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Sensing biological fluids using Resonating Surface Plasmon Polaritons in the THz range

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Abstract **– We study the sensitivity of two different metagrids to the presence of biological fluids on the surface. When a THz beam impinges on each metagrid capped with a dielectric substrate, peaks in transmission related to the onset of high order surface plasmon polaritons appear and allow to estimate the properties of a guest fluid filling the partition volume with a very high sensitivity, comparable with record literature values.**

I. INTRODUCTION

Surface plasmon polaritons (SPPs) are electromagnetic modes propagating at metal-dielectric boundary [1] [2] at frequency comparable with the plasma frequency (ω_p) of the metal. In artificial structures SPPs can be activated at frequency as low as in the THz range by diluting the metal with an operation of removal, that can be applied for instance machining a array of holes [3]. Further reduction of plasma frequency can be obtained by increasing the dielectric constant at the metal boundary. In this way the transmission properties of a system composed of a metallic grid deposited over a dielectric substrate (metagrid, MG) can be ruled by a “transition frequency” ω_t that can be as low as tenths of THz. When a MG is irradiated at a frequency $\omega<\omega_t$, spoof SPPs (SSPPs) modes are activated, whereas for $\omega>\omega_t$ high order SPPs (HOSPPs) resonant modes are triggered [4]. HOSPPs are responsible for enhanced transmission phenomena [5] and can be fruitfully used for sensing since their (evanescent) electric field extension is larger than the MG thickness [6]. Therefore, MGs can detect a substance deposited on their surface exploiting the dependence of resonating HOSPP modes on the dielectric environment, in the same fashion “classical” metasurfaces, consisting of arrays of individual resonators [7], do.

In this paper, performing full wave simulations of two MGs with different unit cells [4] when an analyte is deposited on their surface, we investigate the potential sensing properties of the HOSPPs. This is done both tracking the resonance shift as a function of the dielectric constant of the analyte and extracting a quantitative estimation of the potential figure of merit of the metagrid-based sensors.

II. METHODS

A sketch of the two MG unit cells is reported in the insets of Fig. 1. In particular, the unit cell of a grid (GR) metasurface is realized crossing normally oriented copper wires (Fig. 1(a)), whereas a chessboard (CB) metasurface is obtained by periodically copying a square copper patch (Fig. 1(b)). In both cases we use the same metal width, w = 150 μm, and periodicity, p = 600 μm. The substrate used in this study is a commercial FR4 layer, 160 μm thick.

To acquire label-free information on the dielectric function of biological (water based) fluids, we simulate a liquid analyte placed on the other side of the metagrid surface and having a height of 60 μm (reported with a violet color in the insets of Fig. 1). This value is chosen because of the typical thickness of paper tapes that can be used as sponge to absorb a specific quantity of analyte. In order to evaluate the sensitivity of the GM-based sensors, the dielectric constant of the analyte ε_x is varied between 1 and 2 (typical value of the distilled water is ε_{H2O}=1.77). The THz pulse is transmitted normally to the MG plane.

A full wave simulations is performed using the commercial software CST MICROWAVE STUDIO® in unit cell configuration. In a previous paper [4], a thorough study of the transmission properties of real MGs was carried

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out in the range 0.1 – 1 THz. Here we analyze, for $\omega > \omega_l$, the shift in frequency of the HOSPP resonances versus the refractive index $n_x = \varepsilon_x^{1/2}$ of the analyte, and build a number of calibration curves $f_i(n_x)$, where i is the mode order.

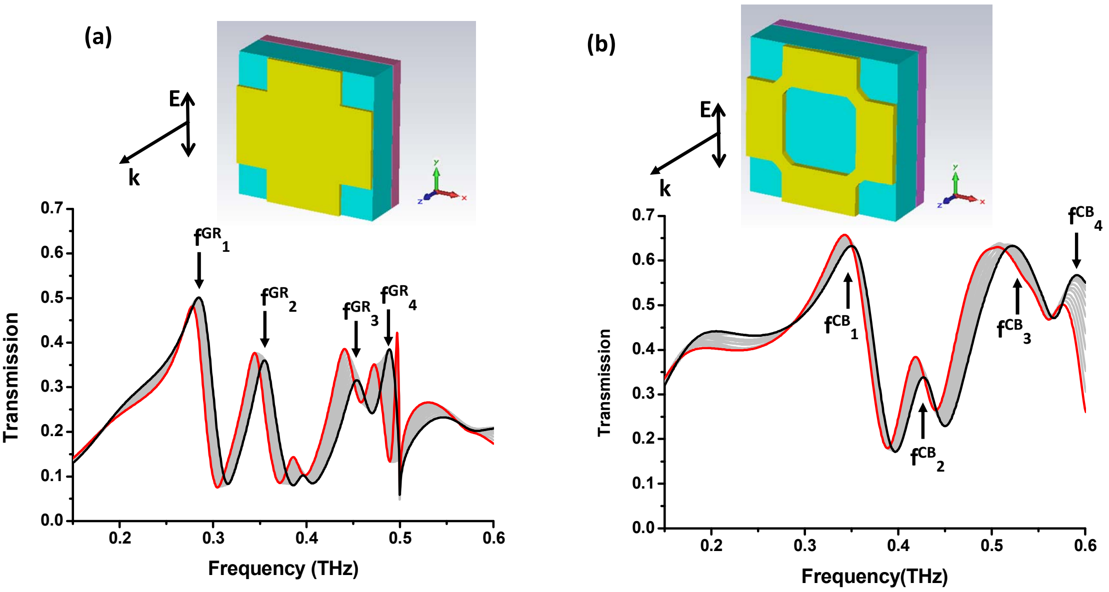

Fig. 1. Signal transmission T of the GR and CB metasurfaces are plotted in (a) and (b) respectively. Insets show the unit cell of the two sensors having the substrate covered with an analyte layer 60 µm thick. In each graph the black curve represents the transmission for a dielectric constant of the analyte $\varepsilon_x = 1$, the red curve for $\varepsilon_x = 2$. Arrows indicate the peaks selected for the sensing analysis. The direction of the THz impinging radiation is given by the propagation vector **k**.

III. RESULTS AND DISCUSSION

In Fig.1 (a) and (b) the signal transmission T of the two metasurfaces are reported. Black and red lines represent transmission using a dielectric constant of the analyte $\varepsilon_x = 1$ and $\varepsilon_x = 2$ respectively. In the plots, the shaded grey area indicates the T-curve evolution between the two boundary values with a step $\Delta\varepsilon_x = 0.1$. All transmission peaks shown in the figure are ascribable to the onset of Bragg modes representing diffractive resonances at the metal-FR4 or metal-analyte boundaries [5]. These modes are intimately related to the effective dielectric constant of each metagrid since their cut-off frequency scales as

$$f_{max}(n_{eff})=c(m_x^2+m_y^2)^{0.5}/(p\ n_{eff}) \qquad (1)$$

where $m_{x,y} = 0, 1, 2$ represent the Bragg order and $n_{eff} =(\varepsilon_m\ \varepsilon_d/\ \varepsilon_m+\varepsilon_d)^{0.5}$ is the effective refractive index, given by the dielectric constant of the metal ε_m and the dielectric layer ε_d (depending in turn on the dielectric constant of the analyte ε_x). We have considered the frequency shift of the four peaks with the highest intensity only, to envisage the case of highly dissipative samples. Selected peaks are indicated by arrows in Fig. 1.

In Fig. 2(a) and 2(b) the curves $f_i^{GR,CB}(n_x)$ with i = 1-4 are reported. Since the frequency dependence on the analyte refractive index is substantially linear, we have applied a linear regression to evaluate the angular coefficient, providing the metagrid sensitivity with an error lower than 2%. Values are measured in nm/RIU (refractive index unit) [8] and are reported for each curve. All calculated sensitivities are of the order of 10^4 nm/RIU, resulting among the highest values reported in THz [7] and IR [9] band. In contrast, figures of merit (FOM), expressed by the ratio of sensitivity and resonance curve FWHM (full width at half maximum) stay in the range of unitary values, pointing to the use of a substrate with lower losses as a desirable choice.

IV. CONCLUSIONS

We have investigated the sensing performance of two metasurfaces with different (grid or chessboard) unit cell in the THz range, having a liquid analyte deposited over the substrate. Varying the dielectric constant of the analyte between 1 and 2 we studied the possible use of each MG for the development of label-free sensing platforms for water-based samples. Simulated sensitivities are comparable with the best results achieved so far, although there is room for the improvement of the sensor Figure Of Merit by a careful choice of a substrate with lower losses.

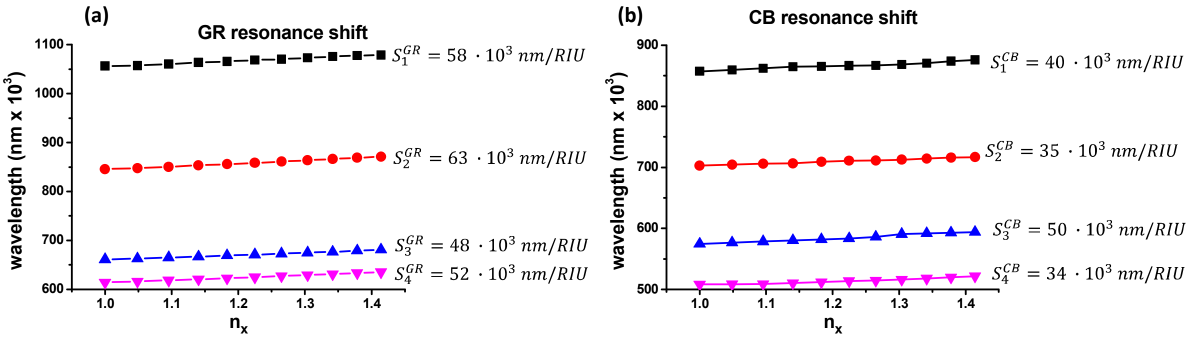

Fig. 2. Resonance shift of 4 HOSPP modes for the GR (a) and CB (b) metagrids respectively. Next to each curve is reported the estimated sensitivity.

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