Passive THz metamaterials

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Abstract

In this work we present our activities in the fabrication and characterization of passive THz metamaterials. We use two fabrication processes to develop metamaterials either as free-standing metallic membranes or patterned metallic multi-layers on the substrates to achieve different functionalities. Our interest lies in metamaterials for a broad spectrum of linear properties in operations with THz waves, such as linear and circular polarizers, absorbers and devices with enhanced transmittivity, single layer dichroic and chiral systems. All the three steps (modelling, fabrication and characterization) will be discussed during the talk.

1. Introduction

Metamaterials (MTMs) have demonstrated a broad range of useful properties from light traps for thin-film solar cells in photovoltaics [1], to THz lasing in active metasurfaces based on plasmonic graphene structures [2], nanosensing of bacteria by field-enhanced fluorescence in plasmonics metasurfaces [3] and coherent 2nd harmonic generation in bulk metamaterials [4].

The main advantage of the metamaterial-based devices is the possibility to broaden photonic component functionalities, e.g. in polarisation control or spatial filtering [5]. While in the visible or near infrared regime these issues can in principle be solved with a conventional approach, the problem of polarization control does not have an easy solution at THz frequencies. Several approaches for using MTMs in the THz range have been proposed and show good potential for applications [6, 7]. In the article we present our efforts in exploiting the metamaterials properties in this frequency range.

2. Fabrication possibilities

We utilize mostly two fabrication procedures for THz metamaterials. The first one is developed for fabricating thin metallic large-area membranes suspended in air. Due to the THz beam spot size, our membranes had to be at least 1x1 cm in area. The thickness of these membranes is 2μm, making them rather fragile and thus extra care when handling them had to be taken. In Fig. 2.1 the main process steps are shown.

Firstly, a Si wafer was covered on the back side with a 1μm thick Si_3N_4. Then, a first UV exposure followed by the wet etching of the Si_3N_4 layer was made in order to define the membrane positions. Secondly, a 50 nm layer of gold on top of a 5 nm Ti layer was deposited on the front side. The obtained bi-metal layer is needed for subsequent electrochemical growth. The third step consists of deposition and UV expose of a 6µm-thick photoresist. Since the resolution of the structure is 1 µm pushing the aspect ratio of the polymer structures to 1:6, careful fine-tuning of the exposure parameters is needed. After the exposure of the photoresist we electrochemically grow 2 µm of Ni. The remaining photoresist is then dissolved in ultrasonic acetone bath and the excess Au/Ti is selectively removed in commercial baths. The last technological step in the fabrication consists in wet back etching of the Si wafer, leaving the free-standing membranes suspended across the aperture. In Fig. 2.2a,b examples of scanning electron microscope images of obtained structures are shown.

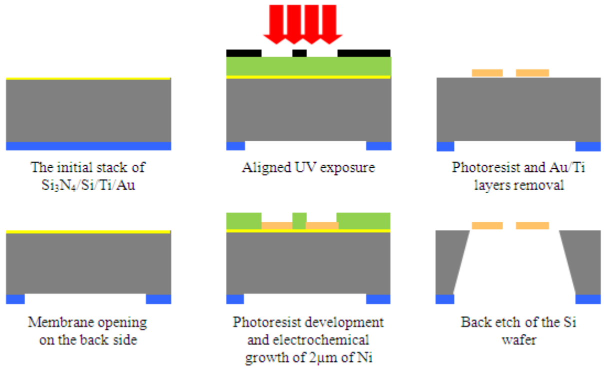

Fig. 2.1: Schematics of the process flow for obtaining the metamaterials membranes.

Another fabrication process is aimed at obtaining multi-level metamaterials. In this case, several aligned exposures increase the complexity of the fabrication process (Fig.2.2c,d). Details about fabrication process will be addressed during the presentation.

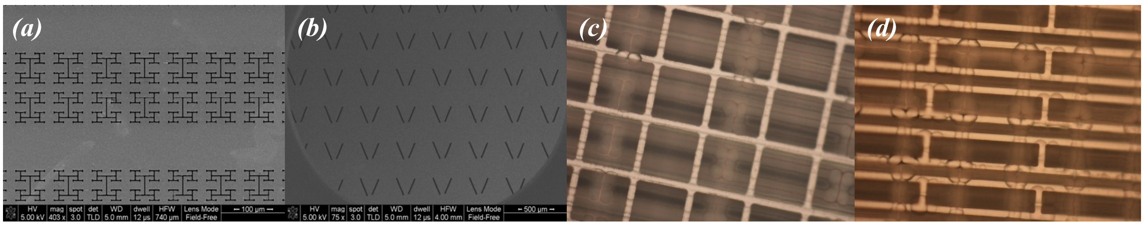

Fig. 2.2: SEM images of the obtained structures. (a) Overview of the periodic array of fractals; the total sample area was 1x1 cm; (b) V-shaped structures fabricated using the same process steps. In both figures, the grey areas represent the Ni while the black areas are the air slits. (c) The second and (d) third metallic layers of a three-layered structure. The shadows of the layers beneath can be observed in (c) and (d) images

3. Optical characterization techniques and results

We use terahertz time-domain spectroscopy (THz-TDS), which employs the air plasma generation of ultrashort THz transients [8, 9] in combination with air biased coherent detection of the THz transients [10]. Both the generation and detection processes are based on the four-wave mixing in air. With air as the nonlinear medium the phase matching conditions are matched over an extremely broad bandwidth range, and therefore the bandwidth of the generation and detection processes is in practice limited only by the laser bandwidth. We use a transform-limited 35-fs laser pulse, resulting in THz transients with a spectral coverage from 1 to 40 THz and THz pulse duration of less than 50 fs. In combination with a standard THz-TDS system based on photoconductive switches covering the low THz range we can perform quantitative THz-TDS on absorptive materials in the 0.05-20 THz range [11].

Results of normal-incidence transmission measurements on fractal membranes are summarized in Fig. 3.1a. The polarization of the beam was varied from E//x (black line) to E//y (yellow/light grey line). We observe distinct resonances in the transmission amplitude and the antiresonance behaviour between them. At 45^0 polarization all three resonances are visible in the transmission spectrum (blue/grey line).

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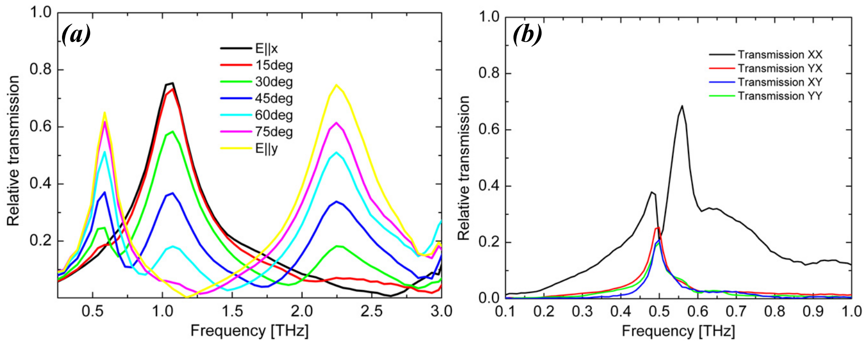

Fig. 3.1: (a) Measured normal incidence transmission amplitude of the fractal membrane. The polarization is gradually changed from E//x (black line) to E//y (yellow line). (b) Relative transmission of the V-shape metamaterial, with sample orientations relative to the incident electromagnetic field polarization 0° (XX, black) and 90° (YX, red) for parallel-aligned polarizers and 0° (XY, black) and 90° (YY, red) for cross-aligned polarizers.

Results of transmission of the V-shaped particles (Fig.2.2b) in parallel and crossed polarizers are given in Fig.3.1b. The single-layer system exhibit a strong interplay of anisotropy, dichroism and chirality. Results of characterization have excellent quantitative correspondence with modelling performed with the FDTD method. Full picture of metamaterials properties will be given in the lecture.

4. Conclusion

We fabricate and characterize metamaterials with designs that exhibit pronounced features in the THz range. Among the observed effects are: strong polarization filtering, chiral and dichroic properties achieved in a single layer metamaterial, enhanced optical transmission and others. Experimental spectra show excellent agreement with the theoretical results.

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