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THz Tripod Metasurfaces for Sensing Applications: From the Basic, to More Elaborated Designs

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***Abstract* – In this work, we propose, design, and evaluate three types of : three types of metasurfaces using tripod-shaped unit cells when working as thin-film sensing devices. The three meta-atoms of the proposed metasensors are a simple solid tripod, a hollow tripod, and a hollow tripod structure with arms. The best design showed a mean numerical sensitivity of 1.42 × 10^{-4} nm for extremely thin samples, meaning an improvement of 381% with respect to the initial designs. These results highlight the importance of using metastructures with complex geometries that enable high-intensity electric field distributions over the whole metasurface.**

I. INTRODUCTION

The use of metasurfaces operating within the Terahertz (THz) regime for sensing applications has gained more attention in the last decades. Such interest is mainly because of the arbitrary manipulation and control of electromagnetic wave propagation allowed with such metastructures and the particular characteristics of THz waves (such as penetrability through non-polar materials, water absorption, or high sensitivity to weak molecular interactions, among others). Many designs have been proposed for different sensing applications [1]–[6]. The most typical metasurface structures are designed by assembling arrays of subwavelength resonators, usually known as meta-atoms. These designs present localized hot-spots of high electric field concentration, very sensitive to environment's changes around these points. However, in some cases, these hot-spots can be too scattered on the structure's surface (discrete points). For sensing devices, this implies that the detection of a sample, especially if we have a tiny amount of it, is highly conditioned because the sample "falls" near these hot-spots. To address such a locality challenge, a new paradigm shift from meta-atoms to more elaborated meta-geometries has been recently proposed to have designs with the electric field highly confined all over the surface and not only at discrete points [7]. These devices have been demonstrated to present clear advantages in terms of the sensitivity achieved in sensing purposes, but they are also more elaborated and difficult to design and manufacture.

In this work, we start from a very simple metasurface consisting of a tripod-based meta-atom (we called this tripod metasurfaces). Its geometry consists of three blades separated from each other by 120 degrees. We carry out modifications to its geometry to improve its detection limit and its sensitivity in thin-film sensing applications based on this design. Our objective is to obtain designs based on meta-structures that are easy to design and manufacture but whose electric field is still as highly distributed as possible.

II. IN SEARCH OF THE OPTIMAL DESIGN

The metasensors proposed in this work are designed to operate in absorption within the THz range between 0.4 - 0.7 THz. They are composed of a tri-layer design consisting of an aluminum (Al) pattern over a polypropylene (PP) substrate with a back metallization (ground plane). All the results were obtained by simulations carried out with the commercial simulator CST Microwave Studio™. The unit cell of the first and most simple design, called "solid" tripod, as well as its reflection coefficient (black curve) and electric field distribution (confined only at the tips of the metallic blades) are shown in Fig. 1(a). To evaluate its performance as a thin-film sensor, we coated its surface with different thin-film thicknesses, ranging from 200 nm to 800 nm, and a permittivity of $\varepsilon_a = 8$, as described in [8]. As observed in Fig. 1, the response of the analyte-free solid tripod exhibits a dip in the reflection coefficient at 620 GHz that moves towards lower frequencies when the analyte thickness increases. With the aim of obtaining a quantitative estimation of the sensing performance, we calculated the sensitivity of each structure, defined as $S = (\Delta f/f_0)/h_a$ and measured in nm^{-1}, where $\Delta f = f - f_0$, with f the resonance frequency for each analyte thickness, h_a, and f_0 the resonance frequency without the analyte. With this definition, the sensitivity achieved by the solid tripod metasurfaces was 3.54×10^{-5} nm^{-1}.

To increase this sensitivity value, we modified the initial design by emptying the tripod metallic part to create a "hollow" tripod metastructure [see Fig 1. (b)]. By comparing the electric field distribution of both metastructures, we can observe that in the hollow tripod structure, the electric field is also confined inside these hollow blades due to the new capacitance generated between the metallic strips. With this new geometry and the previous definition, the hollow tripod achieved a mean sensitivity of 3.72×10^{-5} nm^{-1}, which translates into an improvement of the hollow structure of approximately 5% with respect to the solid tripod. This improvement occurs because the electric field confinement is more spreaded along the surface of the hollow tripod metasurface, making it more sensitive to changes in the refractive index around the surface of the structure. The higher sensitivity can also be confirmed by observing the quasi-linear variation of the reflection coefficient for different analyte thicknesses [left panel from Fig. 1 (b)].

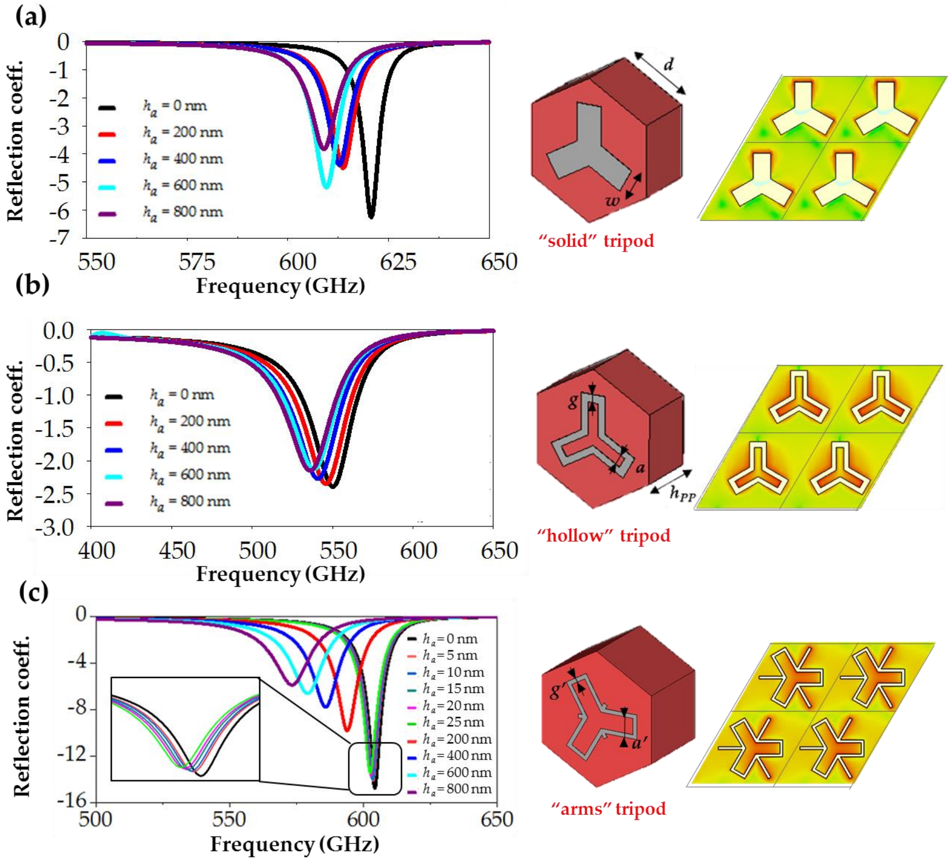

Fig. 1. (a) Reflection coefficient for different analyte thicknesses: 0 nm (black line), 200 nm (red line), 400 nm (blue line), 600 nm (cyan line), and 800 nm (dark pink line), for the solid tripod structure (left), unit cell of the designed solid tripod, with dimensions: periodicity, d = 162.5 µm; metallic layers thickness, t = 0.4 µm; and blade width, w = 58.5 µm (center); electric field distribution over the surface (right). (b) The same for the hollow tripod, with dimensions: the distance between metallic strips, a = 26 µm; and metallic strips width, g = 9.5 µm. (c) The same for the arms tripod, with modified dimensions: the distance between metallic strips, a' = 30 µm; and metallic strips width, g' = 7.5 µm.

III. ARMS-LOADED TRIPOD METASURFACE

The previous results demonstrate that one of the most critical factors on an excellent sensing device is to have as large and distributed electric field confinement as possible. In this way, a final metasurface was designed based on the hollow tripod metasurface. First, we modified the strip width, g, to g', and the gap between strips, a, to a', to optimize these parameters and try to get as deep resonance as possible. After an exhaustive analysis, it was found that the best dimensions were $a' = 30$ µm and $g' = 7.5$ µm. Once the optimal dimensions were found, we wanted to enhance the electric field concentration, and thus, the sensitivity. One way to do that was by rotating the metallic pattern of the metasurface unit cell 30º, and adding arms to each of the three vertices of the metallic pattern, as shown in Fig.1 (c). The optimal length of these arms was tested by performing a parameter sweep of their length, l_{arm}, between 5 µm up to the maximum, limited by the unit cell's size. The higher quality factor resonance in the bare structure with a deep enough resonance was found to be for a length of the arms of $l_{arm} = 10$ µm (see Fig1. (c)). We coated the arms tripod surface with the same analyte and thicknesses as the previous structures with the new design and dimensions. We obtained a mean sensitivity of 7.32×10^{-5} nm^{-1}, meaning an improvement of 196% for the hollow tripod structure. Such a much more sensitive structure allows us to detect much thinner thicknesses than 200 nm, so we coated the metastructure with ultra-thin films, with thicknesses ranging from 5 nm to 25 nm (see inset of Fig.1 (c)), and achieved a sensitivity of 1.42×10^{-4} nm^{-1}. The latter translates into an improvement of 381% for the hollow tripod, which could not detect such ultrathin thicknesses).

VI. CONCLUSION

We have presented three different tripod-based metasurfaces working as thin-film sensors in the THz band. The importance of having a high electric field concentration on the surface of the metasurfaces has been demonstrated. Additionally, it has been shown how this electric field needs to be as much distributed as possible over the metasurface. Two different metastructures have been initially studied, a solid tripod and a hollow tripod metasurface (with the latter having a higher electric field intensity distribution), showing average sensitivities of 3.54×10^{-5} nm^{-1} and 3.72×10^{-5} nm^{-1}, respectively. Finally, a more complex hollow tripod structure with arms has been presented, having a higher and more distributed electric field concentration. With this metasurface, a mean sensitivity of 1.42×10^{-4} was obtained when measuring extremely thin analytes, meaning an improvement of 381% to the initial hollow tripod structure.

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