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Angle-Susceptible Sensing Metasurface in Terahertz Regime

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Introduction

Nowadays thin-film coatings and structures are widely used in advanced industrial and scientific applications that makes the tasks of thin-film sensing highly demanded in practice. Last decade, stimulated by progress in terahertz (THz) instrumentation, a keen interest has been attracted to the THz spectral range to develop its potential for detecting and measuring properties of thin films. The THz radiation can be an alternative to visible and IR waves when examining optically opaque coatings. Meanwhile, due to a relatively large wavelength λ, the conventional spectroscopic methods (TDS-, FDS-, FTIR-, BWO-based) are ill-suited for direct characterization of films with the thickness d of about 2–4 orders of magnitude smaller than λ. This problem can be solved with metamaterials, in particular, with plasmonic metasurfaces (PMSs) [1–5]. The plasmonic resonance exhibits a high sensitivity of its spectral response to the dielectric environment due to a strong field localization what makes possible measuring of analyte layers satisfying $d \ll \lambda$ condition.

The traditional approach of THz thin-film sensing with PMSs is based on detecting a frequency shift of the resonance when the analyte is deposited onto the PMS. In this work, we present the idea to substitute THz spectral measurements for tracking the PMS response at a fixed wavelength upon changing the incidence angle θ of the exciting THz beam. This concept works well for the PMS with a narrowband resonance sensitive to θ.

The results of the numerical investigations and experimental study of such PMS designed as a single-layer array of hexagon-shaped annular slots (Fig. 1) with angle-susceptible resonant transmission near 0.85 THz are presented.

Metasurface design

Originally, the proposed PMS was intended for band-pass filtering applications in experiments on studying sub-THz emission from hot dense plasma during relativistic electron beam-plasma interaction [6, 7]. The listed PMS dimensions provide a resonant pass band centered at 0.5 THz with the relative bandwidth of 63%. Later, when inspecting the angular performance of the PMS of this kind, a higher-frequency "spurious" narrow-band resonance susceptible to the angle of incidence was revealed in the vicinity of 0.8–0.9 THz. A detailed study of this resonance for the purpose of its applicability to thin-film sensing became the essence of the current work.

To pattern the PMS, we employed a contact photolithography technique [8, 9] which was specifically adapted to flexible solid film substrates, such as PP, whose industrial production does not allow obtaining a liquid material suitable for posterior film deposition via spin coating.

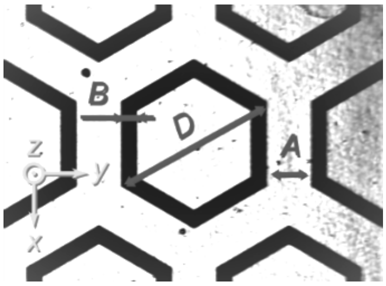

Fig. 1. Reflection-mode microphotograph of the fabricated plasmonic metasurface. The metallic area is light-colored. The slots are patterned in a 0.35 μm thick aluminum layer deposited on a 15 μm thick polypropylene film. D = 220 μm, B = 20 μm, A = 20 μm. The coordinate system *xyz* is introduced to show the structure orientation relative to the incident wave vector $k = (k{\cdot}\sin\theta{\cdot}\cos\phi,\ k{\cdot}\sin\theta{\cdot}\sin\phi,\ k{\cdot}\cos\theta)$.

Experimental setup

The transmission spectra of the designed metasurface were measured on a custom-made THz time-domain spectrometer (TDS) described in Refs. [10, 11]. The PMS prototype under study was mounted on a manually controlled rotary stage capable of tilting the prototype both in TE and TM planes. The measurements were carried out by varying the incidence angle θ of the probing THz beam within 0°–55° with 5° incremental step. The THz-TDS signals were acquired with the time resolution of 125 fs in the range of 100 ps. This corresponds to the resolution of ~10 GHz in the frequency spectrum. The transmission was calculated as the ratio of the Fourier-transform spectra for the time-domain signals registered with and without the PMS prototype. The resulting experimental spectra were averaged over four independent measurements.

Results

Fig. 2 illustrates the typical spectral behavior of the angle-susceptible PMS resonance for different thicknesses d of the analyte overlayer plotted at a fixed angle of incidence θ. A photoresistive material was used as the analyte, whose dielectric permittivity $\varepsilon = 2.7 - j{\cdot}0.25$ was retrieved from direct transmission measurements of a 100 μm thick liquid cell.

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To elucidate the idea of replacing THz spectral measurements by tracking the PMS response at a fixed λ upon changing the incidence angle θ, the PMS transmittance as a function of θ is plotted in Fig. 3. The latter corresponds to the frequency of 830 GHz chosen as an example.

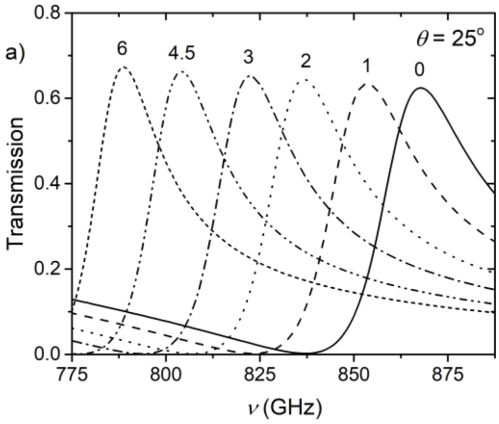

Fig. 2. Transmission spectra for the PMS covered with the analyte of different thicknesses d simulated at θ=25º.

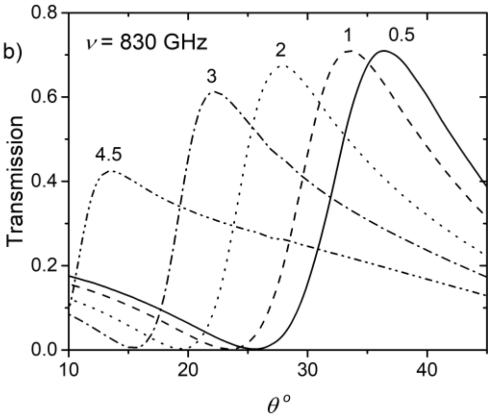

Fig. 3. PMS transmission at 830 GHz as the function of the incident angle θ modelled for different thicknesses d of the analyte overlayer. The numbers indicate the values of d in micrometers.

The presented data remarkably demonstrate the expected effect of shifting the angular peak due to thickening the analyte. Note, the resonance peak amplitude decreases and its bandwidth increases when the analyte thickness d changes from 0.5 to 4.5 μm. This means that the method sensitivity degrades for the thicknesses larger than 4.5 μm. Nevertheless, the peak remains almost stable in amplitude for the thicknesses $d < 1$ μm and the angles of both maximum and minimum transmission can be used to evaluate the analyte thickness. Thus, the proposed approach is estimated to be promising for THz sensing of sub-μm-thick analyte layers, thereby capable of detecting the level of $d/\lambda \sim 10^{-3}$ at least.

Acknowledgements

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