Terahertz metamaterial consisting of three-dimensional microcoils

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Abstract

In this paper we present a metamaterial consisting of 3D submillimeter-sized coils fabricated with an automated wire-bonder. The response of the structure is characterized by terahertz (THz) time-domain spectroscopy and numerical simulations. Depending on the light polarization fundamental and higher order electric or magnetic resonances can be excited. As a first step towards active tunability of the metamaterial, we demonstrate tuning of the q-factor and resonance frequency by variation of the winding pitch of the coils.

1. Introduction

Due to the technical difficulties of fabricating microscopic three-dimensional (3D) structures, in particular, for applications in the submillimeter regime, the vast majority of metamaterials consist of planar structures with only a few exceptions. Using such planar fabrication, three-dimensionality is typically created by either stacking multiple layers or by tilting two-dimensional structures out of plane. Here we report the implementation and characterization of arrays of truly three-dimensional microresonators, as shown in Fig. 1 (a), as metamaterial for the gigahertz to terahertz regime.

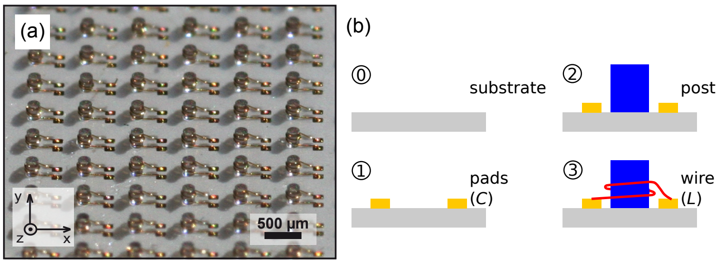

Fig. 1: (a) Microscope image of a THz metamaterial consisting of 3D microcoils. Individual structures are arranged with 700 μm periodicity. (b) Schematic of the manufacturing process. After gold pad patterning, thick SU-8 lithography is used to form the posts and the coils were made by wire bonding.

2. Fabrication

Using an automated wire-bonder a thin wire is contacted to gold pads defined on a substrate, and wound around posts of photoresist . Figure 1 (b) shows a schematic of the fabrication process [1, 2]. In a first step, a Cr/Au layer with 50/500 nm thickness was sputtered onto a glass substrate and structured with standard lithography to define pads of 100 x 150 μm. Subsequently, posts were formed by high aspect ratio SU-8 processing with UV-lithography. The posts had a diameter of 200 μm and were arranged with 700 μm periodicity in both, x- and y-direction. In the final step, starting from the gold pads, an automatic wire bonder wrapped insulated gold wire with a diameter of 25 μm around the posts. This is accomplished by modifying the wire bonder's typical 2D trajectory to a 3D motion around the pillars, whereby the wire gets plastically deformed to the shape of the post. Each coil took about 200 ms to fabricate resulting in a total bonding bond time of about 20 s for an array of 10 x 10 coils.

3. Experiment and Simulation

Conventional THz time-domain spectroscopy is used to experimentally characterize transmission through the fabricated metamaterial array under normal incidence. Complementary simulations are performed by finite element modeling using COMSOL Multiphysics. In the model an individual microcoil is positioned in a 3D simulation volume as shown in the inset to Fig. 2. A terahertz pulse is excited on one boundary and scattering boundary conditions are imposed on the remaining sides.

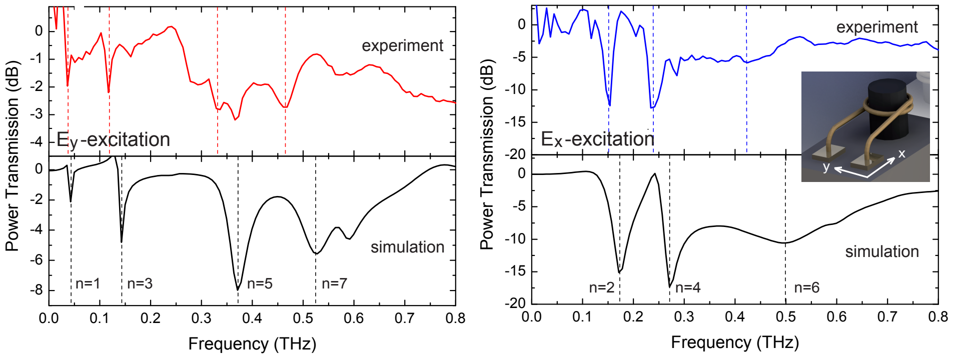

Fig. 2: Measured and simulated transmission spectra for different excitation conditions of the microcoil array shown in Fig. 1. The fundamental resonance (n = 1) and higher order harmonic modes are indicated by vertical dashed lines.

Figure 2 shows measured and simulated THz transmission spectra through the microcoil array for different excitation conditions. Measurements were made with the sample plane normal to the beam for two orthogonal polarizations of the electric field relative to the structures, allowing to excite different resonances, which appear as characteristic transmission minima in the spectra. In both cases, excitation occurs via electric polarization of the structure, either across the gap between the bond pads (Fig 2, left), or along the two parallel wire arms (Fig 2, right). Figure 3 shows snapshots of the simulated electric current vectors for the three lowest order resonances. The color indicates clockwise (blue) or anti-clockwise (red) current flow and the illustration under each plot sketches the corresponding current density standing wave pattern forming along the unwound wire. Depending on the incident field polarization, only modes with either odd or even number of nodes are excited. Odd modes are associated with circulating currents in the ring, resulting in strong magnetic moments, whereas for even modes counter-propagating currents in the coil interfere destructively, so that only an electric dipole is formed along the wire ends [3]. An interesting feature is the transparency peak between the n=2 and n=4 eigenmode, which corresponds to a trapped mode resonance in the coil [4].

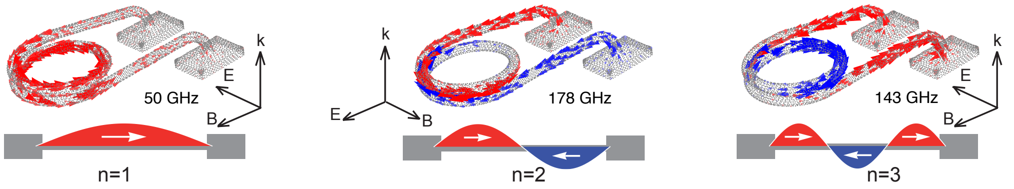

Fig. 3: Simulated current densities in the coils at their three lowest order resonances. The incident field polarization is indicated. The schematic illustration under each plot represents the current density standing waves forming along the unfolded wire.

4. Tuning of resonances

Figure 4 shows a simulation of the transmission spectra for E$_x$-excitation of the metamaterial with varying coil pitch (50-200 μm). We find that both, the q-factor and the central frequency of the transparency peak (trapped mode) are strongly dependent on the pitch. Hence, controlling the pitch, e.g. by mechanical compression, would provide a possibility to actively tune the metamaterial.

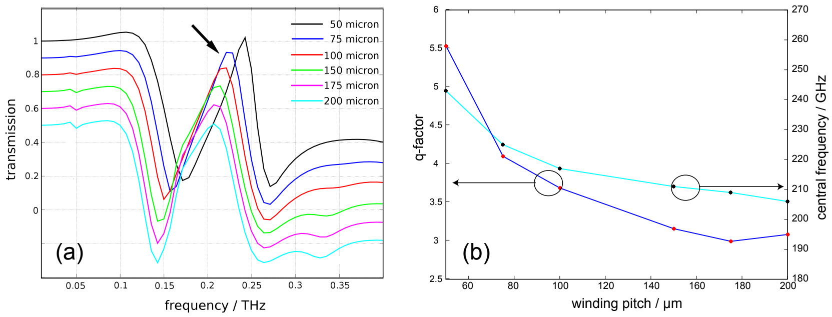

Fig. 4: (a) Simulated transmission spectra for variable coil pitch. (b) Tuning of q-factor and central frequency of the transparency peak (arrow in (a))

5. Conclusion

Automated wire-bonding is used to fabricate terahertz metamaterials consisting of micrometer-sized 3D microcoils, showing electric and magnetic response. The fabrication method provides free control over geometrical parameters such as number, pitch and handedness of the windings. By variation of the winding pitch spectral tunability of the metamaterial is demonstrated.

References

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