Supplemental Document

Optics EXPRESS

# Anomalous contrast in broadband THz near-field imaging of gold microstructures: supplement

ANGELA PIZZUTO,[1,*] XINZHONG CHEN,[2] HAI HU,[3] QING DAI,[3] MENGKUN LIU,[2] AND DANIEL M. MITTLEMAN[4]

[1] *Department of Physics, Brown University, Providence, RI 02912, USA*
[2] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA*
[3] *Division of Nanophotonics, CAS Key Laboratory of Standardization and Measurement for Nanotechnology, CAS Center for Excellence in Nanoscience, National Center for Nanoscience and Technology, Beijing 100190, China*
[4] *School of Engineering, Brown University, Providence, RI 02912, USA*
[*] *angela_pizzuto@brown.edu*



Supplement DOI: https://doi.org/10.6084/m9.figshare.14459982

Parent Article DOI: https://doi.org/10.1364/OE.423528

# Anomalous contrast in broadband THz near-field imaging of gold microstructures: supplemental document

## 1. On-Disk Signal

We measured the relationship between the ground line length and the strength of the on-disk THz reflection signal. The results are shown in Fig. S1. We find an enhanced signal on the first disk, which decreases in the mid-lengths and increases slightly for the longest ground lines. This phenomenon is qualitatively consistent up to the 5$^{th}$ harmonic (the highest possible with our detection system), although the contrast ratio between the signal from the first disk (with the shortest ground line connector) and the signals from the other disks changes with harmonic order. This suggests that the background signal, which is usually suppressed by using higher harmonic orders, has a larger magnitude for the first disk than for the others (and similarly for the last disk, with the longest length of ground line, although to a lesser degree). In other words, since the non-near-field background signal is larger for the disks near the edges of the structure (the ones with the longest and shortest connectors), a higher harmonic order is required in order to effectively suppress this background. We therefore attribute this effect to the disks' relative proximity to the large surrounding gold ground pad. While imaging the disks with the shortest/longest ground lines, a larger portion of the far-field THz spot can be reflected from this large gold pad, and portions of that extraneous far-field reflection can couple to the tip. This creates an additional artifact in the near-field signal which is attributable to background reflection but cannot be as readily suppressed with higher-harmonic demodulation.

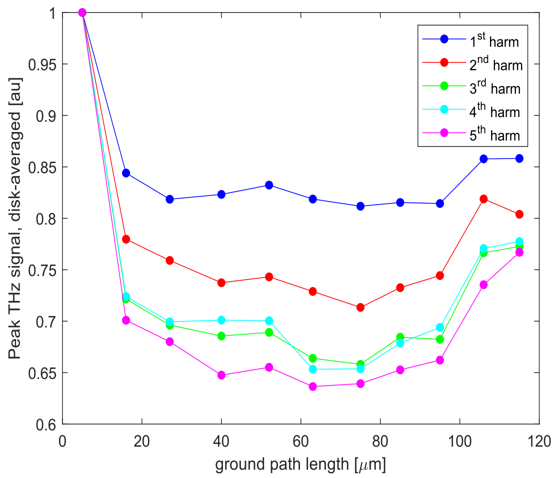


Fig. S1. Peak on-disk THz reflection signal as a function of ground line length, calculated as the average signal on each disk from near-field images. Data up to the 5$^{th}$ harmonic of the tip tapping frequency is shown, normalized by the disk with the shortest ground line.

## 2. Higher Harmonic Image Demodulation

In Fig. S2, we show close-up images of the disk with the 63 μm ground line, obtained using different harmonics of the AFM tip tapping frequency ($1^{st}$ through $5^{th}$ harmonics). As the harmonic order increases, the near-field signal becomes weaker; however, the halo effect is still clear even at the $5^{th}$ harmonic.

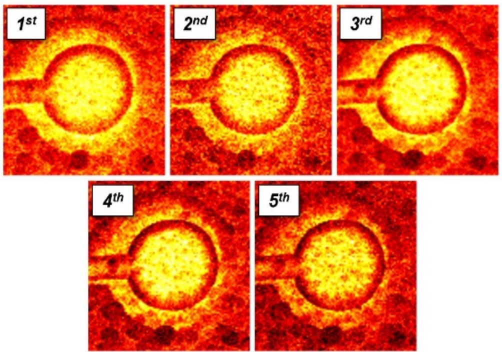


Fig. S2. THz peak-signal reflection images of gold disk with 63 μm-long ground line, demodulated from $1^{st}$ to $5^{th}$ harmonic of the tip tapping frequency (harmonic order noted in top left of each image). Bright yellow indicates stronger reflection while dark red indicates lower reflection.

## 3. $SiO_2$ vs. Si substrate

Excitation of Goubau-Sommerfeld modes along the ground lines is highly dependent on the material composition of the structure, as this contributes to the precise relationship between the free-space frequency and the wavelengths of the guided modes. We perform an additional FD-FEM simulation to determine the scattering properties of the structure at 0.8 THz radiation, substituting a Si substrate for the original $SiO_2$ substrate. We determine, as expected, a shift in the guided mode wavelength, and therefore a shift in the appearance of the electromagnetic "halo". This further supports the idea that a Goubau-Sommerfeld mode standing wave is responsible for the observed effect.

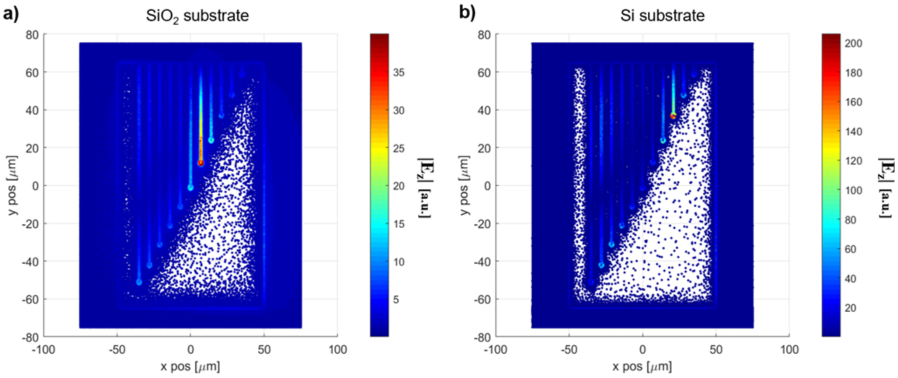


Fig. S3. Far-field FD-FEM simulations of the gold disk structure at 0.8 THz. The $SiO_2$ substrate (left) creates a halo on the 5$^{th}$ disk, while the Si substrate, with a much higher dielectric constant (right), creates a strong halo on the 3$^{rd}$ disk.

## 4. Structure with varying disk size

For comparison purposes, we performed THz near-field imaging on a similar structure, with 8 disks of diameters ranging from approximately 1-8 μm, all with ground lines of approximately 52 μm in length. We find the size of the disk in this range plays no significant role in the on-disk signal, as shown in Fig. S4(c), which shows a one-dimensional line scan of the scattered THz signal through the centers of the eight disks (demodulated using the 3$^{rd}$ harmonic). In particular, we do not observe a halo for the 2 μm diameter disk in this case, even though it is very similar to the areas of the original structure that do feature the halo (as in Fig. 4 of the main text). FD-FEM simulations of the far-field THz response confirm that a halo should be visible in the 3 smallest disks, as shown in Fig. S4(a). To explain this result, we perform additional simulations in which we include a metallic, conical tip with a 50nm radius which is placed 5 nm above the $SiO_2$ substrate and approximately 700nm away from the edge of the 2$^{nd}$-smallest gold disk; the results are shown in cross-section in Fig. S4(b). In these simulations, we find that the conductive tip couples to the structure in a way that significantly affects the signal on the $SiO_2$ substrate, even at locations that are far from the tip. Therefore, we attribute the lack of halo in our experimental images to the extremely complex interplay between the tip and components of the structure. This result further emphasizes the complexity of extracting dielectric information from s-SNOM measurements of samples with complicated metallization patterns.

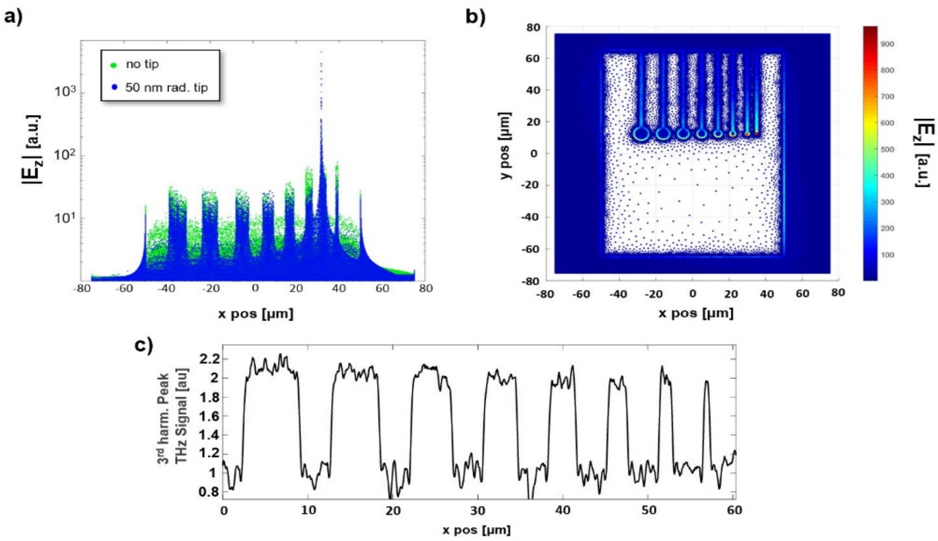


Fig. S4. (a) FD-FEM simulation of 0.8 THz response from structure with varying disk size. (b) Line profile along the disks of simulation shown in S3(a) (green markers), and of same simulation but with a 50 nm -radius, 80um-long conical tip placed 5nm above $SiO_2$ substrate and approximately 700nm from the edge of the 2 μm disk (blue markers). The existence of the tip creates a large enhancement close to the apex but lowers the THz reflection signal on the $SiO_2$ across the entire structure, possibly diminishing the appearance of a halo around the first 3 disks.