A Comparative Analysis of Cross-shaped and double L-shaped Plasmonic Metamaterial Absorbers for Enhanced Light-Matter Interaction

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***Abstract*—This paper explores the innovative use of plasmonic metamaterial absorbers to enhance the interaction between light and matter. Plasmonic metamaterials, engineered with subwavelength features, exhibit unique optical properties that can be tailored for efficient light absorption and manipulation. The study investigates the comparative analysis of two kinds of plasmonic structures used for IR absorption, mainly cross and double L-shaped structures. The paper also discusses recent advancements in the field, highlighting the potential impact of plasmonic metamaterial absorbers on advancing technologies that rely on precise control of light at the nanoscale.**

Keywords—Plasmonics, Surface Plasmon Resonance (SPR), Metamaterial-based Absorbers (MMAs), Metal–insulator–metal (MIM)

I. INTRODUCTION

Plasmonic metamaterials are engineered structures with subwavelength features that can manipulate light in unique ways by exploiting surface plasmon resonances. These metamaterials have gained significant attention for their potential applications in various fields such as optics, sensing, imaging, and energy harvesting. The study of plasmonic metamaterial absorbers contributes to the advancement of nano-photonics and the development of next-generation optical devices. These devices hold promise for miniaturization, increased functionality, and improved performance compared to traditional optical components. Here, we try to observe the optical properties of two types of MMAs with the help of COMSOL Multiphysics and compare the absorption spectra of the same.

II. METAMATERIALS

Metamaterials (MM) are artificially designed materials that possess unique properties due to their geometrical design. It is a composite made up of many layers of metallic patterns separated by dielectric. MMAs offer perfect absorption, thus making them highly efficient to capture solar energy and to be used with sensors, bolometers, wireless power transfer, and perfect light absorber.

The metallic pattern is the first layer, which is arranged periodically. The second layer consists of a substrate or dielectric layer. Finally, the third layer is another periodic metallic pattern.

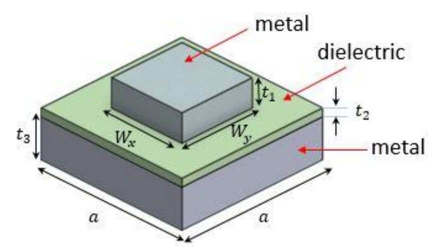

Fig 1: Unit cell of MIM metamaterial absorber [3]

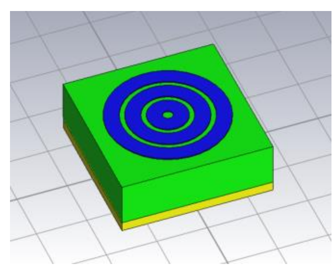

Fig 2: 3D schematic of an absorber based on vanadium oxide [2]

III. MECHANISM OF METAMATERIAL ABSORBERS

Metamaterial absorbers operate based on the principles of resonance and the manipulation of electromagnetic waves at the nanoscale. The mechanism of metamaterial absorbers involves the interaction of incident electromagnetic waves with specifically designed structures to achieve efficient absorption within a desired wavelength range. Many metamaterial absorbers leverage **surface plasmon resonance (SPR)**, where free electrons at the metal-dielectric interface oscillate collectively in response to incident light. This resonance can be tuned to specific wavelengths by adjusting the geometrical parameters of the metamaterial structure. The geometry of these structures, such as the size, shape, and arrangement of elements, is crucial for controlling the absorption spectrum. Adjusting these parameters allows tailoring the metamaterial to absorb light at specific wavelengths.

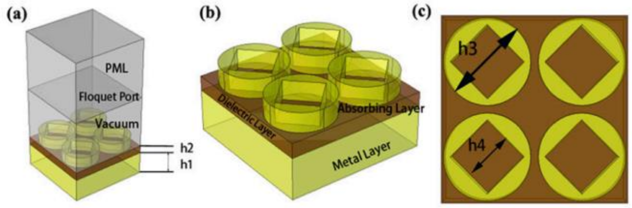

Fig 3: (a) a single periodic unit structure, (b) front view of the absorber, (c) top view of the absorption layer having four identical ring patches [4]

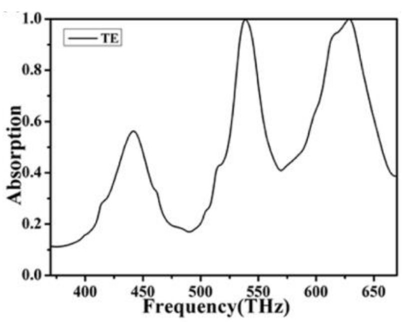

Fig 4: Absorption curves under TE mode [4]

IV. DOUBLE L-SHAPED METAMATERIAL

A wide-angle, polarization-independent and dual band infrared perfect metamaterial absorber made of double L-shaped gold patches was proposed on a dielectric spacer and opaque gold ground layer. Numerical and experimental results demonstrate that the absorber has two near-unity absorption peaks, which are result from magnetic polariton modes generated at two different resonant wavelengths. In addition, the proposed structure also shows good absorption stability in a wide range of incident angles θ for both TE and TM incidences at azimuthal angle φ = 0°.

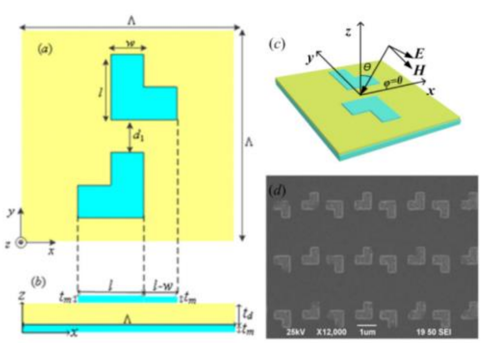

Fig. 5. (a) Top view and (b) side view of a unit cell of the L-shaped metamaterial absorber, (c) TM incident wave impinging on the structure in x-z incident plane (where the azimuthal angle φ = 0°) with an incident angle of θ to z–direction, (d) SEM image of the fabricated L-shaped metamaterial absorber

The thicknesses of the SiC layer and gold layer are td = 0.27 μm and tm = 0.1 μm, respectively. The structure has a lattice period of Λ = 2.6μm in both x-direction and y-direction. The width and length of the single L-shaped patch are w and l, respectively. The vertical distance between two L-shaped patches is d1 = 0.4 μm. Since the thickness of the metallic film used here is much larger than the typical skin depth in the infrared, the reflection is the only factor limiting the absorption. The absorption is given by A = 1-|S11|^2 where |S11| represent the reflection coefficient.

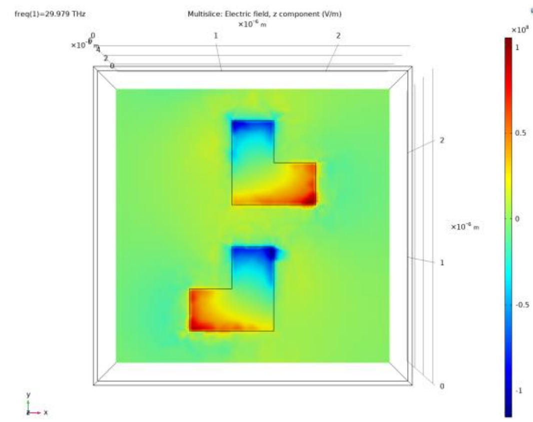

Fig 6: E-field distribution (z-component) for frequency f = 29.979 THz

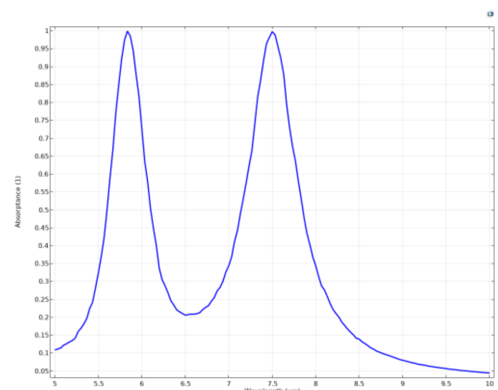

Fig 7: Absorption Spectra for the double L-shaped plasmonic structure

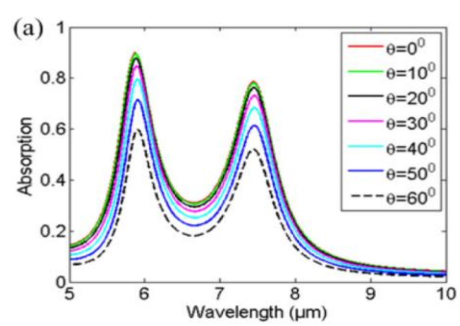

Fig 8: Absorption spectra of single L-shaped metamaterial with different incident angles

V. CROSS-SHAPED METAMATERIAL

The proposed ultra-narrow bandwidth IR absorbers are composed of an array of gold (Au) nanostructures and a continuous ground layer separated by a subwavelength thickness silicon dioxide (SiO2) layer [1]. The top nanostructures are cross-shaped, with lateral dimensions denoted as a (width), b (length), and Λ (periodicity). The thickness of SiO2 (tox = 200 nm) and Au (t_Au = 100 nm) was appropriately chosen for strong SP confinement and a wide lithographical tunability of the spectral absorption band in MWIR (λ = 4–7 µm).

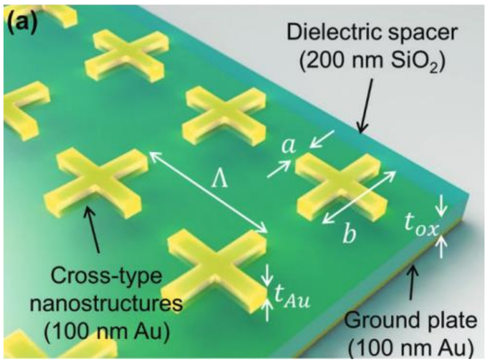

Fig 9: 3-D demonstration of the proposed structure

When the electromagnetic waves in a specific spectral band impinge on the absorber, the electric dipole resonance is excited in the array of nanostructures, inducing antiparallel currents on the ground layer via plasmonic coupling in the subwavelength dielectric gap. As indicated by the magnetic field intensity (|H|), the current loop gives rise to a strong magnetic field confinement. With the right level of loss to support critical coupling and conjugate matching, near-unity absorption is achieved at the designed spectral band.

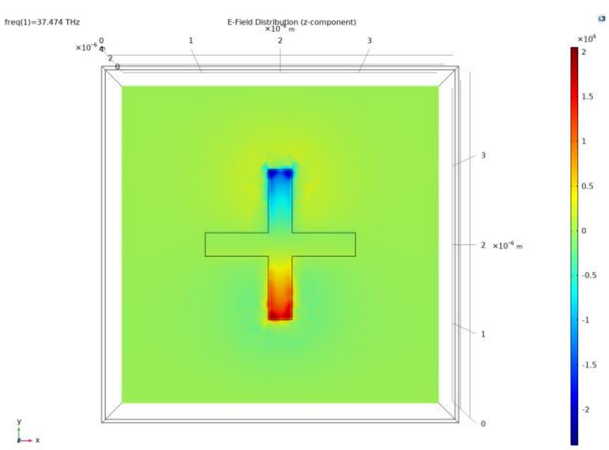

Fig 10: E-field distribution (z-component) for frequency f = 37.474 THz

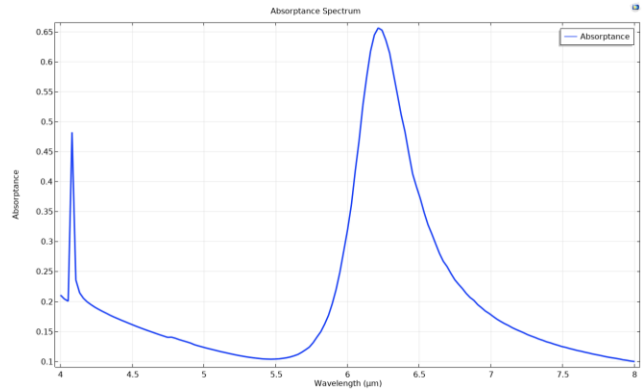

Fig 11: Absorption Spectra for the cross-shaped plasmonic structure

VI. WHY PLASMONICS?

One of the best studied applications of plasmonic materials is sensors for detecting chemical and biological agents [5]. In one approach, researchers coat a plasmonic nanomaterial with a substance that binds to a molecule of interest— say, a bacterial toxin. In the absence of the toxin, light shining on the material is re-emitted at a specific angle. But if the toxin is present, it will alter the frequency of the surface plasmon and, consequently, the angle of the reflected light. This effect can be measured with great accuracy, enabling even trace amounts of the toxin to be detected and measured.

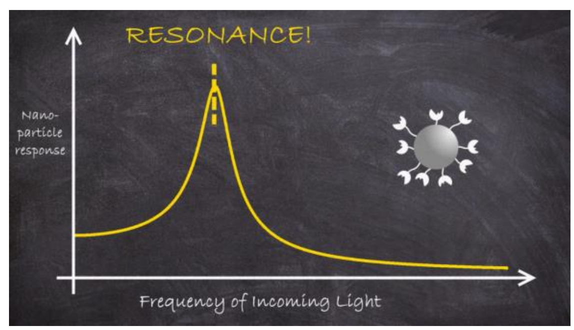

Fig 12: Resonance frequency in the absence of analyst.

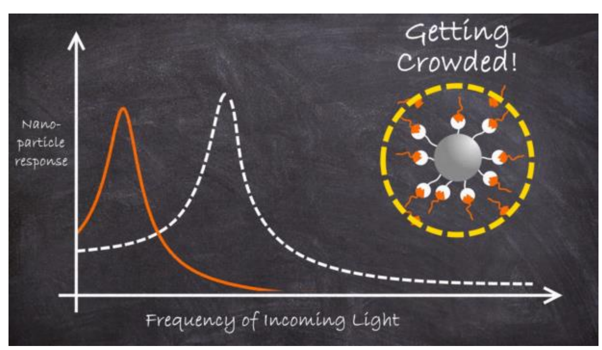

Fig 13: Resonance shift in the presence of analyst.

VII. CONCLUSION

In conclusion, the exploration of plasmonic metamaterial absorbers for enhanced light-matter interaction represents a significant stride in the field of nano-photonics with far-reaching implications across various scientific and technological domains. The intricate interplay of resonance, geometry, and material properties allows for the precise control of electromagnetic waves at the nanoscale, enabling the development of highly efficient absorbers. The cross-shaped MMA was found to have one absorption peak while the double L-shaped MMA had two of them. As the understanding of the underlying mechanisms continues to deepen, future research may unlock even more sophisticated designs and functionalities.

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REFERENCES

[1] Kang, L., et al. "Ultra-narrowband metamaterial absorbers for high spectral resolution infrared spectroscopy." Advanced Optical Materials 7.17 (2019): 1900517.

[2] Sun, Y., et al. "Ultra-wideband tunable metamaterial perfect absorber based on vanadium dioxide." Optica 29.2 (2022): 2703-2707.

[3] Zhou, H., et al. "Nearly total absorption of light and heat generation by plasmonic metamaterials." Physical Review B 83.16 (2011): 165107.

[4] Zhang, Y., et al. "Dual band visible metamaterial absorbers based on four identical ring patches." Applied Sciences 10.9 (2020): 3159.

[5] Tours Through Physics: Nanoplasmonics (Part 2), Sensing, Science and Diagnostics : https://youtu.be/iUyPssG9f_M?feature=shared