Tunable Multi-Frequency Optical Metamaterial Absorber Based on Geometrically Scaled Double Split Ring Resonators

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***Abstract*—This paper presents a geometrically scalable metamaterial absorber based on a double split ring resonator (DSRR) operating in the optical frequency regime.The DSRR and their complementary counterparts are among the most widely used unit cell configurations in the meta-material absorbers due to their strong LC resonance, high field confinement, and ability to achieve near unity absorption at designed frequencies. The proposed design enables controlled multi-frequency absorption at 423 THz, 518 THz, 640 THz, and 831 THz through systematic scaling of the resonator dimensions. Numerical simulations using the finite-difference time-domain (FDTD) method are conducted to analyze the electromagnetic response of the structure. The results demonstrate near-perfect absorption at the target frequencies with reflection minima below 20 dB. Unlike conventional designs, this work establishes a direct relationship between geometrical parameters and resonance behavior, enabling predictable tuning of absorption characteristics. Furthermore, the study explains the emergence of higher-order resonances at lower frequencies due to electromagnetic coupling between concentric rings. The proposed design provides a flexible platform for engineering multi-band optical absorbers for sensing, filtering, and photonic applications.**

I INTRODUCTION

Metamaterial absorbers (MTMAs) have attracted significant attention due to their ability to achieve strong and selective electromagnetic absorption using subwavelength structures. They have garnered significant interest due to their unique electromagnetic features, which enable the efficient absorption of electromagnetic radiation in a specific frequency range or multiple frequency ranges. These absorbers are useful in many applications such as sensing, filtering, imaging, and photonic devices. Their designs are based on artificially engineered structures that enable tailored absorption properties [1]–[7]. They have been extensively researched due to their potential applications in photonics [2], [3], [5].

Different designs have been proposed in the literature to achieve either broadband absorption or absorption at specific frequencies. Among these designs, split ring resonators (SRRs) and double split ring resonators (DSRRs) are widely used because they provide strong resonance behavior due to their inductive and capacitive properties, as well as their ability to operate across microwave, terahertz, and optical frequency regimes.

In [2], a wideband near perfect light absorber in the mid-wave IR region using a multiplexed plasmonic metal structure is presented. The wideband near-perfect light absorber is made of two different size gold metal squares multiplexed on a thin dielectric spacing layer on top of a thick metal layer in each unit cell. A polarization insensitive and wide-angle broadband nearly perfect absorber by planar MTM in the visible regime is studied in [3]. The bandwidth of the absorption spectrum can be effectively expanded by combining multiple resonant elements. Shimaa I. Sayed et al. [5] designed a highly efficient broadband MTMA based on a Manganese–Silica–Manganese three-layer structure with a shaped pattern at the top layer for maximum absorption efficiency.

Despite the large number of reported designs, most metamaterial absorbers are limited to fixed resonance frequencies that are determined once the geometry is defined. This makes it difficult to systematically control or tune the operating frequency without redesigning the entire structure. In addition, achieving multiple resonance frequencies using a single resonator remains challenging, as many existing approaches rely on combining different resonators or using complex geometries.

Moreover, MTMAs are important for applications such as optical filtering, spectroscopy, sensing, and imaging. However, most of the existing work focuses either on fixed resonance frequencies or on broadband designs, with limited ability to systematically tune or control multiple resonances using a single structure. In many cases, different resonators are combined, or the design is optimized in a trial-and-error manner.

In this work, a DSRR-based absorber is proposed and numerically investigated. The structure is designed to achieve resonances at multiple frequencies in the terahertz region through geometrical scaling without getting complicated structure. The electromagnetic response and underlying resonance mechanisms are analyzed using the FDTD CST Microwave Studio through the simulation of scattering parameters and surface current distributions. The paper is organized as follows: Section II presents the structure design, Section III illustrates the results and discussion, and the work is concluded in Section IV.

II STRUCTURE DESIGN AND BASIC EQUATIONS

The proposed absorber consists of a double split ring resonator (DSRR) printed on a dielectric substrate. The structure is composed of three layers: a patterned metallic DSRR layer on the top, a dielectric spacer layer, and a continuous metallic ground plane at the bottom as illustrated in Fig.1.

The structure is composed of three layers: a patterned silver DSRR layer on the top, a dielectric spacer layer, and a continuous metallic ground plane (silver) at the bottom. The ground layer suppresses electromagnetic transmission, allowing the structure to operate as an efficient absorber. The substrate material of spacer is SiO2 has relative permittivity 3.9, thickness of quarter wavelength, and conductivity of 13.3 * 10^7S/m. Table I depicts the missing dimensions of DSRR.

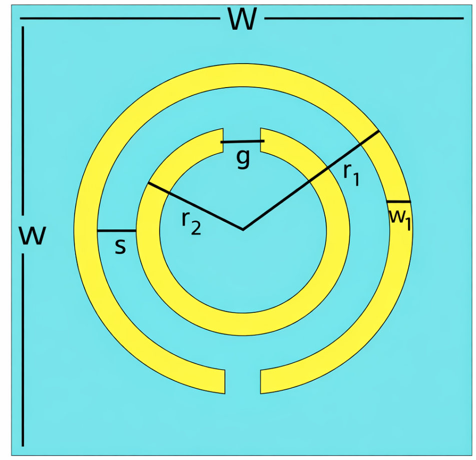
The incident electromagnetic wave is modeled as a plane wave propagating normally to the metamaterial surface, with the electric field oriented parallel to the split gaps. Under this excitation, the electric field induces charge accumulation across the gaps, producing circulating surface currents along the rings.

The resonance frequency of the structure is determined by the effective inductance "L" of the metallic rings and the capacitance "C" introduced by the split gaps. The resonance condition follows the classical LC resonance relation:

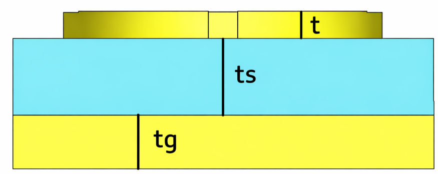
$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

The absorptivity of the structure is calculated from the scattering parameters using the following relation:

$$A(\omega) = 1 - R(\omega) - T(\omega) \quad (2)$$



(a)



(b)

Fig. 1: Unit cell geometry of the proposed DSRR: (a) front view, (b) side view

where $R(\omega)$ and $T(\omega)$ represent the reflection and transmission coefficients, respectively.

Since the ground plane blocks transmission ($T \approx 0$), the absorptivity can be expressed as

$$A(\omega) = 1 - |S_{11}|^2 \quad (3)$$

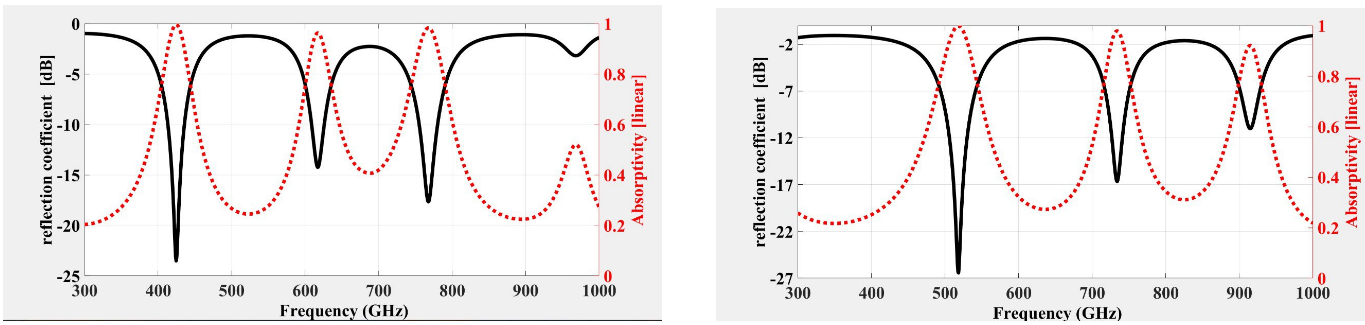
By systematically adjusting the ring dimensions, gap width, and spacing between the rings, the resonance frequency can be tuned across the optical frequency spectrum. The geometrical parameters used for the DSRR structure are summarized in Table I.

III RESULTS AND DISCUSSION

Fig 2 shows the scattering parameters in terms of reflection coefficient and absorptivity of the proposed structure tuned at 423 THz and 518 THz. The simulated reflection coefficients for the designed structures demonstrate clear resonance dips at 423 THz, 518 THz. The depth of these dips indicates strong coupling between the incident electromagnetic field and the resonator with absorption 100% at both resonance. Surface current presented in Fig 3 for the case of 423 THz for explanation and confirmation of resonance (the color gradient from maximum to minimum is donted from red to light blue color). It confirms that the resonance mechanism is primarily driven by electric field induced charge accumulation at the split

TABLE I: Geometrical parameters of the proposed DSRR unit cell for different resonance frequencies.

Parameter	423 THz (nm)	518 THz (nm)	640 THz (nm)	831 THz (nm)
W	288	230.4	180	288
r_1	128	102.4	80	80
r_2	80	64	50	50
w_1	16	12.8	10	10
g_1	32	25.6	20	20
s	32	25.6	20	20
t_g	40	40	40	40
t_s	60	60	60	60
t	32	25.6	20	20



(a) 423 THz

(b) 518 THz

Fig. 2: Simulated reflection coefficient (S_{11}) and absorptivity of the proposed DSRR absorber at (a) 423 THz and (b) 518 THz.

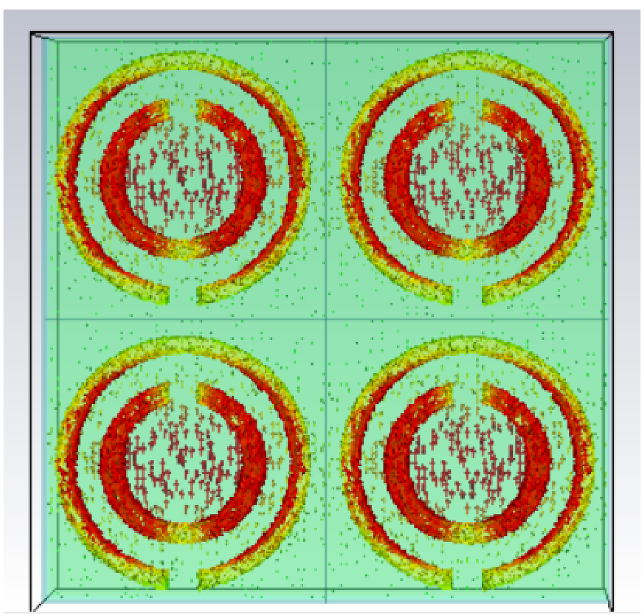
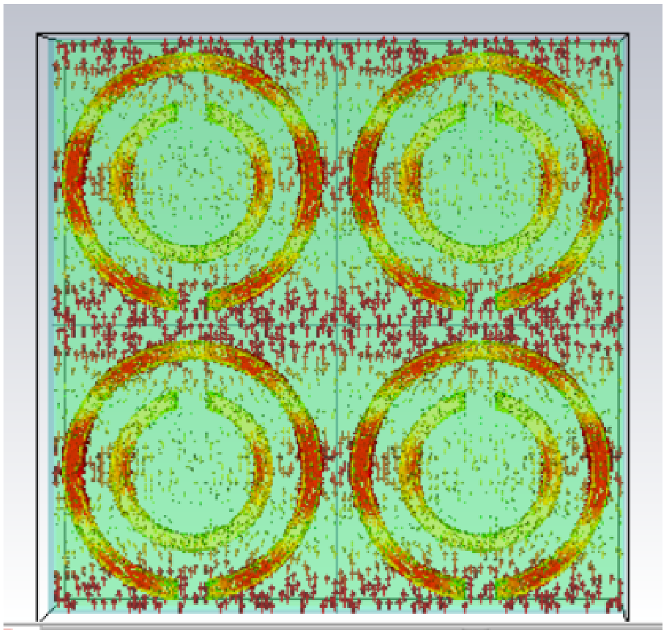
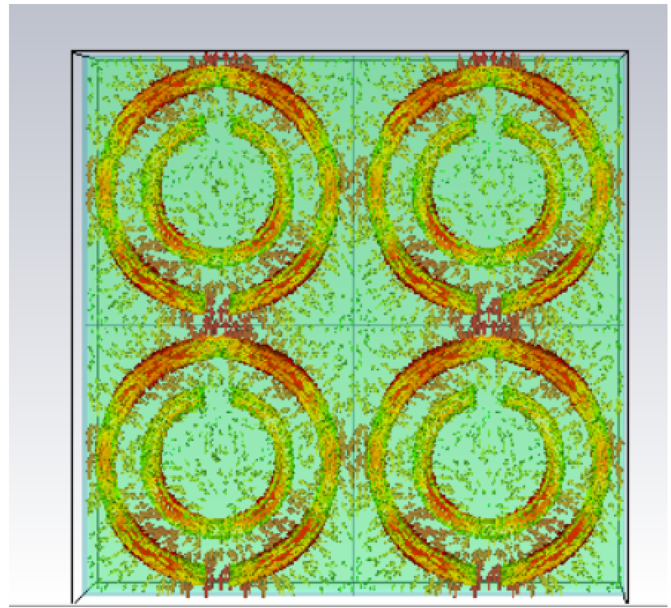


Fig. 3: Surface current of the proposed DSRR absorber at 423 THz.

gaps, leading to circulating currents and energy confinement within the resonator.



(a) 618 THz



(b) 767 THz

Fig. 4: Surface current of the proposed DSRR absorber at (a) 618 THz and (b) 767 THz.

Also it is very important to point out that for the cases of 420 THz and 520 THz designs, multiple resonant dips are observed in the reflection spectrum as depicted in Fig 2. These additional resonances originate from higher order surface current modes supported by the ring structure as well as electromagnetic coupling between the inner and outer rings. This can be confirmed if one see the surface current for the design at 420 THz which originates higher order mode resonance at 617.5 THz and 767 THz) due to the current maxima and nodes depicted at Fig 4 (surface current is gradient from red to light blue color).

Similarly, Fig 5 illustrates the reflection coefficient and the absorption coefficient at 640 THz and 831 THz. At 640 THz, the fundamental resonance remains dominant, while a secondary resonance appears at higher frequencies. In contrast, the 831THz design exhibits only a single dominant resonance within the simulated frequency range. This behavior is mainly attributed to geometrical miniaturization of the resonator and increased material losses at higher frequencies, which suppress higher order resonant modes.

To further evaluate the proposed structure, a comparison is made with previously reported terahertz metamaterial absorbers. Wen et al. reported a dual-band terahertz metamaterial absorber with two distinct absorption points near 0.45 THz and 0.92 THz, where the absorber response is related to two LC resonances generated using an electric split ring resonator structure [8]. Although strong absorption was achieved, the design was limited to only two resonance bands. In another work, Lu et al. proposed an ultrathin terahertz dual-band absorber using an asymmetric double split ring resonator and obtained two almost equal strong absorption peaks at 4.48 THz and 4.76 THz with absorptivity of 98.6% and 98.5%, respectively [9]. In that design, the tuning process depends on introducing asymmetry by shifting the gap position.

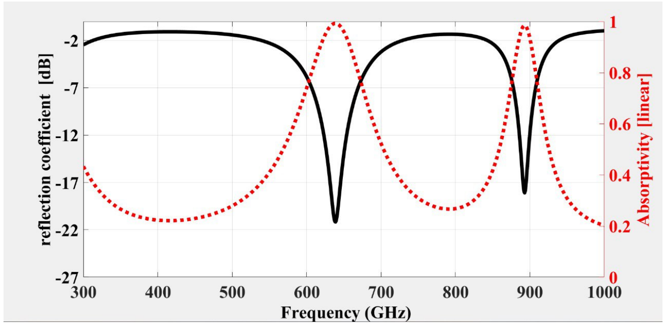
Compared with these works, the proposed design achieves four resonance frequencies using the same DSRR concept through systematic geometrical scaling shown in Table II. In addition, the absorption level in the proposed structure approaches 100% at the designed resonances, while the tuning mechanism is based on changing the physical dimensions of the resonator rather than introducing structural asymmetry or using more complex resonator arrangements. This gives a more direct relation between geometry and resonance behavior and makes the tuning process more predictable.

IV CONCLUSION

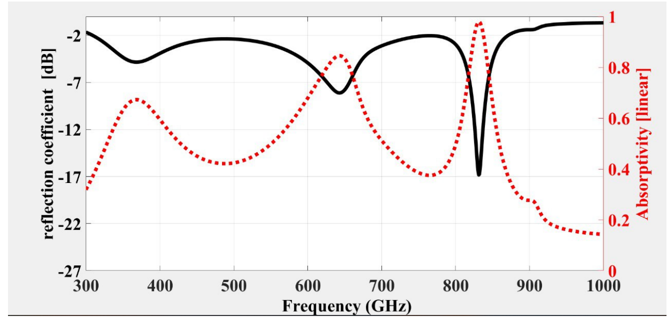
A DSRR-based metamaterial absorber operating in the optical and near-infrared frequency regime has been numerically investigated. By modifying the geometrical parameters of the resonator, the resonance frequency can be tuned from 423 THz to 831 THz. Simulation results demonstrate strong absorption

TABLE II: Comparison with previous works

Work	Structure type	Resonance frequencies	Number of resonances	Peak absorption	Main tuning approach
Wen et al. [8]	Electric split ring resonator (eSRR)	0.45 THz, 0.92 THz	2	Over 99.99% simulated; 80.8% and 63.4% measured	Different split gaps / dual LC resonances
Lu et al. [9]	Asymmetric DSRR	4.48 THz, 4.76 THz	2	98.6%, 98.5%	Gap asymmetry
This work	Geometrically scaled DSRR	423 THz, 518 THz, 640 THz, 831 THz	4	$\sim$100%	Geometrical scaling



(a) 640 THz



(b) 831 THz

Fig. 5: Simulated reflection coefficient (S_{11}) and absorptivity of the proposed DSRR absorber at (a) 640 THz and (b) 831 THz.

at the designed resonance frequencies. Multiple resonances observed in the lower-frequency structures are attributed to higher-order current modes and electromagnetic coupling between the inner and outer rings, whereas the highest frequency design primarily supports the fundamental LC resonance. The proposed DSRR absorber provides a flexible platform for designing frequency-selective optical devices such as sensors, filters, and photonic components.

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