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Transmission and Reflection Properties of Terahertz Fractal Metamaterials

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Abstract: We use THz time-domain spectroscopy to investigate transmission and reflection properties of metallic fractal metamaterial structures. We observe loss of free-space energy at certain resonance frequencies, indicating excitation of surface modes of the metamaterial.

OCIS codes: (160.3918) Metamaterials; (300.6495) Spectroscopy, terahertz; (310.6628) Subwavelength structures, nanostructures

1. Introduction

Metamaterials (MTMs) are currently considered for extensive broadening of the functionalities of photonic components, for example in control over light polarization [1]. A tricky problem at THz frequencies is that no so many good designs have been proposed for polarization devices. We believe that planar fractal MTMs could be good generic candidates for the THz range, assuming relevant scaling of geometrical sizes. Such structures have been characterized previously [2,3], however, only in transmission. To gain further insight into the MTMs properties the transmission spectra (both amplitude and phase) should be complemented with the corresponding reflection data, for instance as it was done theoretically in the microwave region [4]. Here we report on fabrication and comprehensive characterization of a THz fractal MTM that show resonant transmission and reflection at certain frequencies within the 0.4 – 1.2 THz range. A clear polarisation-dependent behaviour is monitored, and a region with enhanced losses at 1.05 THz is identified. Such losses are possibly associated with the coupling to surface modes.

2. Fabrication

The structures (Fig 1. left) were fabricated on a high-resistivity (>10 kΩ/cm) Si substrate. The substrate was coated with a 50 nm thin Au layer and then, using optical lithography, the structures were defined in polymer. The next process step involved electrochemical growth of 4 μm of Ni and selective removal of the Au layer. The structures were afterwards removed from the substrate, thus obtaining free-standing metal films which are easier to characterise due to the lack of losses and Fabry-Perot resonances.

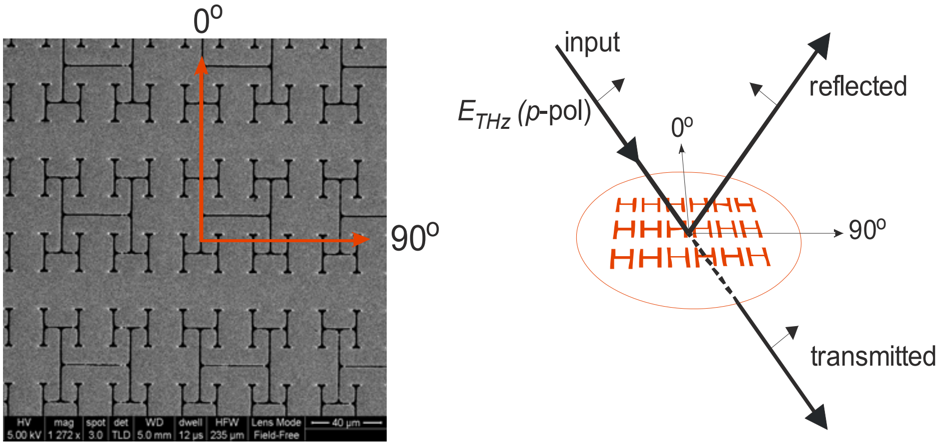

Fig. 1: (left) Microphotograph of the sample structure and (right) experimental geometry for the measurements, indicating the p-polarization of the THz light and the rotation angle of the reflection plane with respect to the structure.

3. Measurements

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Transmission and reflection measurements were carried out with a standard THz time-domain spectroscopy (THz-TDS) system [5]. The sample geometry and the excitation angles are shown in Fig. 1. In the transmission experiments the THz light was incident on the sample at an angle of 20°, with identical transmission coefficient measured at normal incidence, indicating little influence of the transmission properties on the incidence angle. In reflection the incidence angle was fixed at 30 degrees by the experimental setup. We performed measurements at two different rotations of the sample with respect to the reflection plane – 0° and 90° as indicated in Fig. 1. In the transmission experiments the reference signal was recorded through an empty aperture, and in the reflection measurements, the reference signal was recorded with a plane, unstructured metal surface with a reflection coefficient of -1. The amplitude of the measured reflection coefficient was difficult to measure in absolute terms due to slight variations of the surface profile of the sample. However, we estimate the uncertainty on the reflection amplitude to be approximately 10%. Figure 2(a) shows the measured transmission amplitude and phase, and Fig. 2(b) shows the corresponding reflection amplitude and phase. At 0° rotation of the sample we observe a transmission peak at 0.55 THz, and at 90° rotation a slightly broader transmission peak at 1.0 THz. Both these resonances are also seen as pronounced dips in the reflection spectra. At each resonance we observe a characteristic phase jump of π radians of the transmission spectra. And a smaller phase jump in the reflected signal.
The geometric air fraction of the surface is approximately 5%. The structuring of the surface thus allows a significantly enhanced (up to 16x) transmission at the resonances.
Interestingly, we observe a deep minimum (t = 0.3%) in the transmission amplitude and a marked π phase jump at 1.05 THz through the sample at 0° rotation. The minimum of the transmission amplitude is not accompanied as usual by an increase in the reflection coefficient, thus clearly indicating that energy is absorbed to excite a surface mode at this particular frequency. Further experiments, e.g. Attenuated Total Reflection (ATR) measurements, are being performed to support this conclusion.

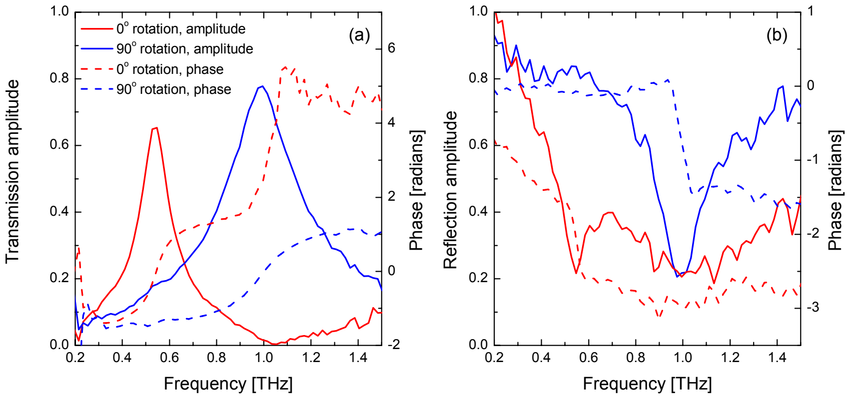

Fig. 2: (a) Transmission and (b) reflection coefficients (solid curves: amplitude, dashed curves: phase) with results for 0° rotation of the sample shown in red and 90° rotation shown in blue.

4. Conclusions

We have characterized the transmission and reflection properties of a 4-μm thick free-standing metal film with a fractal metamaterial hole structure. For orthogonal incidence rotations the transmission is strongly enhanced near the frequencies of the first resonant currents in the fractal structure, in agreement with simulation results. In addition to the enhanced transmission, we observe a marked energy loss at a specific frequency for one of the sample orientations, indicating that energy is coupled with high efficiency from the free-space mode of the THz field to the structured surface.

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