric field at the apex of the cone where  $r_b = 5 \ \mu m$ . The field confinement is comparable to the diameter of the tip apex (1 \ \mumm m) as predicted [13], and the field enhancement reaches the value of ~200 for this geometry.

#### 3. Radially polarized THz pulses

In order to excite the radial surface mode on the indium tip experimentally, we use a radiallypolarized THz source, consisting of a 1  $\mu$ m thick layer of InAs, deposited onto a GaAs substrate. This is bonded to a 500  $\mu$ m thick sapphire window and the GaAs substrate is thinned to 20  $\mu$ m [35]. The emission process is as follows: the InAs wafer is excited at

normal incidence with 100 fs pulses from a mode-locked Ti:Sapphire laser at  $\lambda = 800$  nm, which generates fast moving charge carriers along the InAs surface. These emit a copropagating radially polarized THz beam [28]. This process is shown schematically in Fig. 2(a).



Fig. 2. (a) An illustration of the generation process of radial THz pulses from an InAs wafer. (b) and (c) show the spatial distribution of electric field on a plane 300  $\mu$ m from the InAs source at  $t = t_1$  and  $t = t_2$  respectively. (d) A space-time map taken across the dashed line shown in (b).

The spatial and temporal properties of the InAs emission was evaluated using a THz-TDS and near-field microscopy system. A collection mode near-field probe [36] with a 5  $\mu$ m input aperture (spatial resolution 3.9  $\mu$ m [1]) was used to detect the spatial distribution of the THz emission on a plane ~300  $\mu$ m below the source. Images of the THz field generated by the InAs are constructed by raster scanning the aperture probe on a plane parallel to the InAs source. Time domain measurements are made using an optical delay line.

The spatial distribution of the THz emission from this source is shown in Figs. 2(b) and 2(c) for two different time delays ( $t = t_1$  and  $t = t_2$ , respectively). Figure 2(d) shows the temporal evolution of the THz emission, measured along the dashed line in Fig. 2(b). As the aperture probe is configured to detect THz fields polarized along the *x*-axis only, the measured field distributions have a crescent shape. The true THz emission is in fact radially symmetric [28].

#### 4. Characterization of field confinement by indium tips

The THz-TDS and near-field microscopy system was also used to measure the fields at the apex of the indium tips. The experiment is constructed as shown in Fig. 3(a). The base of the indium tip is aligned to the axis of the optical beam, and the apex is brought close to the aperture plane. As before, near-field images of the THz field induced by the tip are constructed by raster scanning the tip over the surface of a 5  $\mu$ m aperture probe.



Fig. 3. (a) Schematic of the experimental setup. The tip is raster scanned in the *x*-*y* plane. The blue arrow shows the polarization of the surface waves excited by the tip on the metallic surface of the probe. A visualization of the probe is inset. (b) The spatial field distribution measured by the aperture probe when ~10  $\mu$ m from the apex of a ~300  $\mu$ m long tip. (c) A space time image recorded along the dashed line in (b). (d) is the space-time image shown in Fig. 2(d), cropped to facilitate direct comparison with (c).

It should be noted that aperture probes of this type are sensitive to THz fields polarized both perpendicular and parallel to the plane of the aperture [3,37], meaning that both the radiation from the InAs source directly, and surface waves excited and travelling on the metallic surface of the probe can be detected. However, as discussed in [28] the transmission of these two field components through the aperture differs. Briefly, the fields polarized parallel to the plane of the aperture produce the electric field (on the back side of the aperture) proportional to the incident field, whereas the fields polarized perpendicular to the surface (surface waves, for example) generate a potential across the aperture, resulting in the transmitted field proportional to the gradient of the electric field along the surface. This is important for understanding the field distributions observed with the aperture probes when multiple field polarizations are detected simultaneously. This was not significant in the emission spectrum of InAs, which primarily contains components polarized in the plane of the probe surface. However, multiple polarizations are expected to exist at the apex of the indium tips. As discussed above, the photoconductive detector inside the probe senses the field transmitted through the aperture with the polarization along the x-direction, therefore the detected field is a sum:  $E_{det} = A (dE_x/dt) + B (dE_z/dx)$  where A and B are proportionality coefficients representing the aperture transmission properties [28].

Figure 3(b) shows the instantaneous electric field distribution in the vicinity of a tip of length ~300  $\mu$ m with the tip positioned ~10  $\mu$ m from the surface of the aperture probe. Comparing this to the emission of InAs shown in Fig. 2(b) and 2(c), the field distribution is

generally similar, with two lobes of opposing polarity. However, where the InAs emission is a minimum (the center), the presence of the tip induces a maximum in the same location. This is in good agreement with a surface mode being focused along the length of the tip.

Temporal evolution of the field reveals a more complex structure. Figure 3(c) shows a space-time map of the field recorded along the x-axis shown in Fig. 3(b). The THz field is detected earlier at the center of the map, corresponding to the position of the tip. Away from the tip, the THz field is detected later as evident from V-shaped wave front. A V-shaped wave front on this scale is not seen in the incident THz pulse of Fig. 3(d). We suggest therefore that the tip induces a surface wave on the surface of the aperture probe, as the velocity of the wave measured by the aperture probe is approximately the speed of light (black dashed line in Fig. 3(c)).



Fig. 4. (a) The waveform with the aperture probe when the apex of a ~250  $\mu$ m long tip is within 1  $\mu$ m of the aperture (red line), and the THz emission of InAs (black line), which is magnified 10x for clarity. The Fourier transforms of the time-domain waveforms are inset. Again, the InAs emission is magnified 10x. Both spectra are multiplied by 1/f to account for the filtering properties of the aperture probe. (b) The spatial field distribution of the same tip at the peak of the pulse P1. (c) Approach curve for a  $\sim 200 \ \mu m$  long tip. The diamonds show with approximate error, the peak electric field of the THz pulse, measured using the 5  $\mu$ m aperture probe. The red dashed line is a function, fitted to the experimental results. Inset: apex of the tip, showing the measurement axis (dashed green line).

To estimate the electric field enhancement at the tip apex, it is brought to within 1  $\mu$ m of the aperture probe. Figure 4(a) shows the waveform measured when the tip is close to the aperture. The field of the incident wave, also shown in the figure, is evaluated in the same configuration but with the indium tip removed and the detector aperture located at the field maximum,  $\sim 250 \ \mu m$  away from the beam axis (as shown in the incident beam profile in Fig. 2(b)). The measured enhancement is approximately 40 times greater than the emission from InAs. The spatial distribution of the THz field in Fig. 4(b) shows that the field is confined to a spot of ~5  $\mu$ m in diameter.

As the aperture collects the incident field over a 5x5  $\mu$ m<sup>2</sup> area, the measured field at the apex of the indium tip is averaged over this area, effectively reducing the measured field confinement and enhancement at the tip apex. It is therefore highly likely that the field

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enhancement on the 100 nm scale is far greater than the observations made in Fig. 4, as was seen in the FDTD simulations.

Other than the peak P1, the waveforms in Fig. 4(a) do differ. The polarity difference can be attributed to the spatial field distribution of the THz emission from InAs, in Fig. 2(b) and (c). The low frequency component of the wave at the apex of the tip not seen in the InAs far-field emission has been seen previously in near-field measurements with Fe-doped InGaAs [28], and it indicates better coupling of the low-frequency emission to the surface waves propagating along the tip. The feature P2 is not present in the InAs emission either. This has the correct time delay for a reflection along the length of the ~250  $\mu$ m long tip. This effect of pulse reflection was also seen by Wang *et al.* [38], where an long needle tip had a circular aluminum barrier placed along its shaft. The spectrum inset in Fig. 2(a) shows a peak slightly below 0.5 THz, which is likely due to the reflection seen in the time-domain waveform. Other features in the waveform.

In the absence of an aperture probe or sample, the electromagnetic field at the apex of a scattering probe is expected to decay exponentially with increasing distance from the apex. Figure 4(c) shows the THz field measured for increasing tip-aperture distance, fitted to the exponential shown by the dashed line. We note however that the aperture probe acts to integrate the field over the  $5x5 \ \mu m^2$  aperture area. This effectively reduces the gradient of the approach curve.

### 5. Evaluation of scattering efficiency

The near-field aperture probe technique provides insight into the field distribution near the apex of the indium probes. However, to apply the tips to scattering probe microscopy, equally important is their far-field scattering characteristics, as typical systems are configured with a detector placed in the far-field. To evaluate the far-field scattering efficiency of the indium tips, we set up a scattering experiment with far-field detection at position D2, shown in Fig. 3(a). We expect the field detected at D2 consists of two components: emission from the InAs source ( $E_{InAs}$ ) reaching the detector directly, and the field scattered by the tip ( $E_s$ ). It is not directly possible to separate these field components experimentally; we therefore assume that the field measured at D2 is a linear superposition of the individual field components. We therefore propose the following experiments to identify each field component. Firstly, when no tip is present, the detected field consists of only emission from the InAs, and  $E_{det,1} = E_{InAs}$ . When the indium tip is excited with the radial beam, the detected field becomes  $E_{det,2} = E_{InAs} + E_s$ . Therefore,  $E_s = E_{det,2} - E_{det,1}$ , represents the field scattered by the tip, and the scattering efficiency can be defined as  $E_s/E_{InAs}$ , for comparison with the FDTD simulations.

Firstly, we use a 10  $\mu$ m aperture probe as D2 for continuity between the experimental near-field and far-field measurements, because the probe has similar frequency filtering properties compared to the probe used in the near-field measurements in Fig. 4. The detector is placed ~5 mm from the tip on the plane indicated by the dashed lines in Fig. 3(a). This is integrated into the THz-TDS system for coherent detection of the scattered terahertz radiation. The position of the tip relative to the sample is not modulated in order to quantitatively investigate the scattering properties of both the probe and InAs source.

Figure 5(a) compares waveform of the THz pulse emitted after photo-excitation of the InAs surface (black line) with the waveform of the pulse detected when an indium tip (200-400  $\mu$ m) is incorporated into the system (red line). Subtracting these allows us to identify the scattered field  $E_s$ , and the corresponding waveform is shown by the blue line in the figure. The scattered field is detected after a small temporal delay (0.7 ps), as expected. The spectrum of the field enhancement  $E_s(\omega)/E_{InAs}(\omega)$  is shown in Fig. 5(b). For comparison, the figure also shows the Fourier transform of the source ( $E_{InAs}$ ) by a black line (the spectrum is multiplied by 1/f to account for the filtering properties of the THz detector with an input aperture [36]). Comparison with the InAs source spectrum shows that the scattered field is

spectrally modified. In this experiment however, we do not resolve a clear dipolar resonance, although the scattered field due to the tip is clearly present. We note that the peak at around 1.2 THz is likely due to a higher order resonance excited along the tip length, and we expect that the dipolar resonance peak is at ~0.4 THz.



Fig. 5. Indium tips in a scattering probe configuration. An aperture probe with a 10  $\mu$ m aperture is used in (a) to detect THz emission from the InAs source and the scattering from the tip. Waveforms from InAs only (black line), when the tip is present (red line) and the scattered field (blue line) are shown. The scattered field is offset by 1.5 pA on the *y*-axis for clarity. (b) Fourier transforms of the waveforms shown in (a). The InAs emission spectrum (black line) is multiplied by 1/f to account for the filtering properties of the aperture probe. The green line shows the ratio of the scattered field to the InAs emission. The plot is shaded in areas where the noise level is high. (c) and (d) are the waveforms and spectra when a PCA is used for detection.

As the aperture probe has a low signal to noise ratio at the low-frequency part of the spectrum, the experiment is repeated with a photoconductive antenna (PCA) THz detector. The measured waveforms are shown in Fig. 5(c). It should be noted that the indium tips are not identical in the two experiments. Again, we take the Fourier transform of  $E_s$  and  $E_{tip}$ , and show  $E_{InAs}$  and  $E_s/E_{InAs}$  in Fig. 5(d). The scattering efficiency spectrum contains a single peak, at 0.3 THz.

The peak in the scattering spectra in Fig. 5(d) (and the lack thereof in Fig. 5(b)) can be explained by considering the antenna resonance of the indium tips. For the scattering experiments, the tips were between ~200-400  $\mu$ m, making their resonant frequency lie below 1 THz according to the modified half-wave dipole model from Section 2. We therefore expect the lack of a significant peak in the scattering spectrum when using the 10  $\mu$ m aperture probe

shown in Fig. 5(b) is due to low aperture transmission in the sub-THz range. Figure 5(d) on the other hand shows a strong resonant peak at 0.3 THz. When we again compare this to the modified half wave dipole, we estimate the tip length to be ~250  $\mu$ m, within the measured range, meaning we can predict the tip length using the model with reasonable accuracy. We note that we do not observe the same spectral filtering effects seen by Wang *et al.* in [39]. We anticipate that this is due to the length of the tips in that work being significantly longer than the free-space THz wavelength. The indium tips on the other hand can act as THz dipole antennas as their length is similar to the THz wavelength, meaning the spectral filtering effect is not present. We suggest that for the indium tips to resonate in the THz frequency range, they should be fabricated with length  $L < 150 \,\mu$ m.

For practical applications of the resonant tip as a THz near-field microscopy probe, we now evaluate the effect of the tip environment on the scattered field. The strongest effect can be achieved by bringing a metallic surface close to the tip apex. We measured the fields scattered by the tip when the metallic surface was placed at distances of  $< 1 \mu$ m, and  $\sim 2 \mu$ m from the tip apex. The corresponding waveforms are shown in Fig. 6(a). We found a noticeable difference between the waveforms at the time delay corresponding to the scattered field. We estimate that the amplitude of this difference signal is approximately 0.25 pA, which is  $\sim 1/3$  of the total amplitude of the detected field.

We note that in scattering probe microscopy, the difference in fields at two different sample-probe distances is typically measured. The difference waveform in Fig. 6(b) therefore allows us to evaluate the relative amplitude of the near-field signal ( $E_{nf}$ ) due to the metallic surface, for the sample-probe amplitude modulation amplitude of ~1-2  $\mu$ m. The near-field difference signal of ~30% (in electric field) compared to the field detected directly from the InAs source suggests that the radial polarization excitation scheme employed here together with the resonant THz probe can yield a THz scattering near-field microscopy configuration with low background signal.

The variation in indium tip geometry found in the fabrication process (shown in Fig. 1(a)-1(c)) promises resonant response across the THz range. However, fabricating probes with consistent geometry was difficult in this study, where the soldering iron was moved by hand. By automating the fabrication process, it should be possible to fabricate indium tips with predictable and consistent geometry. We expect that the geometry of the indium tips is determined primarily by the temperature of the soldering iron and substrate, speed of Iron retraction, and the amount of indium on the soldering iron. Additionally, using the same fabrication process, it may be possible to fabricate scattering probes with materials other than indium, such as tin, or a tin/lead alloy. These materials may allow for geometries or scattering characteristics not possible with indium.



Fig. 6. Scattering waveforms measured with the 10  $\mu$ m aperture probe. (a) waveforms measured > 1  $\mu$ m (black line) and < 1  $\mu$ m (red line) from a metal surface. (b) the difference between the waveforms shown in (a).

We have demonstrated resonant scattering tips for THz near-field microscopy with the aim of improving scattering efficiency through dipolar resonance. The tips, fabricated from indium, have length 50-500  $\mu$ m, and an apex diameter in the tens of nanometers, meaning the expected spatial resolution is at the level of the highest resolution achieved to date in the THz spectral range [6]. The tips are fabricated directly to the surface of a wafer of InAs, which generates radially polarized terahertz radiation. This source delivers a simple alternative to present THz excitation schemes by exciting a radial mode along the length of the tip, and promises reduced background signals. This probe is shown to tightly focus the radially polarized THz beam at the apex of the indium tip, and is capable of launching surface waves on metallic films. Further, both experimental and numerical measurements show that the indium probes exhibit enhanced scattering in the THz frequency range due to the dipolar mode excitation.

Vol. 25, No. 22 | 30 Oct 2017 | OPTICS EXPRESS 27885

### Funding

EPSRC (EP/L015277/1, EP/P021859/1, EP/J017671/1); Royal Society (UF130493).