Effect of coupling between stacked resonators of an inkjet-printed THz metamaterial

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Abstract

Double and multi-layer metamaterials consisting of stacked, L-shaped resonators have been fabricated by ink-jet printing of silver nanoparticle ink onto the opposite sides of dielectric substrates. Using THz time-domain spectroscopy and numerical simulations the effect of coupling between the stacked structures is investigated.

1. Introduction

Optical metamaterials promise useful applications in sensing, imaging, focusing etc. Many applications require a bulk metamaterial that extends in all three dimensions rather than just a single monolayer of planar metamaterial structures. Due to the technical challenges associated with fabricating truly three-dimensional (3D) microscopic features [1] the vast majority of bulk metamaterials are made by stacking 2D layers. Since the resulting effective material properties depend strongly on mutual arrangement and spacing between the resonant structures, controlling these parameters is of great importance during the fabrication process. Recently, we have demonstrated inkjet-printing of metallic ink as a viable route for producing 2D metamaterial layers with a resonant response at GHz to THz frequencies, which has the advantages of being a fast, flexible, and low-cost alternative to conventional microfabrication techniques [2]. Here, we report the implementation and characterization of inkjet-printed 2D metamaterials consisting of stacked L-shaped micro-resonators. Printing the structures on opposite sides of a flexible dielectric substrate (polyimide, Kapton) of well-defined thickness provides a convenient method for fabricating mechanically flexible metamaterial double layers consisting of well aligned, stacked structures. Stacking these double layers results in a bulk metamaterial with optical properties resulting from the resonant response of the individual structures and from the coupling between the stacked resonators. THz time-domain spectroscopy and FEM-based simulations are used to characterize these and analyze the effect of coupling between resonators in the stacked metamaterials.

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2. Discussion

Periodic arrangements of L-shaped resonators (250 µm side length) have been printed on opposite sides of an optically transparent polyimide substrate. After one layer has been printed, the substrate is flipped and placed in the printer again in order to print the second layer. Alignment is controlled through an optical microscope which was attached to the printhead before the second layer is printed. Fig. 1 sketches a resulting metamaterial structure and the polarisation of the incident THz-electric field. Fig 2. shows a magnified section of an inkjet-printed metamaterial sample. Measured and simulated THz transmission through one pair of L-shaped resonators separated by a 25 µm thick substrate (blue curve) and 125 µm thick substrate (red curve) are shown in Fig. 3. Fig. 4 shows the measured and simulated THz transmission of two stacked pairs of L-shaped resonators separated by a 25 µm spacer (blue curve) and a 125 µm spacer (red curve). The single pairs themselves are separated by a 25 µm thick substrate. The transmission spectra in Fig. 3 show a blue-shift of the low-frequency resonance when the distance between the single L-shaped resonators is decreased. In addition the transmission peak between the two resonances gets narrow and even more transmissive. The transmission spectra shown in Fig. 4 shows a frequency shift as well as a decrease in transmission at the first resonance when the distance between the two pairs of resonators is increased. When increasing the distance between the two resonator pairs both resonances show a an additional splitting as a result of coupling between the resonator pairs.

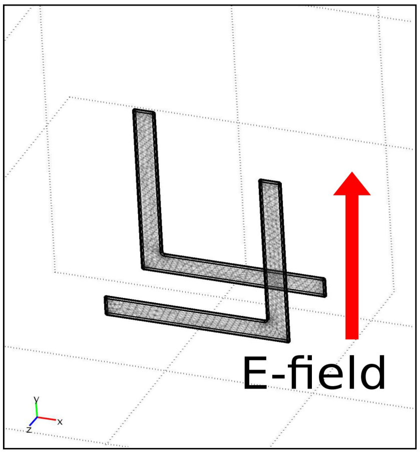

Figure 1: Unit cell geometry and polarisation of incident THz field

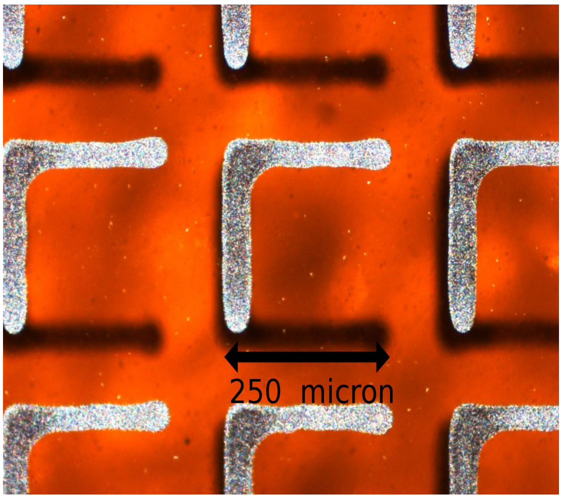

Figure 2: Inkjet-printed metamaterial sample consisting of stacked L-shaped resonators

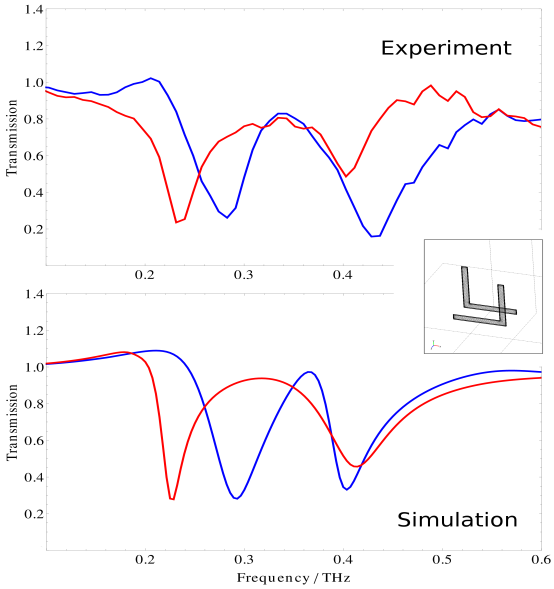

Figure 3: Transmission of metamaterial consisting of a single resonator pair

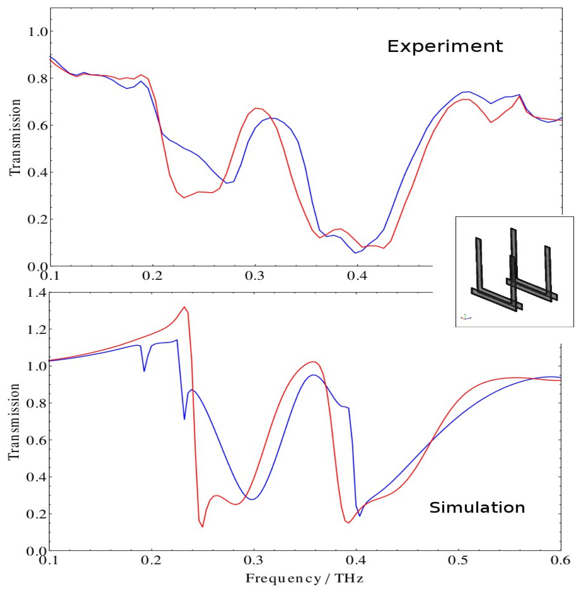

Figure 4: Transmission of metamaterial consisting of two stacked resonator pairs

All transmission spectra are dominated by the two fundamental resonances of the single L-resonators. When the separation between the structures is decreased, the resonant modes shift significantly, as a result of increased coupling (Fig. 3). Remarkably, the transmission peak between the two modes approach each other. As we will show this feature corresponds to a trapped mode resonance with counteroscillating currents in the facing arms. In two stacked double layers (Fig. 4) inter-layer-coupling leads to additional splitting of the fundamental modes. Based on experiment and simulation a detailed discussion of coupling between the structures will be given. All the mentioned features can be explained considering the contribution of the surface currents on the resonators to the electromagnetic far-field

3. Conclusion

We have fabricated THz metamaterials consisting of two and multiple layers of stacked L-shaped resonators. The structures have been fabricated by printing silver containing ink onto opposite sides of a dielectric substrate, which represents a fast, flexible and low-cost alternative to conventional microfabrication. Coupling between the stacked resonators leads to modifications in their transmission spectra such as frequency shifts, line narrowing and band splitting. As demonstrated these effects can be controlled by changing the separation between the structures, enabling tuning of the spectra.

Note that the transmission above 1 in the simulated spectra in Fig. 4 is still under investigation and likely due to a numerical artefact. If the reason for it will be found before the conference, the correct spectra will be shown instead.

References

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