Comparison of angular-selective metasurfaces as tools for sub-THz single-frequency sensing

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Abstract. We demonstrate and numerically characterize a set of single-layer metasurfaces based on capacitively-coupled bent metal strips deposited on a thin polypropylene film operating as band-stop filters at 139.1 GHz. Due to a high inter-digital coupling capacitance between neighboring inclusions formed by the strips, the resonance of the metasurface becomes highly sensitive to the incidence angle of a plane wave. At the same time, a narrow-band resonance is achieved by reducing the conductor length along the vertical polarization direction of the incident wave. We propose to use both properties for designing a sensor, which analyses the thickness of a thin slab of a known substance deposited over the structure by tracking the angle at which the minimum of transmission can be measured at a single frequency. We compare three versions of the proposed geometry by numerical calculation of the transmission coefficient depending on both the incidence angle and analyte slab's thickness. We select the most suitable structure for sensing.

1. Introduction

The sub-terahertz range starting from 100 GHz enables many important applications including astronomy, security, and spectroscopy [1]. Due to the possibility of relatively strong interaction between non-ionizing sub-THz waves and thin material slabs, spectroscopy is particularly useful for label-free sensing of various substances and biological samples [2]. However, the strong interaction of sub-THz waves with materials slabs is impossible to reach when the thickness is small compared to the wavelength, i.e. for micron-thick or even thinner slabs.

Recently, to improve sensing capabilities of thin films it was proposed to use metasurfaces, the two-dimensional and typically resonant periodic structures with subwavelength periodicity. Unit cells of such structures consist of resonant inclusions that under illumination with plane waves produce tiny electric-field hotspots with dimensions much smaller than the wavelength. Due to this resonant field confinement, metasurfaces provide a high sensitivity of films with deep-subwavelength thicknesses [3, 2]. The presence of an analyzed substance (analyte) slab deposited on a metasurface typically shifts the resonant frequency that can be detected using spectroscopy techniques. Based on this principle, many configurations of sub-THz and THz metasurfaces have been proposed for thin-film sensing (see e.g. in [4, 5, 6, 7]). A recent review of the topic is available in [8].
Conventional THz thin-film sensors based on resonant metasurfaces with high quality factor require spectroscopy quasi-optical setups being complex and expensive. In [9] a metasurface sensor with an alternative operational principle was proposed, in which an angular sensitivity of the metasurface properties is employed. The corresponding metasurface is designed so that the resonance frequency becomes dependent on the incidence angle. Also, it is sensitive to the presence of an analyte slab as for any metasurface sensor. Hence the thickness of the slab with a known permittivity can be measured by tracking the angle of incidence corresponding to the maximum/minimum of the transmission coefficient at a single operational frequency. The metasurface with a deposited analyte should be placed between a single-frequency source and detector and mechanically rotated. The main advantage of this technique concerning others is that it doesn’t require expensive equipment such as a table-top spectrometer to measure the thickness of thin layers.

In this work, we propose and study a new set of metasurfaces for single-frequency thin-film sensing at 139.1 GHz having pronounced angular dependence of the stop-band resonance. This frequency corresponds to a commercial IMPATT-diode-based monochromatic radiation source from Terasense Group Inc., USA.

To increase angular sensitivity of the resonance we develop the idea of using chains of interconnected high-quality-factor resonators [10]. We propose and compare three single-layer metal patterns with a new shape of the subwavelength resonators implemented as bend capacitively-coupled metal strips and select one of them to be the most suitable for sensing films with thicknesses of less than 2 µm.

2. Metasurface design and characterization
Each of the three proposed unit cells consists of meandered strips etched in a single aluminum-based layer, which is placed on top of a polypropylene (PP) thin film with a thickness of 30 µm and a relative permittivity of 2.25. The aluminum layer has a conductivity of 1.5·10^7 S/m with a thickness of 0.4 µm.

The unit cells of three proposed structures are depicted in Fig. 1. Structure (a) is a starting one. It consists of two S-shaped bent metal strips. Each one has a vertical part in the middle, which is assumed to be parallel to the polarization direction of the incident wave. There are also relatively long horizontal parts responsible for making the unit cell resonant and for the strong capacitive coupling to similar shapes in neighboring unit cells. Differences in the metalization strips number of studied designs are justified by the fact that we must suggest the design which has the narrow-band resonance at the operation frequency and high aperture efficiency simultaneously to achieve the required performance. One of the adjusted parameters is the distance between the top and bottom trains. It was chosen for each design separately to provide a resonance behavior on an operating frequency of 139.5 GHz. The metasurfaces belong to the class of band-stop frequency-selective surfaces where high capacitive coupling between unit cells increases the sensitivity of the resonance frequency to the angle of incidence [10]. The width of all strips as well as the width of gaps between them was chosen to be 10 µm. The minimum possible value within the requirements of the presumed photolithographic manufacturing technology.

As shown by numerical simulations, the electric field is localized in the gaps between the capacitive horizontal strips. With the aim to enlarge the area covered by the electric-field hotspots two other structures were introduced. Structure (b) differs from (a) by having two parallel meandered strips in each S-shape. Structure (c) has ramified strips with further increased coupling capacitance. Note that to keep the resonant frequency at the normal incidence at the
same position of 139.1 GHz, all three structures have the same vertical periodicity of 340 µm, but different horizontal periodicity: 291, 200, and 250 µm for (a), (b) and (c), respectively.

All three structures were modeled and numerically analyzed with CST Microwave Studio 2020 (Frequency Domain Solver was used) by calculating transmission coefficients in the range of incidence angles. TE-polarization was kept with respect to the direction of vertical strips. The incidence angle is equivalent to the rotation angle of the metasurface in the proposed optical scheme of the sensor. The transmission properties were calculated for the analyte’s relative permittivity of 2.65 and the slab thickness varied from 0.4 to 1.6 µm. It was also observed in the numerical study that the presence of an imaginary part in the permittivity has no much effect on the efficiency of the sensor. Therefore, it was decided to consider the analytes with the real part of permittivity only.

Initially, each metasurface was tuned to have a minimum of the transmission coefficient at 139.1 GHz in the absence of the analyte for the normal incidence (rotation angle of zero degrees). As the analyte of a given thickness of 1 µm appears, the minimum can be observed at another incidence angle defined as Θ. Therefore the structure should be rotated by the same angle to recover the minimum of transmission between the source and detector at 139.1 GHz.

For each design, we introduce a set of parameters to compare: the required rotation angle Θ (for the analyte slab’s thickness of 1 µm), the width of the frequency stop band at the normal incidence in the presence of the analyte, and the angular accuracy (defined as the ratio of Θ to the half-width of the angular dependence of the transmission coefficient taken at the level of half maximum of spectrum characteristic). The calculated values of these parameters are summarized in Table 1. The angular accuracy is the most important parameter for our consideration. The higher the angular accuracy, the more precisely the properties of the analyte slab can be found by mechanical rotation because a small increment of thickness will lead to the abrupt increment of the required angle of rotation. The difference in angular accuracy for the proposed designs is illustrated in Fig. 2.

While the angle of rotation Θ is similar for all the structures and stays within the range of 24-30 deg, the angular width of the curves is very different. As can be seen, structure (c) is the most suitable for angular sensing since it provides the highest angular accuracy. Also, its value of Θ is slightly larger than for (a) and (b). In contrast, structure (b) has the minimum angular accuracy among the considered structures.

For two structures with low (b) and high (c) angular accuracy we investigated the dependence of the required rotation angle Θ on the deposited analyte slab’s thickness. The results are presented in Fig. 3. As can be seen, the two curves are almost similar, so the range of mechanical rotation for the sensors based on metasurfaces (b) and (c) is the same.

Next, we estimated how technical fabrication features could affect the parameters of the selected designs. The minimum width of the metal strips is 10 µm, while the tolerance of the presumed technological procedure is about 1 µm. This was found to have almost no effect on the parameters. Due to the strong miniaturization of unit cells, dissipative losses take place around the resonance frequency (mostly conductive losses in the aluminum strips).
Figure 2. Angular dependence of transmission coefficient magnitude at 139.1 GHz for three proposed metasurfaces with a deposited 1-µm-thick analyte slab. Dashed lines indicate the levels at which angular accuracies calculated.

Table 1. Comparison of parameters of three suggested designs.

| Parameter/Design                  | (a) | (b) | (c) |
|-----------------------------------|-----|-----|-----|
| Stop-band width, GHz              | 2.49| 3.96| 1.79|
| Rotation angle Θ, deg, (for 1-µm analyte) | 26  | 26  | 31  |
| Angular accuracy                  | 7.4 | 4.3 | 8.8 |

Therefore, for structures (b) and (c) we investigated the effect of the conductivity deviation from the nominal value of 1.5·10⁷ S/m. Thus during the metal deposition and consequent photolithography procedure, the conductivity may drop to 7.5·10⁶ S/m. Fig. 4 shows the spectra of the transmission coefficients with the nominal and reduced conductivity for structures (b) and (c). The results are shown for the normal incidence in the presence of a 1-µm-thick analyte slab. It can be checked that the conductance deviation also has a little effect on the metasurface properties. Indeed, for the transmission coefficient minimum, a frequency shift of fewer than 450 MHz for both structures is observed.

3. Conclusions
In this work, we proposed and numerically compared three versions of an angular-sensitive resonant metasurface operating in the transmit regime at 139.1 GHz. It was shown that the version with the shape having ramified strips with increased capacitive coupling with neighboring unit cells (structure (c)) had the most sensitive resonance to the angle of incidence. This property results in the highest accuracy of determination of the analyte slab’s thickness of the sensor based on this metasurface. In particular, for the analyte’s relative permittivity of 2.65, the sensor covers the range of thicknesses from 0.4 to 1.6 µm with the required mechanical rotation by the angle from 15 to 35 degrees. At the same time, the angular accuracy was found to be
Figure 3. Dependence of the required rotation angle Θ on the analyte slab’s thickness for metasurfaces (b) and (c).

around 2 degrees, i.e. better than 0.1 µm for the accuracy of thickness measurement.

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