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Invited Paper

Spectroscopy and mapping of resonant fields in terahertz plasmonic resonators

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ABSTRACT

Plasmonic terahertz (THz) resonators provide a promising route for exploring strong light-matter coupling phenomena. Double-metal resonator designs in particular enable strong enhancement of the THz field and provide well-defined field orientation and confinement within a sub-wavelength size volume. The strong field confinement however limits access to the internal fields essential for investigations of light-matter coupling. We propose and investigate a method for mapping and spectroscopic analysis of the internal fields in double-metal plasmonic THz resonators. We use aperture-type scanning near-field THz microscopy to access strongly confined fields with sub-wavelength spatial resolution of ~5 μm (~λ/100). Combined with the THz time-domain spectroscopy technique, the near-field method allows us to perform spectroscopic studies and investigate the field evolution inside the resonator. This experimental method opens doors to studies of strong light-matter coupling at THz frequencies in individual plasmonic resonators.

Keywords: terahertz, near-field microscopy, terahertz time-domain spectroscopy, plasmons, resonators, light-matter coupling, metamaterials.

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1. INTRODUCTION

Plasmonic terahertz (THz) resonators have emerged as a promising route for exploiting light-matter coupling in semiconductors. A planar metallic resonator, such an antenna or split-ring resonator, fabricated on a semiconductor surface can be used to concentrate the electric field within a sub-wavelength volume. This can lead to enhancement of the electric field amplitude orders of magnitude higher compared to focused THz beams. THz resonators have already been exploited to induce non-linear effects, as well as to enable light-matter interaction in the strong and ultra-strong coupling regimes [1-4].

Double-metal plasmonic THz resonators are particularly attractive for investigations of light-matter coupling phenomena. In addition to coupling the energy of a THz plane wave to a deeply sub-wavelength volume [5], the double-metal geometry provides a simple configuration to control the polarization of the confined THz field, its spatial distribution and the amplitude. Furthermore, the geometry of double-metal resonator, which consists of two isolated planar metallic structures separated by a dielectric layer, is ideal for incorporation of semiconductor quantum wells and quantum dots, and thus enabling strong interaction of the THz waves with electronic excitations, such as quantum well excitons.

Despite the enhanced coupling of THz waves to a small volume inside a double-metal resonator, the effect of the resonator on a plane waves is relatively low. As a result, far-field experimental studies of light-matter coupling using single THz resonators have not been realized so far. Typically, light-matter interaction effects are investigated by probing transmission or reflection properties of resonator arrays. These studies however rely on models of collective response within the array. The collective response includes the interaction between the resonators in addition to their individual response. The reflectivity and transmission spectra as a result can also display collective modes with weak field confinement and undesired inter-resonator coupling.

These effects can be avoided in isolated THz resonators. THz near-field microscopy techniques have been applied recently to investigate single resonators [7-10]. Sub-wavelength aperture THz near-field probes discussed in this contribution were applied to probe plasmonic resonators made of metallic [6] and semi-metallic [7], including graphene [8], structures. As an alternative method, near-field electro-optic and magneto-optic sampling was used to investigate THz antennas and split-ring resonators [9-11]. Micro-fabricated commercial THz photoconductive switches were utilized recently to map vector fields near a dipole antenna [12]. These near-field techniques also enable time-resolved mapping of the THz field, which can provide insight into the process of resonator excitation [13].

The majority of demonstrated applications so far have considered open plasmonic resonators with modes partially distributed on the resonator surface. Here we discuss application of aperture-type THz near-field microscopy for mapping and spectroscopy of the internal fields in double-metal THz resonators. In order to access the electromagnetic fields inside the resonator we exploit the mirror symmetry of the structure and the metallic surface of the near-field probe. It allows us to map the field inside the resonator. Spectroscopic analysis of the internal field shows two plasmonic modes with characteristic frequencies of 0.5 and 1 THz. Applications of aperture-type THz near-field microscopy for light-matter coupling experiments will be discussed.

2. NEAR-FIELD MAPPING OF THE INTERNAL FIELD

Consider a planar resonator positioned above a metallic surface at a distance of smaller than the resonator size as shown in Fig. 1. The metallic surface serves as a mirror plane and forms a double-metal resonator, where the bottom half is replaced by an image of the top resonator. In this configuration, the normal component of the field $E_z(x,y)$ within the mirror plane is equivalent to the field inside the double-metal resonator.

An aperture in the metallic plane provides access to this field inside the resonator. For a small aperture, only a fraction of the resonator energy couples below the mirror plane and thus the field distribution and spectroscopic analysis can be performed without significant disturbance of the internal field.

The top resonator design considered here is based on a spoof surface plasmon geometry shown in the inset of Fig. 1 [14]. The top resonator alone supports a series of plasmonic modes with the first two exhibiting relatively narrow THz resonances [15]. Together with the metallic surface of the near-field probe, the top resonator forms a structure equivalent to a double-metal resonator, with the plasmonic mode confined between the top (real) and the bottom (image) resonator.

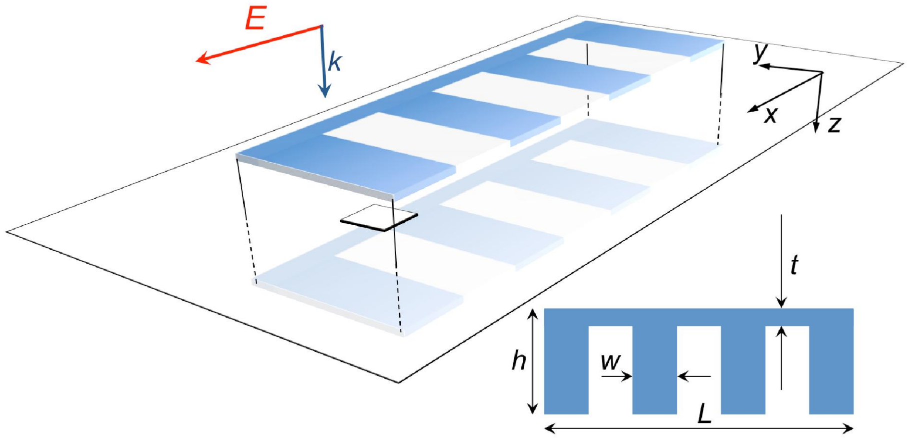

FIG. 1: Schematic diagram of the experiemntal system consisting of a planar plasmonic THz resonator and a metallic plane of the near-field probe, which together form a double-metal resonator. A sub-wavelength aperture in the plane is used to sample the internal fields in the resonator. The inset shows the resonator design.

The top resonator was designed with the following dimensions: L=140 μm, h=50 μm, w=20 μm, t=8 μm. Samples were fabricated by electron-beam lithography and thermal evaporation of a 200 nm thick Au layer on a 0.5 mm thick quartz substrate. Numerical modeling of this design showed the first two resonances at 0.5 and 1 THz.

The resonator was positioned near a gold surface of a THz near-field probe with a 5x5 μm^2 aperture and an embedded THz photoconductive antenna detector [16]. The detector was placed within 300 nm below the aperture to sample the weak THz field coupled through the aperture.

The resonator was excited at normal incidence from the substrate side using a short THz pulse generated in a ZnTe crystal by 100 fs optical pulses with the central wavelength of ~800 nm [13]. The THz beam was polarized along the x-axis and it had an approximate diameter of 500 μm.

The incident THz pulse polarizes the resonator and launches surface waves on the resonator surfaces. The surface waves travel from one side of the resonator to the other and form standing waves. The standing waves represent fundamental modes of the resonator and the resonance frequencies are determined by the resonator dimensions.

To detect the internal field, the near-field probe is scanned in the mirror plane and the field coupled through the aperture is sampled by the photoconductive THz antenna. An example of the corresponding instantaneous field distribution is shown in Fig. 2. The map shows a symmetric field pattern with the strongest signal found at the center of the narrow horizontal bar. We expect that the normal component, E_z, dominates in that region due to the boundary condition (E_x=E_y=0) imposed by the metallic surfaces.

The E_z component of the internal field couples through the aperture only if there is non-zero gradient of the field dE_z/dx [6,17]. Therefore the detected field map represents a distribution of the spatial field derivative dE_z/dx, and the symmetric map of the detected field corresponds to an anti-symmetric E_z field distribution [17]. The symmetric map is consistent with previous investigations of metallic and semi-metallic resonators excited THz pulses at normal incidence [6-8,17].

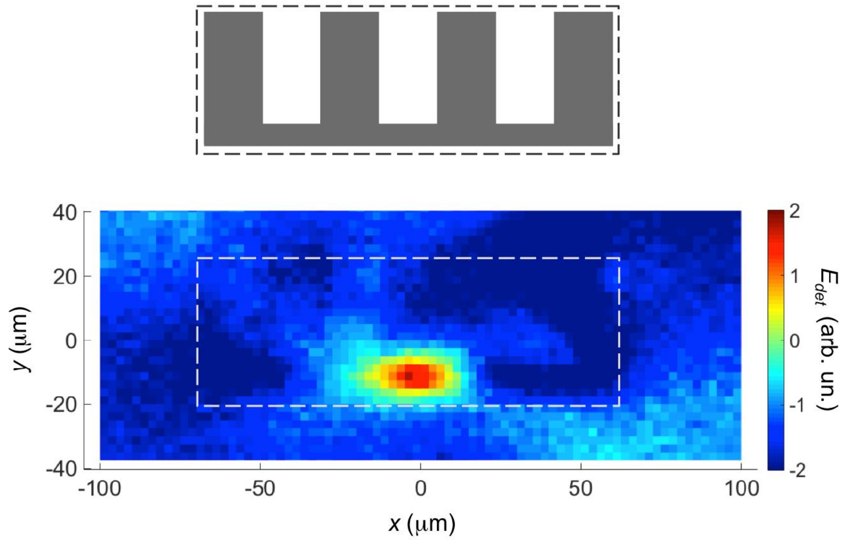

FIG. 2: THz field map on the resonator recorded by the near-field probe ~2 ps after excitation by a THz pulse. The resonator strucure is schematically shown above the map and the location of the resonator in the map is marked by the dashed rectangle.

3. TERAHERTZ SPECTROSCOPY OF THE INTERNAL FIELD

The area in Fig. 2 where the strongest signal is detected can serve as an access point for spectroscopic analysis of the internal fields. We recorded time-domain waveforms of the field coupled though the aperture as it is scanned along the *y*-direction scan though the bar center. The corresponding space-time map is shown in Fig. 3.

The map clearly shows the incident THz pulse at *t*=1 ps and its replica arriving at *t*=8-9 ps, after reflections within the substrate. The incident pulse and the replica are detected at any position as long as the metallic features of the resonator do not block the aperture. The detected field is strikingly different when the horizontal bar is positioned directly in front of the aperture, therefore preventing the incident field from reaching the aperture directly. We observe oscillations lasting over 25 ps after the excitation by the incident pulse instead. The map in Fig. 3 suggests that the field inside the resonator is localized within the horizontal bar, confirming the results in Fig. 2.

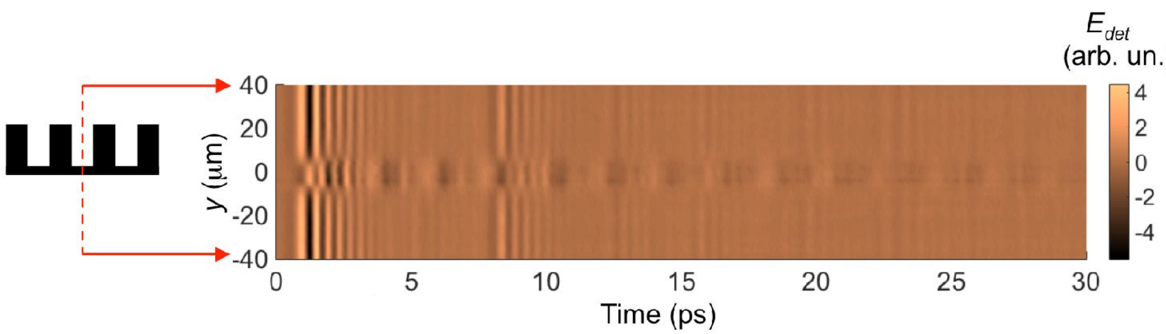

FIG 3: Space-time map of the field detected by the near-field probe along the *y*-axis, as shown schematially on the lelt side of the map by a dashed line.

Fourier transform of the space-time map in Fig. 3 shows that the oscillation correspond to two resonances excited by the incident THz pulse. The characteristic frequencies are 0.5 THz and 1 THz as expected from numerical simulations. Figure 4 shows the Fourier transform map, where each spectrum is normalized to the near-field spectrum of the THz wave transmitted through the substrate alone. At the resonance frequencies, the signal detected by the near-field probe is enhanced up to 10-20 times compared to the incident field (see inset of Fig. 4).

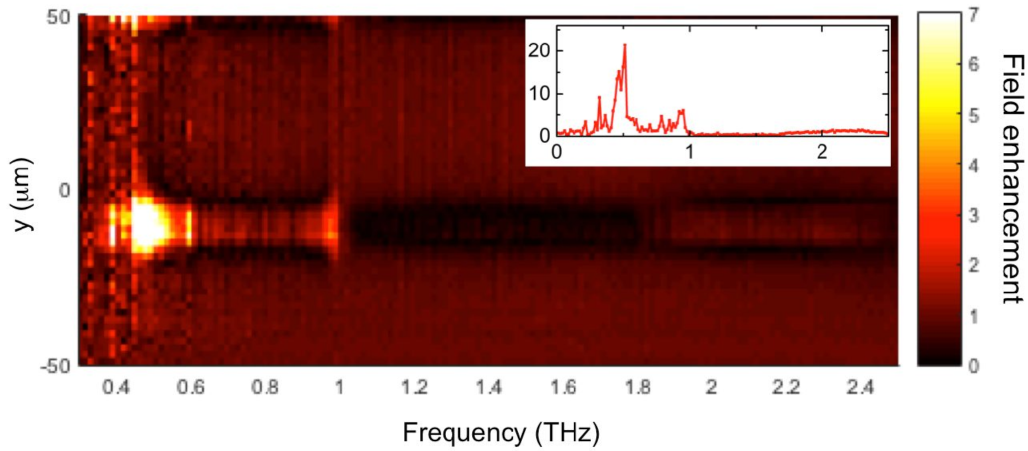

FIG 4: Fourier transform of the space-time map in Fig. 3 normalized to the spectrum of the incident field detected by the near-field probe for the substrate alone. The inset shows the normalized spectrum detected for the probe position at the center of the horizontal bar.

To identify the nature of these resonances, we recorded temporal evolution of the field along the resonator bar as shown in the inset of Fig. 5. The wave pattern is significantly disturbed in comparison to the incident field. After the incident pulse passes (t>3 ps), we observed a regular symmetric pattern [Fig. 5]

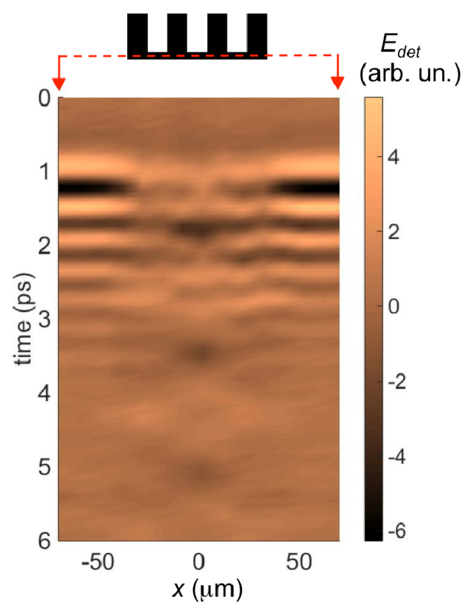

FIG 5: Space-time map of the field detected by the near-field probe along the x-axis, along the hirizontal bar.

4. RESONATOR MODE ANALYSIS

To analyze the field pattern in Fig. 5, we performed Fourier transforms of each waveform in the map. Figure 6 displays the amplitude and phase spectra of the field along the horizontal bar at the frequency bands corresponding to the spectral peaks, 0.5 and 1 THz.

We find that the amplitude and phase patterns in the region of 0.5 THz don't display strong variation along the bar, whereas the patterns show distinctive structure at 1 THz. There are three peaks in the field distribution around 1 THz compared to a uniform distribution of the field at 0.5 THz. Furthermore the relative phase alternates between $-\pi/2$ to $\pi/2$ for the field at 1 THz, whereas the phase remains constant along the bar at 0.5 THz. We therefore conclude that the two modes observed in the Fourier spectra [Fig. 4] correspond to the $\lambda/2$ and $3/2\lambda$ modes [13].

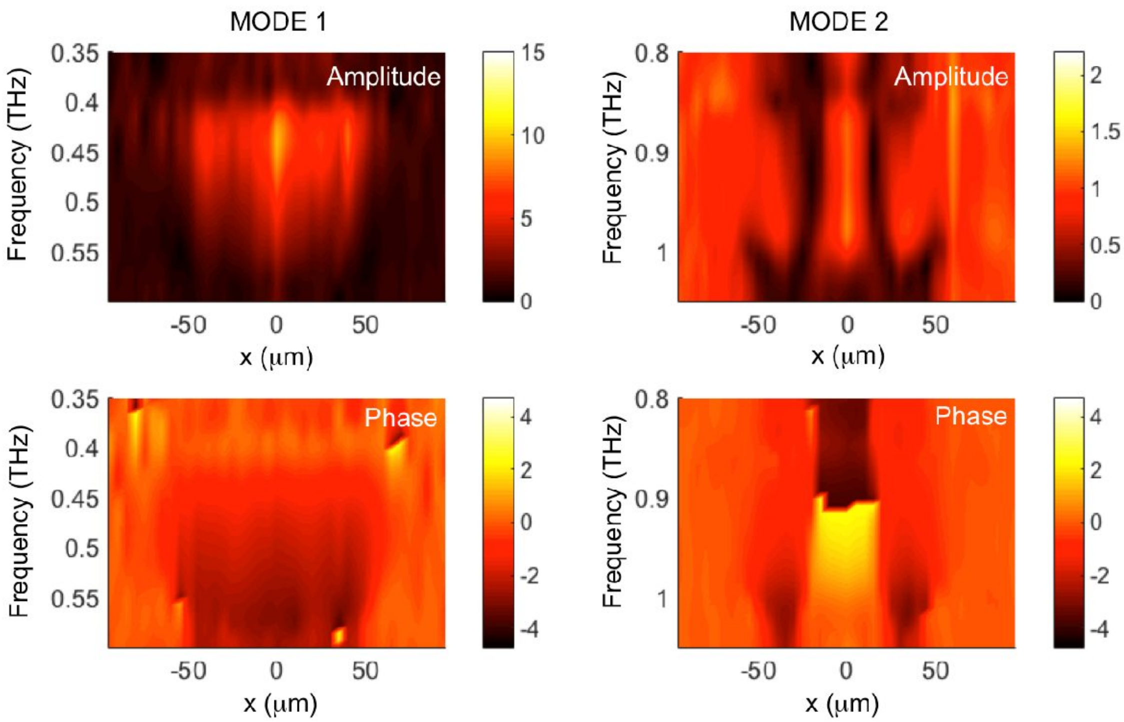

FIG 6: Spectral amplitude (top row) and phase maps (bottom row) recordeed along the resonator horizontal bar for two frequency bands: 0.35-0.60 THz (left) and 0.8-1.05 THz (right).

5. SUMMARY AND CONCLUSIONS

In the context of application of this THz near-field microscopy approach for light-matter coupling investigations the results presented here allow us to make two important points: (1) aperture-type THz near-field microscopy enables detection of the THz field inside the double-metal resonator; and (2) THz light-matter interactions can be studied in a sub-wavelength volume avoiding inhomogeneous broadening or inter-resonator coupling occurring in arrays of resonators.

In conclusion, we demonstrate an experimental method for spatial mapping and spectroscopic analysis of the internal resonant THz fields in plasmonic double-metal THz resonators. Combined with the THz time-domain spectroscopy technique, the method opens doors to spectroscopic studies of strong light-matter coupling in deep sub-wavelength volumes in at THz frequencies.

6. ACKNOWLEDGEMENTS

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