International Journal of
Technology and
Systems
(IJTS)

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CARI
Journals

Journal of Technology and Systems
ISSN : 2788-6344 (Online)
Vol. 6, Issue No. 7, pp 1 – 12, 2024
www.carijournals.org

Terahertz Sensing with Extraordinary Optical Transmission Hole Arrays

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Accepted: 16th Sep 2024 Received in Revised Form: 26th Sep 2024 Published: 15th Oct 2024

Abstract

Purpose: The purpose of this paper is to substantiate the enhanced performance of hyperbolic anisotropic (HA) meta-surfaces at anomalous extraordinary optical transmission (EOT) resonances. These resonances exhibit distinct transmission peaks highly sensitive to environmental changes, making them particularly valuable for sensing applications. By demonstrating improved transmission efficiency and sensitivity, this study aims to contribute to developing advanced sensing technologies that leverage the unique properties of HA meta-surfaces in detecting minute variations in their surroundings.

Methodology: To verify the enhanced sensing performance of anomalous EOT resonances, this study employs a well-established experimental method involving depositing a thin analyte layer of varying thicknesses onto the meta-surface. The study aims to determine which resonance condition provides optimal sensitivity by comparing the performance between regular and anomalous EOT resonances. It explores the improved performance of HA meta-surfaces at anomalous EOT resonances, which occur under certain non-standard conditions, offering potentially superior sensing capabilities compared to regular EOT.

Findings: The results indicate that when the analyte is applied to the non-patterned side of the metasurface, the anomalous EOT resonance achieves superior sensing performance. This enhanced sensitivity can be attributed to the unique interaction dynamics between the incident THz waves and the meta-surface structure under abnormal conditions.

Unique Contribution to Theory, Policy and Practice: This phenomenon is beneficial in the terahertz (THz) range, making HA meta-surfaces ideal for thin-film label-free sensing applications. The EOT resonance occurs due to the interaction between incident light and the periodic structure of the holes, leading to enhanced light transmission at specific wavelengths. The findings highlight the potential of using anomalous EOT resonances in HA meta-surfaces to develop highly sensitive and efficient sensors for detecting changes in thin films, paving the way for advanced sensing technologies in various scientific and industrial applications.

Keywords: *Terahertz, Regular EOT, Anomalous EOT, Sub-wavelength Hole Array, Metasurface.*

I. INTRODUCTION

Terahertz (THz) sensing has emerged as a crucial technology in various fields, including security screening, biomedical diagnostics, and material characterization. Its ability to penetrate non-conductive materials and provide high-resolution spectral information makes it an attractive tool for non-invasive sensing applications. A particularly promising approach within this domain is the use of Extraordinary Optical Transmission (EOT) through hole arrays, which enhances the sensitivity and specificity of THz sensors.

EOT occurs when light transmission through a subwavelength hole array (HA) [1] exceeds what classical aperture theory predicts, facilitated by resonant interactions with surface plasmons. According to classical aperture theory by Bethe [7], When the light of a specific wavelength falls on a sub-wavelength aperture, it is diffracted isotropically in all directions evenly, with minimum far-field transmission as described by Bethe. EOT is partly attributed to the presence of surface plasmon resonances and constructive interference. Additionally, the overlapping of evanescent wave coupling plays a significant role in this phenomenon. Holes can emulate plasmons at other regions of the electromagnetic spectrum where they do not exist. This phenomenon has been extensively studied in the optical and infrared ranges; however, due to the nature of holes to emulate as plasmons, surface plasmon resonance enhances the EOT effect on both sides of a metallic film in terahertz-range transmission. Recently, a variant known as Anomalous EOT (AEOT) has garnered attention due to its ability to achieve even higher Figures of Merit (FOM) than regular EOT configurations, particularly for label-free thin-film sensing applications. Gordon et al. and Garcia et al. investigated the transmission through single rectangular holes in metal films. Gordon et al. used numerical simulations to show that enhanced transmission occurs near the cutoff wavelength of the fundamental mode in the waveguide formed by the rectangular hole[9]. EOT has potential applications in sensing, color filters, metamaterials, metalenses, optical trapping, and the enhancement of nonlinear effects.

EOT sensors generally comprise hole arrays (HAs) arranged in a square unit cell. However, depending on the wave's polarization, a rectangular unit cell excites two distinct EOT resonances, known as regular and anomalous EOT. The anomalous EOT resonance is excited when the wave is polarized along the shorter periodicity of the holes, and the HA is loaded with a dielectric slab of minimum thickness and permittivity. Surface plasmons (SPs) amplify the fields linked to evanescent waves, leading to increased transmission. When the metal film is sufficiently thin, this tunneling effect can become resonant as the SP modes on both sides of the film can overlap and interact through the holes [8]. [13] discusses the spectral position of extraordinary optical transmission (EOT) resonances in metallic arrays of rectangular holes in the near and mid-infrared regions.

II. THEORETICAL BACKGROUND

The resonance in extraordinary optical transmission (EOT) originates from the interaction between leaky surface modes at the metal-dielectric interface and the incoming radiation. It cannot couple on a flat, non-perforated thin metal film due to the inability to simultaneously conserve energy and momentum. However, the periodic array of holes in perforated metal sheets relaxes the momentum conservation constraint and alters the behavior of surface modes, enabling coupling with the incident radiation. As a result, radiation is transmitted through the holes. The transmission is further enhanced by the re-illumination of the holes by the surface modes, leading to an additional buildup of resonant transmission [12].

For the initial study, the paper designed an ideal lossless unit cell with the following parameters: Aluminum coated with an analyte layer of zero thickness. It was excited by both regular and anomalous EOT to compare its sensitivity. The occurrence of anomalous EOT, as discussed in [5] [6], depends on the characteristics of the substrate used (h_{PP} and ϵ_{PP}) and the dimension of the unit cell in the y-axis, as well as the large HA periodicity, dy. The anomalous EOT resonance cutoff can be calculated using the

$$\textbf{Auxiliary factor } F = h_{PP}\, p(\epsilon_{PP} - 1)/d_y \qquad (1)$$

If $F \geq 0.25$, the anomalous EOT peak will appear. In order to get anomalous EOT at the cut off frequency, thickness of the substrate was kept $h_{PP} = 78.25\ \mu m$ to get $F = 0.25$. From the previous research, the regular EOT resonance exists even without a substrate, so the paper considered structure without substrate layer. The performance on the meta-surface is evaluated in the terms of sensitivity, S (Figure 5) and Figure of Merit, FOM(Figure 6). Sensitivity refers to the ratio of the resonance wavelength change to the analyte thickness,

$$\textbf{Sensitivity } S = \Delta\lambda/ha \qquad (2)$$

Yet, sensitivity alone may not fully determine a sensor's quality. Therefore, FOM refers the sensitivity to the full width at half maximum (FWHM) of the resonance peak,

$$\textbf{Figure of Merit } FOM = S/FWHM\ (mm^{-1}) \qquad (3)$$

It indicates that a sensor with a high-quality factor has a narrow spectral line and a relatively high FOM.

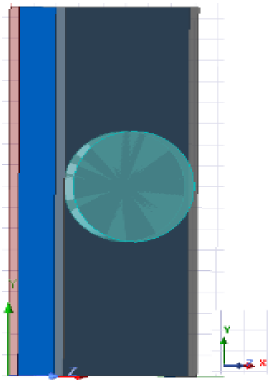

Figure 1: Unit cell showing the Al layer(gray), substrate (blue) and analyte (red)

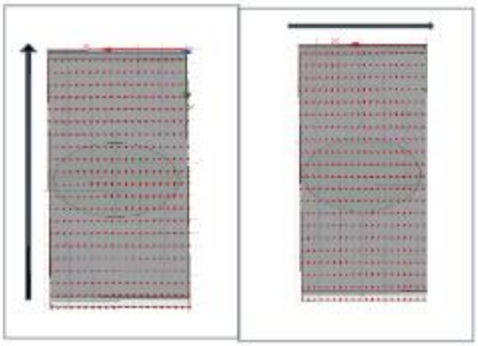

Figure 2: Regular EOT excitation (a) electric field is applied parallel to d_y and Regular EOT excitation (b) electric field is applied parallel to d_x

III. PROPOSED APPROACH

A. Anomalous and Regular EOT Excitation

As illustrated in Figure 1, the meta-surface consists of a periodic array of circular holes on an aluminum (Al) layer with a thickness of 0.5 µm, placed on a substrate of two different thicknesses: 50 µm and 75 µm. The substrate has a permittivity of $\varepsilon_{PP}= 2.25$. [2] [3] The Al-layer is a non-dispersive medium with conductivity σ = 1.5 × 107S/m. Dimensions of the rectangular HA unit cell are dx = 115.5µm, dy = 350µm, and a hole diameter of 105 µm. The HA was excited at normal incidence using two different linear polarization states: regular EOT resonance excitation, where the electric field is parallel to the large period of the structure (dy) shown in Figure 2(a), and an anomalous EOT resonance excitation where the electric field is parallel to the short period of the structure (dx)as in Figure 2(b).

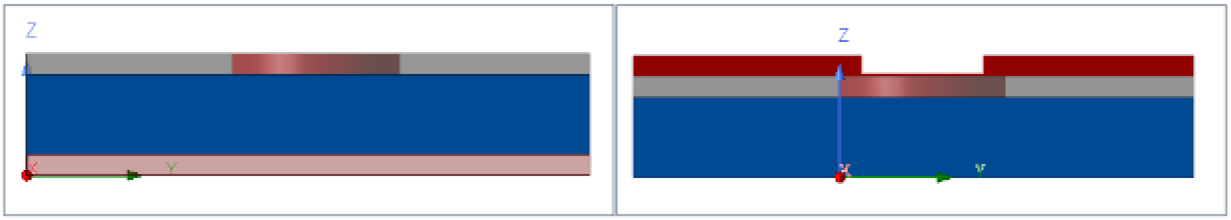

Figure 3: Deposition of the analyte is done on the HA (a) and substrate (b) faces

The sensitivity of the metasurface was evaluated by applying a non-dispersive and lossless analyte with permittivity $\varepsilon_{PP} = 2.65$ and varying thicknesses (from 3 µm to 13 µm) either on the substrate side or the HA side. All design and numerical simulations were conducted using the HFSS.

B. Excitation of the meta-surface with laser pulse

When a metasurface is excited by a laser pulse, its transmission coefficient changes depending on the properties of the metasurface and the laser pulse parameters. Plasmonic meta-surfaces can exhibit nonlinear transmission and saturable absorption behavior when excited by intense laser pulses. At low pulse intensities, the transmission coefficient remains linear based on the polarization of the incident light. As the pulse intensity increases, the transmission coefficient decreases due to the saturable absorption of the plasmonic resonances, leading to a lower saturated transmission coefficient.

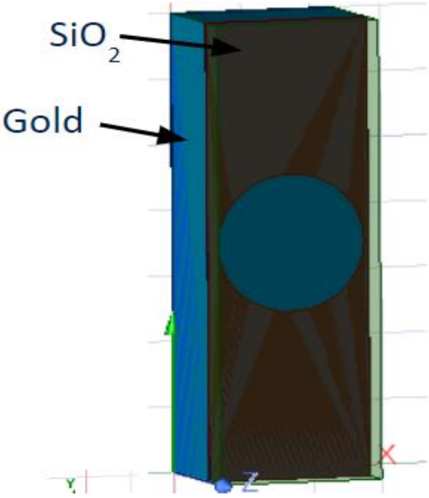

Figure 4: Unit cell with a thin layer of SiO_2 deposited on Gold

Figure 4. shows the modeling unit with a hole array of diameter 105µm on the SiO_2 of (thickness, t = 0.5µm) deposited on the Gold layer of thickness 50µm. Dimensions of the unit cell remain the same as in the previous case. The HA was excited at normal incidence in two different cases: 1) Excitation with radiation- When a laser of wavelength 375µm hits the surface of the metasurface, 2) When optical transmission through the metasurface occurs in the Terahertz frequency range without any laser pulse.

IV. RESULTS

A. Anomalous and Regular EOT Excitation

As illustrated in Figure 5, (black line), for a unit cell without the analyte, the regular EOT resonance occurs at 0.81 THz, while the anomalous EOT resonance appears at 0.84 THz. To assess this analyte with thickness ranging from 3 µm to 15 µm with 3 µm increments is added on top. During anomalous EOT excitation, the analyte is placed on the outer surface of the PP substrate, whereas in the regular EOT case, the analyte is coated on the Al layer. As analyte thickness increases, the transmission peak shifts to a lower frequency (Figure 5).

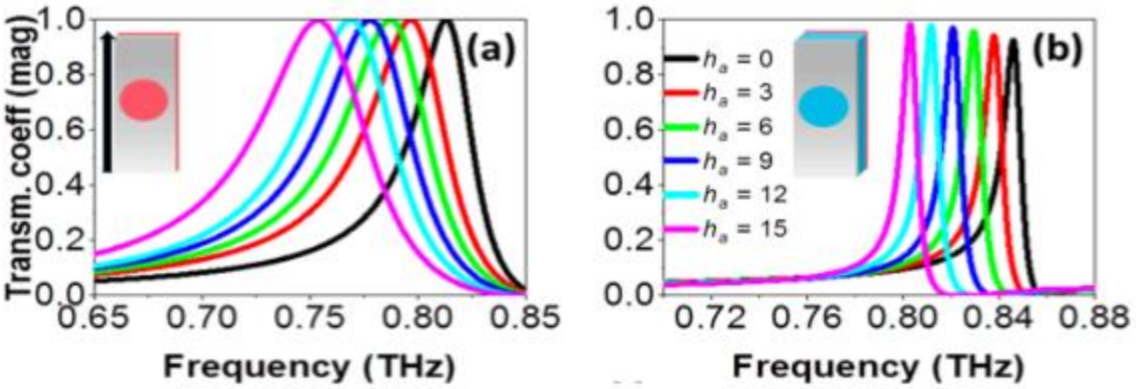

Figure 5: Transmission coefficient for the regular EOT (a) and anomalous EOT (b) resonance of an ideal lossless HA [4]

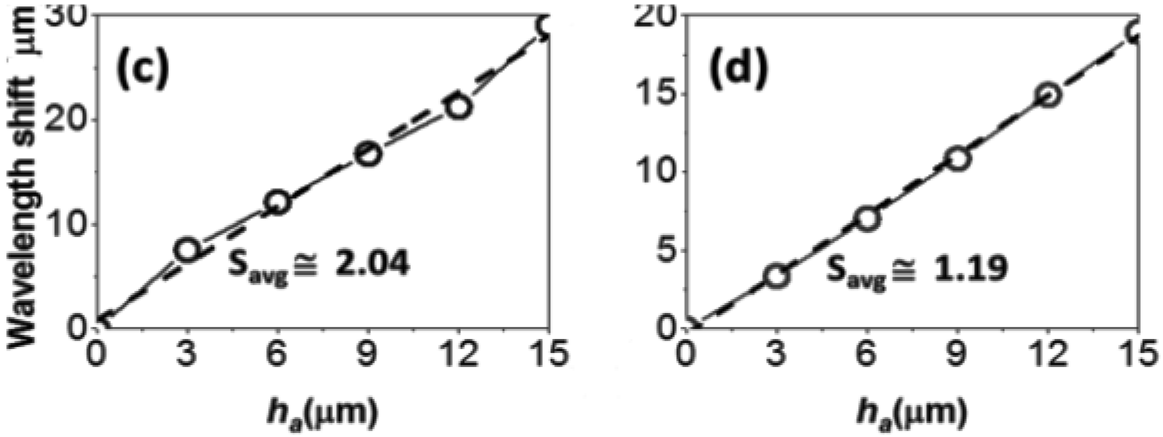

Figure 6: Wavelength shift for the (c)regular EOT resonance and (d) anomalous EOT resonance [4]

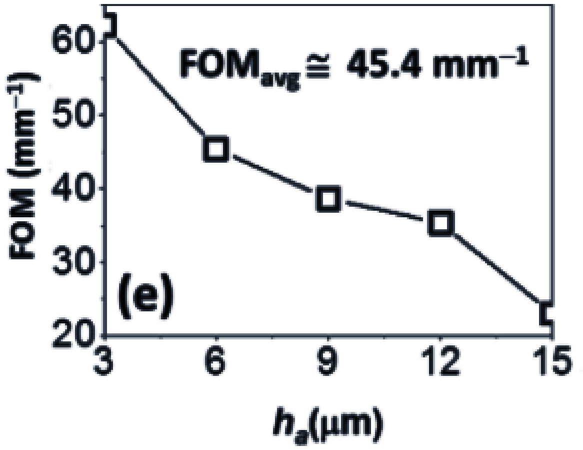

Figure 7: FOM for the (e)regular EOT resonance and (f) anomalous EOT resonance [4]

When both the graphs from Figure 6 are compared, the experiment shows that the regular EOT configuration performs slightly better than the anomalous EOT in average sensitivity, with values of 2.04 and 1.19, respectively (Fig 6). However, the FOM indicates that the anomalous EOT is better than regular EOT resonance, with an increment of 153.7 mm−1 (Fig 7). Therefore, anomalous EOT exhibits better performance for sensors than the regular EOT.

The study evaluated the performance of the anomalous EOT resonance with two different substrate thicknesses, h_{PP} = 75 µm (Figure 8) and h_{PP} = 50 µm (Figure 9), corresponding to F = 0.24 and 0.16, respectively. Sensitivity is evaluated by depositing four different analyte thicknesses: ha = 3 µm, 7 µm, 10 µm, and 13 µm. Two different cases were considered: analyte deposited on the HA and PP sides.

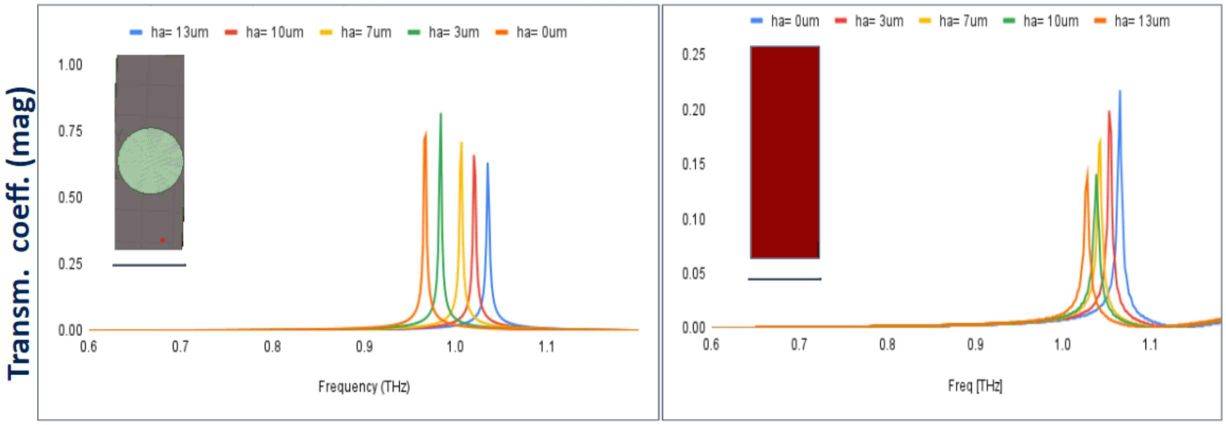

Figure 8: Anomalous EOT excitation (a) hPP = 75 µm analyte on substrate and (b) hPP = 75 µm analyte on HA

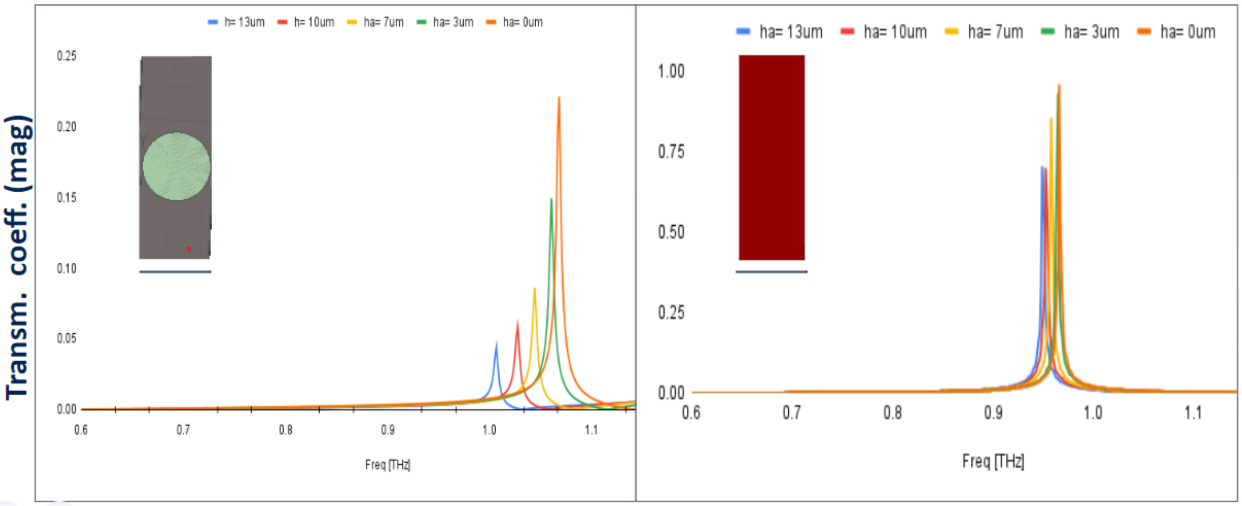

Figure 9: Anomalous EOT excitation (a) hPP = 50 µm analyte on substrate and (b) hPP = 50 µm analyte on HA

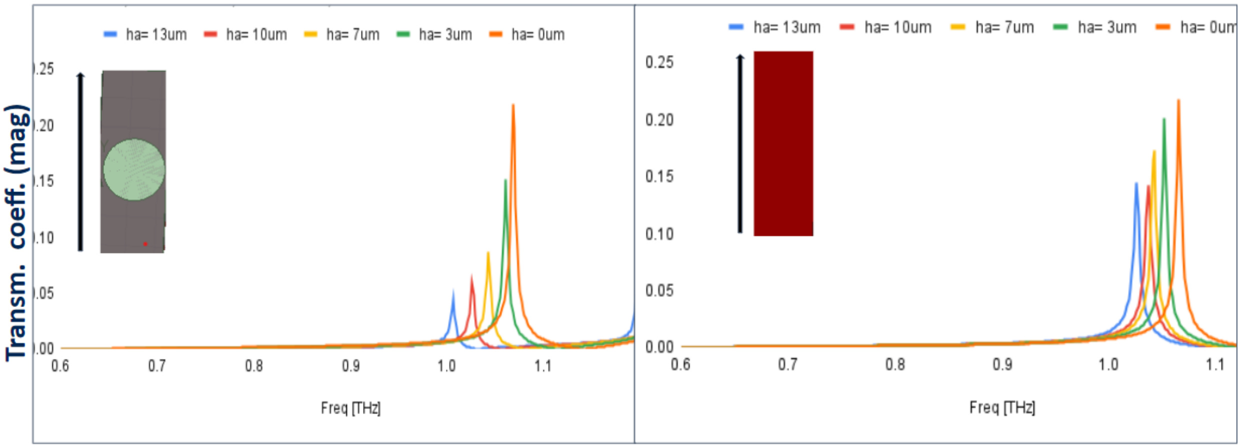

Figure 10: Regular EOT excitation (a) hPP = 75 µm analyte on substrate and (b) hPP = 75 µm analyte on HA

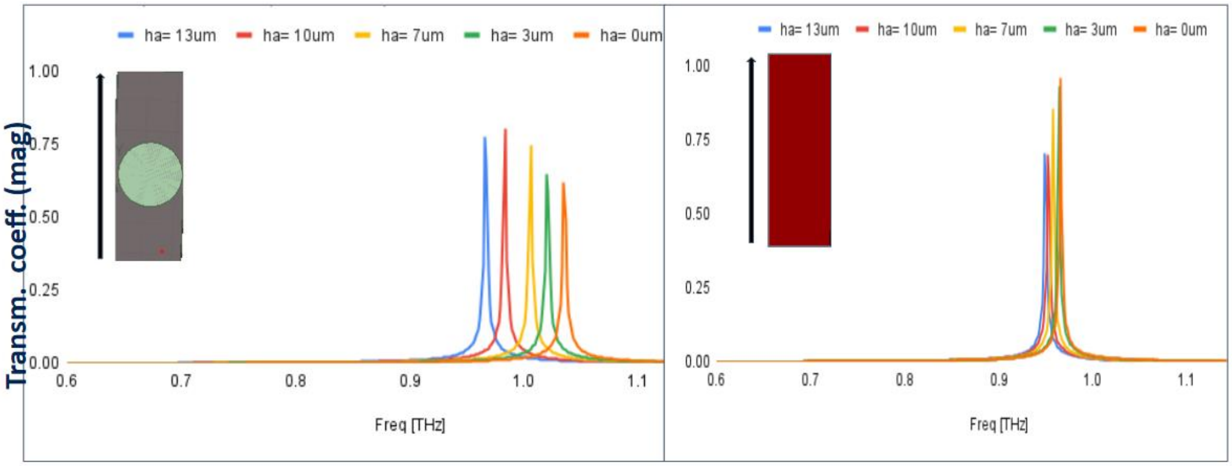

Figure 11: Regular EOT excitation (a) hPP = 50 µm analyte on substrate and (b) hPP = 50 µm analyte on HA

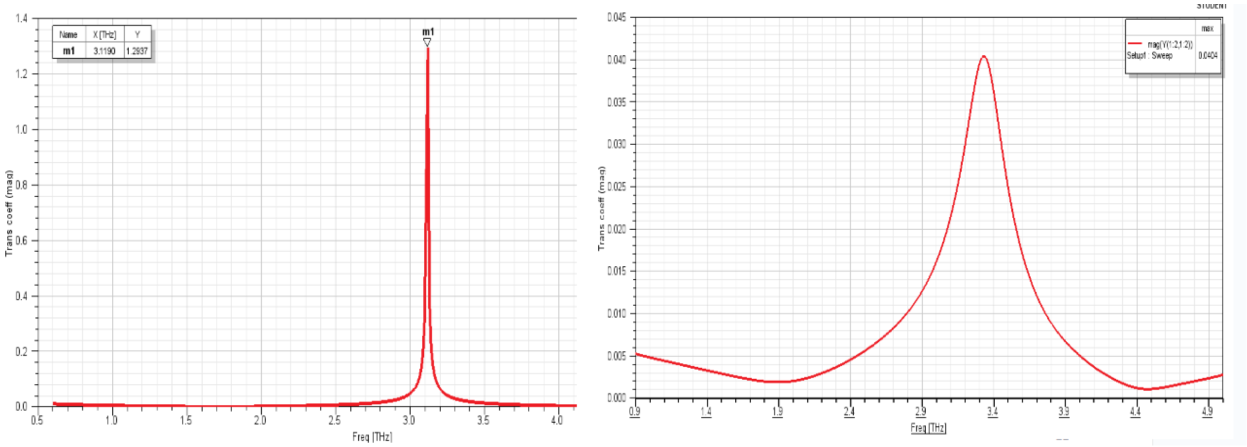

Figure 12: Anomalous EOT excitation (a) without radiation and (b) with radiation on SiO2 and gold unit cell

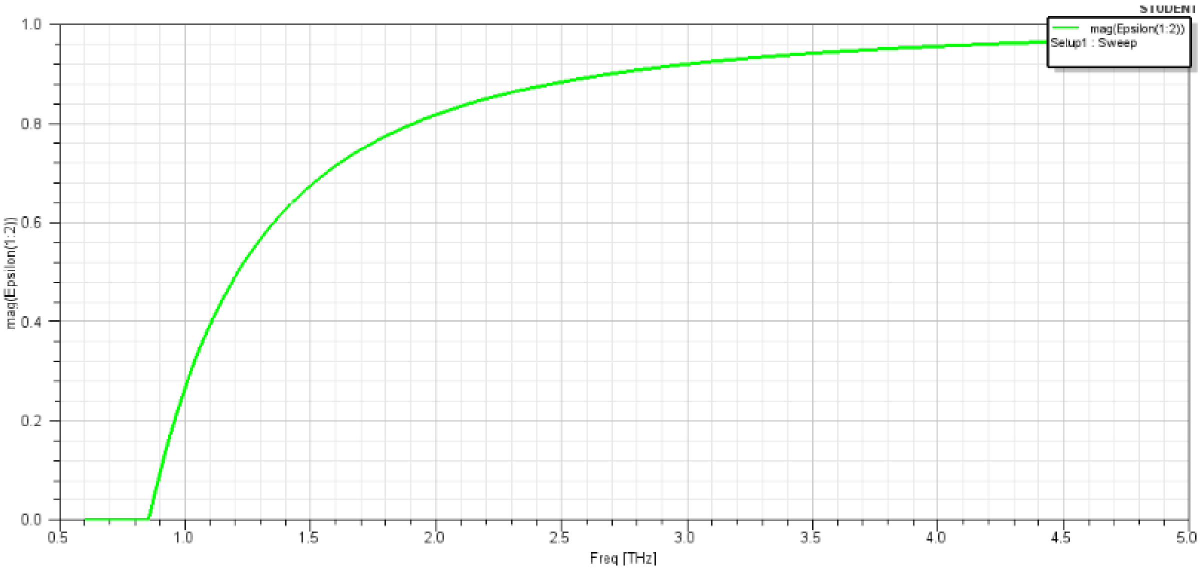

Figure 13: Graph of Permittivity vs Frequency for unit cell with a thin layer of SiO2 deposited on Gold

B. Excitation of the meta-surface with laser pulse

The transmission coefficient vs frequency graph of SiO2 and Gold is plotted in Figure 12. In (Figure 12(a)), excitation of HA without radiation shows that its transmission peak value is 1.29 at approximately 3.12 THz and is very narrow compared to excitation of HA with radiation, which has a broader peak of 0.04 at 3.4THz. This indicates that Figure 12(a) has higher resonant behavior with higher selectivity than excitation without radiation graphs with broader resonance and less selectivity. Excitation without radiation shows negligible transmission outside the peak and a strong resonance effect at a specific frequency. HA excitation with radiation has some transmission for a more comprehensive frequency range and broader spectral characteristics. The permittivity in all the cases remains the same. It does not change with the change in linear polarization state or when a laser pulse hits the metasurface.

V. CONCLUSION AND FUTURE OUTLOOK

For the ideal case, the study gets an average FOM of 153.77 mm−1 for anomalous EOT, much higher than the regular EOT excitation FOM. Thus, the performance of the anomalous EOT resonance is better for thin-film sensors. In anomalous EOT, the transmission coefficient is approximately 0.88 for 75 µm thick substrate coated with analyte film and 50 µm thick substrate with analyte film coated on HA. The transmission coefficient for a 75 µm thick substrate (Figure 10) decreases for both substrates coated with analyte or analyte film coated on HA for regular EOT. However, in the case of a 50 µm thick substrate (Figure 11), the transmission coefficient is approximately equal to the unity for both cases. For better performance of EOT on HA, a non-dispersive substrate with complex permittivity can be used and compared for both regular (vertical) and anomalous (horizontal) polarization states. EOT without radiation has a high-quality factor (Q-factor) resonance with highly selective transmission and higher efficiency at a particular frequency. EOT with radiation has broader spectra, which may be more suitable for applications requiring a more comprehensive frequency range but with less transmission efficiency.

VI. RECOMMENDATIONS

HA meta-surfaces demonstrate exceptional capabilities for thin-film label-free sensing applications. The anomalous extraordinary optical transmission (EOT) resonance occurs due to the interaction between the incident light and the periodic structure of subwavelength holes or apertures on the meta-surface. This interaction significantly enhances light transmission at specific wavelengths, creating distinct transmission peaks that are more sensitive to environmental changes. Thus, the enhanced performance of HA meta-surfaces in the THz range opens up new possibilities for creating advanced sensing technologies across a wide range of scientific and industrial fields. This could lead to innovations such as material characterization, security screening, and process control in industries where real-time, high-precision sensing is essential.

ACKNOWLEDGMENT

I thank Prof. Sebastian Gomez-Diaz for proposing this valuable project approach. Damia Casas Casajuana, Kindred Griffis, and Ryan Kim contributed differently, offering design approaches for the meta-material and simulation tips.

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