

Received 24 June 2025, accepted 11 July 2025, date of publication 16 July 2025, date of current version 23 July 2025.

Digital Object Identifier 10.1109/ACCESS.2025.3589588

RESEARCH ARTICLE

3D-Printed Lightweight Metamaterial Absorber Using Rectangular Perforations

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This work was supported in part by the National Research Foundation of Korea (NRF) grant funded by Korean Government [Ministry of Science and ICT (MSIT)] under Grant 2021R1A2C3005239; and in part by Chung-Ang University Research Grants, in 2024.

ABSTRACT Metamaterial absorbers (MMAs) are designed to achieve near-total absorption of electromagnetic radiation. In radio-frequency fields, MMAs exhibit absorption behavior that stems from RF resonance. Thus, MMAs are useful in fields such as stealth coatings. However, the use of MMA unit cells for stealth applications is limited due to their heavy weight. In this paper, we demonstrate that a weight reduction of up to 61.31% and a 66.22% decrease in PLA volume can be achieved in a Jerusalem Cross MMA unit cell, with minimal impact on key absorptive properties such as resonant frequency and absorptivity. This was accomplished by selectively removing material from the corners and near-edge regions of the dielectric layer within the unit cell. The simulation results were verified with an array consisting of 12×12 MMA unit cells, where resonant behavior was observed at 10.33 GHz with an absorptivity of 99.84%. Polylactic acid was used as the dielectric material for 3D printing, and the conductive surfaces were fabricated using silver paste. The results of this study demonstrate the feasibility of lightweight MMA designs for real-life applications.

INDEX TERMS 3D printing, lightweight, metamaterial absorber, perforation, resonance.

I. INTRODUCTION

Electromagnetic wave absorbers absorb electromagnetic waves by converting their energy into heat (or other forms), minimizing reflected waves. These electromagnetic wave absorbers play a significant role in modern society, with a range of applications including electromagnetic shielding in wireless communication, stealth technology, and enhancing absorption efficiency in solar energy systems [1], [2], [3], [4], [5], [6], [7], [8], [9]. Recent advances have enhanced the absorber's performance across a broad spectrum, from radio frequencies (RF) to the gigahertz (GHz) range, demonstrating versatility in applications such as signal processing and telecommunications [10], [11]. These absorbers exploit

RF resonance to attenuate electromagnetic waves effectively, making them highly desirable for applications such as stealth technology, where minimizing radar detectability is paramount.

However, conventional electromagnetic wave absorbers often require impractically large thicknesses relative to the targeted wavelength of the waves to be absorbed [12], [13], [14]. Accordingly, electromagnetic wave absorbers that employ metamaterials have been proposed [15]. Metamaterials consist of periodic conductive patterns of metallic substances and thin dielectric layers [16], [17]. Altering these geometries can change the metamaterial's electromagnetic properties, enabling applications that range from antennas to absorbers [18], [19], [20].

Metamaterial absorbers (MMAs) leverage this technology to absorb electromagnetic waves. This approach enables

The associate editor coordinating the review of this manuscript and approving it for publication was Shah Nawaz Burokur¹.

MMA to achieve highly efficient absorption, with applications in radar cross-section reduction and electromagnetic interference mitigation [21], [22]. Moreover, these absorbers can function without special materials [23].

The intrinsic impedance is a unique quantity that characterizes the medium during the propagation of electromagnetic waves and corresponds to a value that is only dependent on the material's inherent parameters. For a metamaterial absorber, the impedance of the metamaterial $Z_m(\omega)(\Omega)$ is given as a function of the frequency using the following formula:

$$Z_m(\omega) = \sqrt{\frac{\mu_m \mu_0}{\varepsilon_m \varepsilon_0}} \quad (1)$$

where μ_m is the relative magnetic permeability of the metamaterial, μ_0 (H/m) is the magnetic permeability of a vacuum, ε_m is the relative permittivity of the metamaterial and ε_0 (F/m) is the permittivity of a vacuum.

If the structure of the absorber is appropriately designed to have the same intrinsic impedance as air, it would also exhibit similar electromagnetic wave behavior [24]. In other words, if $\mu_m/\varepsilon_m = 1$ is achieved, $Z_m(\omega)$ becomes equal to the impedance of air (Z_0). In such absorbers, there is almost no reflection of the incident electromagnetic waves. Taking advantage of this characteristic, high-absorption lightweight electromagnetic wave absorbers can be fabricated using metamaterials, for applications where weight is critical to performance [25]. Artificial intelligence (AI) tools and machine learning can be utilized to simulate performance and predict optimal conditions of the MMAs in advance [26].

The absorption rates of conventional MMAs are usually improved through thicker designs with greater weight. The search for lightweight solutions has driven research into diverse materials and structural optimizations, aiming to reduce weight while maintaining performance, as demonstrated by recent studies on material efficiency and structural design [27], [28], [29], [30].

Previous studies have developed lightweight metamaterial broadband absorbers by using lighter materials including carbon nano tubes (CNTs) [31], [32], implementing much more compact MMA design through graphene [33] or polyimide [34], or adding complementary patterns [35].

This study aims to create a narrowband lightweight absorber that maintains its absorption rates at pre-reduction absorption levels, with a reflection coefficient less than -10 dB. A key novelty of this study is the use of 3D printing not only for the direct fabrication of complex metamaterial absorber (MMA) geometries from CAD models, but also for enabling structural weight reduction through selective material removal. By identifying regions with minimal influence on electromagnetic performance, we introduced strategically placed perforations that significantly reduce the overall mass while preserving high absorption efficiency at target resonance frequencies. This approach demonstrates the unique advantage of additive manufacturing in integrating electromagnetic functionality with mechanical optimization.

II. RESULTS

A. UNIT CELL DESIGN AND SIMULATION RESULT

The MMA was designed based on the Jerusalem Cross (JC) resonator, one of the simplest absorber designs which is invariant to partial elimination of the dielectric layer [36]. Polylactic acid (PLA) was used for the dielectric layer, a commonly used material in 3D printing [31]. The resonator was designed to operate at 5 GHz with a relative permittivity of 2.8. The conductive JC pattern was formed using a silver paste, while a thin copper tape was employed as the bottom ground plane [37]. The parameter values in Fig. 1 are $b_w = 25$, $j_s = 9.5$, $j_w = 1.5$, $h_1 = 9.0$, $h_2 = 6.0$, $w_t = 0.5$, $e_s = 0.2$, $e_b = 0.2$, and $e_w = 2.0$ (unit: mm). The unit cell geometry was studied using the finite element method-based EM software ANSYS High-Frequency Structure Simulator (HFSS). In the fabricated MMA, the relative permittivity and loss tangent of the PLA were measured to be 2.525 and 0.055, while the resistance of the silver paste used in the JC pattern was found to be 2.6 Ω .

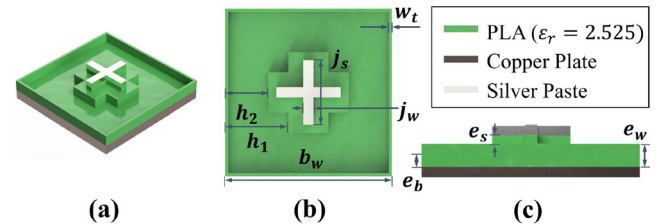


FIGURE 1. Proposed unit cell. a 3D view, b top view, and c side view of the proposed unit cell.

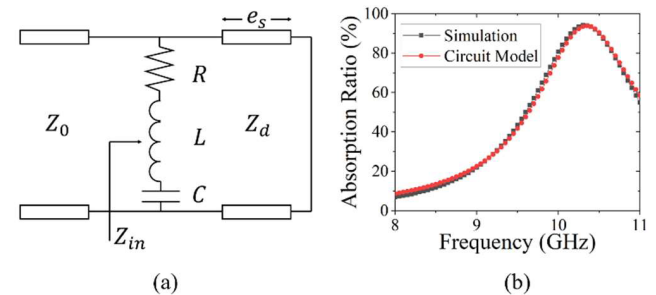


FIGURE 2. a Equivalent circuit and b comparison of simulated and calculated absorption ratios of MMA. Z_0 , Z_d , and Z_{in} are the characteristic impedances of free space, dielectric substrate, and metamaterial, respectively.

Absorption ($A(\omega)$) can be expressed as

$$A(\omega) = 1 - \Gamma(\omega) - T(\omega) \\ = 1 - |S_{11}(\omega)|^2 - |S_{21}(\omega)|^2, \quad (2)$$

where $T(\omega)$ represents the transmission coefficient, and $\Gamma(\omega)$ is the reflection coefficient expressed as

$$\Gamma(\omega) = \frac{Z_0 - Z_{in}(\omega)}{Z_0 + Z_{in}(\omega)}, \quad (3)$$

where $Z_{in}(\omega)(\Omega)$ is the impedance of the metamaterial. Since the copper plate is on the far side of the MMA, the transmission coefficient can be assumed to be 0. Thus, the absorption

ratio equals 1 when $\Gamma(\omega) = 0$. Using equation 3, this condition is achieved when $Z_0 = Z_{in}(\omega)$. From equation 1 and using $\mu_{air} \cong 1$ and $\varepsilon_{air} \cong 1$, the impedance of the transmission line Z_0 can be calculated as approximately 377Ω . Impedance matching of the equivalent circuit, illustrated in Fig. 2(a), was achieved using values of 0.01 pF, 20.49 nH, and 75.7Ω for effective capacitance (C), inductance (L), and resistance (R), respectively.

Fig. 2(b) shows good agreement between the absorption ratios calculated from the circuit model and the full-wave simulation. The parameters b_w , j_s , and j_w were selected based on considerations of 3D printability, resonance frequency range of 8 to 12 GHz, and reflection coefficient (S_{11}) value less than -10 dB.

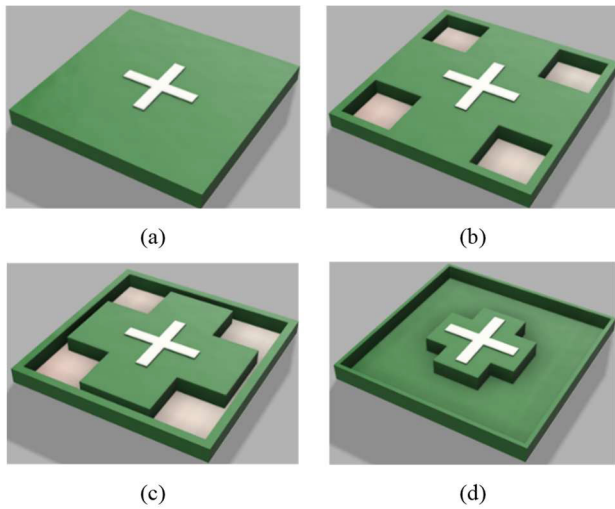


FIGURE 3. Steps of unit cell weight reduction: a unit cell before perforations, b square perforations on corners, c line-like perforations on edges, d addition of bottom plate and trimming of cell walls.

We initially carved square holes at the four corners of the unit cell with a 1 mm margin, as depicted in Fig. 3(a) and Fig. 3(b), to reduce weight without affecting electromagnetic performance. Subsequently, as shown in Fig. 3(c), we extended the perforations along the edges of the unit cell with the same 1 mm margin, further removing low-impact material and thinning the sidewalls. Finally, in Fig. 3(d), a PLA bottom plate with a thickness of 0.2 mm was added beneath the unit cell to close the openings. This bottom plate was introduced to eliminate the need for temporary support structures during 3D printing, which are typically difficult to remove and may compromise dimensional accuracy. This design evolution allowed us to achieve a lightweight structure while maintaining both mechanical stability and fabrication reliability.

The mass of a unit cell for each of the steps in Fig. 3(a), (b), and (d) was measured to be 267.8 g, 178.6 g, and 103.6 g, respectively, corresponding to weight reductions of 33.31% and 61.31% at the perforation stages depicted in Fig. 3(b) and Fig 3(d), respectively. Additionally, the design shown

in Fig. 3(d) requires 66.22% less PLA material, by volume, compared to the design in Fig. 3(a).

Fig. 4 displays the simulated absorption ratio values of the original JC design and weight-reduced final design.

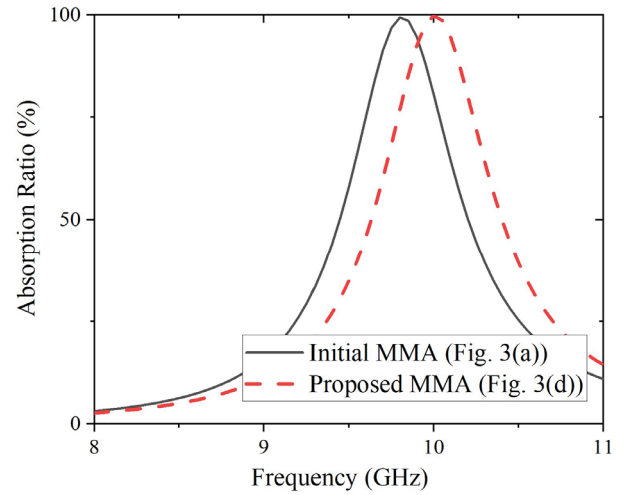


FIGURE 4. Absorption ratio of the initial MMA (Fig. 3(a)) and the proposed MMA (Fig. 3(d)).

Fig. 5 displays the simulation results from varying parameters j_s and b_w in the ranges of 8.0–10.1 and 22–27, respectively, with h_1 and h_2 as 0 (unit: mm). It is shown that the increase of j_s is correlated with a reduction in the resonant frequency. Within the specified range, alterations negligibly affected the reflection coefficient.

Given the potential for slight variations in resonance frequency and reflection coefficient resulting from unit cell weight reduction, it was imperative to establish a baseline model that was resilient to such alterations. A resonant frequency near 10 GHz and a reflection coefficient sufficiently low were the determined requisite attributes.

From the simulation results, the following values were selected as a starting point for reducing the weight of the MMA unit cell: $j_s = 9.5$ mm, $j_w = 1.5$ mm, and $b_s = 25$ mm. Fig. 6(a) displays the simulation results for the variations in the width of the square perforations displayed in Fig. 3(b). The resonant frequency of the initial MMA was found to be 9.8 GHz. We selected the width of the perforated square as 8.5 mm, which, accounting for the 0.5 mm wall thickness, resulted in a final value of $h_1 = 9.0$ mm. The rationale behind this choice is elaborated in the following simulation.

Fig. 6(b) displays the simulation results for variations in the width of the line-like perforations alongside the edges of the MMA with a margin of 1 mm, as displayed in Fig. 3(c). The simulation results indicated that as the width of the line-like perforation increased, the resonant frequency also increased. To maintain the resonant frequency of the proposed MMA within ± 0.5 GHz of that of the initial MMA, we selected 5.5 mm as the width of the line-like perforation, which, accounting for the 0.5 mm wall thickness, resulted in a final value of $h_2 = 6.0$ mm.

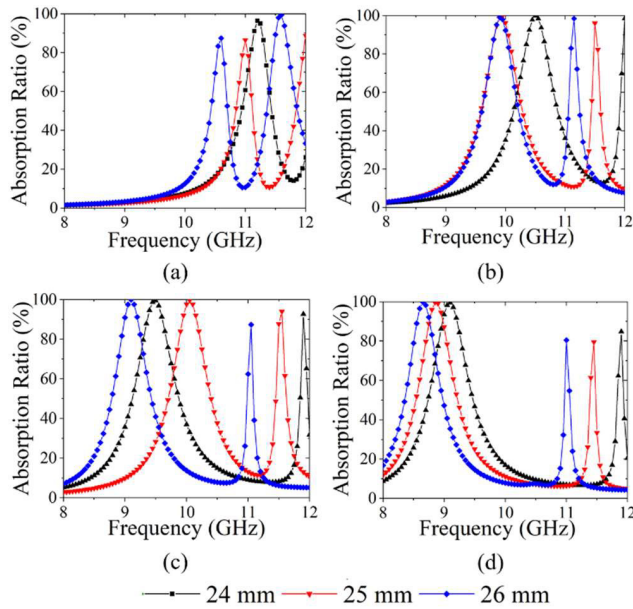


FIGURE 5. Reflection coefficient for different values of b_w : a when $j_s = 8.0$ mm b $j_s = 8.9$ mm c $j_s = 9.5$ mm d $j_s = 10.1$ mm.

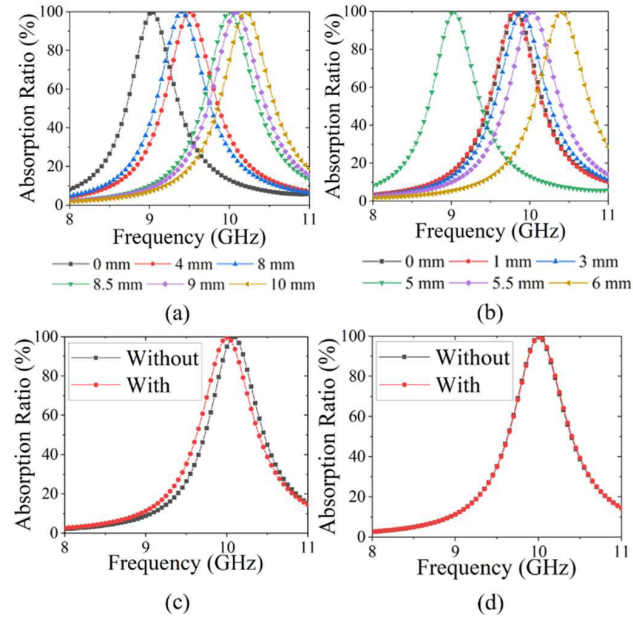


FIGURE 6. Change of MMA performance over a width variation of square perforation, b width variation of line-like perforation, c existence of a bottom plate, and d wall trim.

Fig. 6(c) and Fig. 6(d) present the simulation results comparing the structures with and without a 0.2 mm-thick bottom plate, and before and after trimming the walls by 0.5 mm, respectively. In both cases, the absorptive performance shows negligible variation, indicating that these structural modifications do not compromise electromagnetic functionality. Nonetheless, these design adjustments are essential: the addition of the bottom plate simplifies the fabrication process by eliminating the need for support structures—which are often

unnecessary and prone to removal errors—while wall trimming effectively reduces the overall weight of the structure.

Fig. 7(a) and Fig. 7(b) represent the resonant frequency variation as a function of removed area in the structure shown in Fig. 3(b) and the structure in Fig. 3(c), respectively. The data points are selected based on the perforation values and their associated resonant frequencies illustrated in Fig. 6(a) and Fig. 6(b). The x-axis represents the cumulative perforated area, while the y-axis indicates the corresponding resonant frequency. As the cumulative removed area increases, the effective dielectric constant of the MMA decreases, resulting in a higher resonant frequency. In Fig. 7(a), the resonant frequency is 9.8 GHz when no area is removed and increases to 10.4 GHz when 400 mm² is removed (i.e., 10mm perforation in Fig. 6(a)). The corresponding bandwidths are 0.15 GHz and 0.2 GHz. In Fig. 7(b), the resonant frequency increases from 9.05 GHz at 289 mm² of removed area (i.e., $h_1 = 9.0$ mm, no line-like perforation steps applied) to 10.2 GHz at 481 mm² (i.e., $h_1 = 9.0$ mm, $h_2 = 6.5$ mm). The respective bandwidths are also 0.15 GHz and 0.2 GHz. This trend is clearly illustrated in the graphs in Fig. 7.

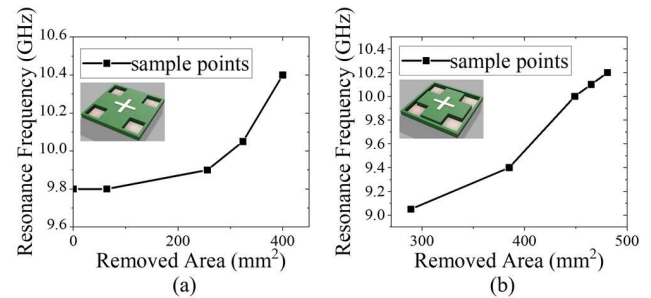


FIGURE 7. Resonance frequency variation as a function of removed area in a the structure shown in Fig. 3(b) and b the structure in Fig. 3(c). The total unit cell area is 625 mm².

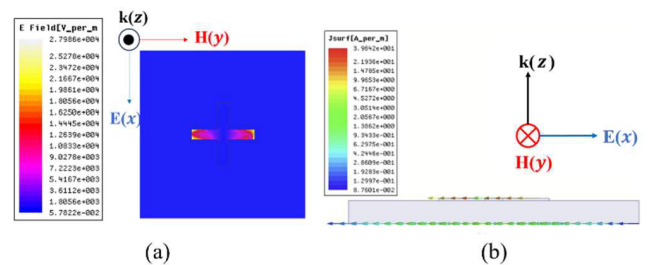


FIGURE 8. a Electromagnetic field magnitude and b current density vector.

Owing to the selected sizes for the square and line-like perforations, we selected $h_1 = 9.0$ mm and $h_2 = 6.0$ mm for the final design. The resonant frequency for the final design was 10.0 GHz, with a difference of +0.2 GHz from the initial MMA design. The JC MMA operates through LC resonance, as demonstrated by the simulation results in Fig. 8, which displays an instance of oscillating electric field magnitude and current density vectors. In this system, the conductive regions (comprising silver paste and copper ground) functioned as the electrical components of an LC circuit, resulting

in effective RF absorption. Furthermore, the electric field and current density vectors are weakly present at the corner and edge PLA parts of the unit cell. This suggests that those parts have negligible influence on the overall absorptive behavior of the MMA.

The unit cell depicted in Fig. 1 exhibits four-fold rotational symmetry, which yielded reflection characteristics independent of the polarization angle (ϕ) of the incident electromagnetic (EM) wave at normal incidence, as illustrated in Fig. 9. The angular stability of the structure was assessed by evaluating its response under transverse electric (TE) and transverse magnetic (TM) polarizations.

The results shown in Fig. 10(a) and Fig. 10(b) illustrate the absorption performance under oblique incidence for TE and TM polarizations, respectively, up to an incidence angle of 30° . As the angle increases, the absorption characteristics gradually deviate from those observed at normal incidence ($\theta = 0^\circ$), particularly beyond 20° . The response in TM mode remained consistent with that in TE mode, as illustrated in Fig. 10(b) for $\phi = 90^\circ$.

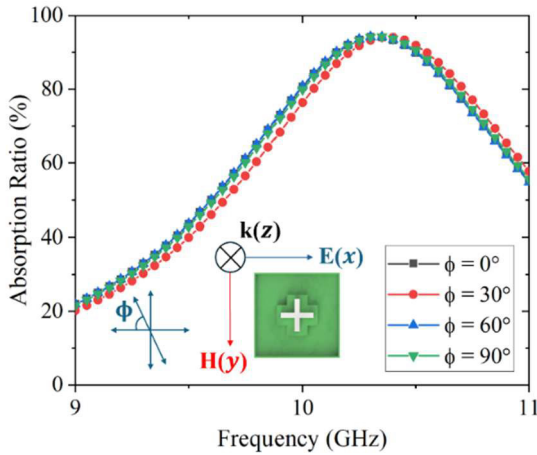


FIGURE 9. Simulation results based on polarization angle at normal incidence.

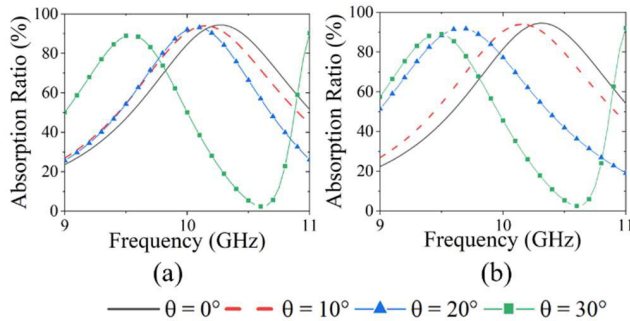


FIGURE 10. Simulation absorption ratio under oblique incidence for a TE and b TM mode.

B. FABRICATION AND MEASUREMENTS

The proposed model was 3D printed using PLA. After 3D printing, silver paste was applied to the conductive regions.

The absorber was dried in an oven at 60° for 24 hours. After drying, copper tape was affixed to the back of the substrate to serve as the conductive layer.

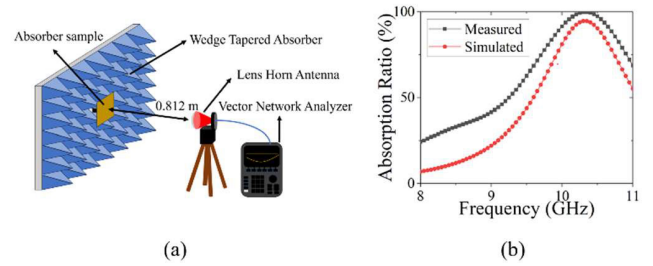


FIGURE 11. a Measurement environment of the proposed absorber. b Comparison of absorption ratio between simulated results and fabricated sample.

Fig. 11(a) displays the measurement setup for assessing the fabricated sample. A wedge tapered absorber (WTA) was used to reduce electromagnetic wave noise. We fixed the copper plate to the WTA and installed a lens horn antenna (LHA-30-WR90) in front of the copper plate, aligned at the same height. Plane waves were generated by the antenna, and the reflected waves were measured using a vector network analyzer N9951A (VNA), with time gating applied. First, we measured the reflective properties of the underlying copper plate. Secondly, we placed the MMA in front of the copper plate and measured the reflective properties. Then, we evaluated the absorptivity of the MMA by comparing the values with and without the MMA. The net S_{11} value of the MMA was obtained by subtracting the calibration setup's S_{11} values from those of the second measurement. Fig. 11(b) compares the final simulation results of the absorption ratio with the results measured from the experiment.

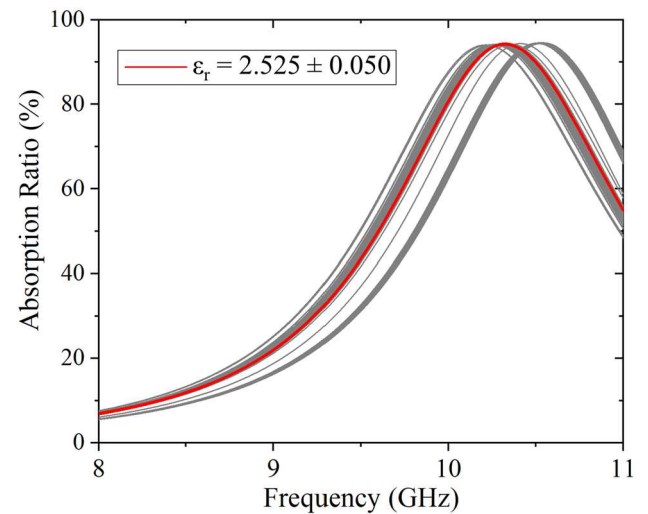


FIGURE 12. Simulated absorption spectra for varying relative permittivity values of PLA ($\epsilon_r = 2.525 \pm 0.050$).

Fig. 12 represents the simulated absorption spectra obtained by sweeping the PLA's relative permittivity from

2.475 to 2.575 in 0.002-unit increments. The sweep range corresponds to a ± 0.050 variation around the nominal value of 2.525. The ± 0.050 range reflects known uncertainty in the dielectric properties of PLA in the microwave band, based on prior measurements [38]. The ± 0.050 error range in relative permittivity results in a 10.35[+0.20, -0.15] GHz and a 94.1395[+0.3394, -0.1143]% range in resonance frequency and absorption, respectively. The results show that the resonance frequency shifts moderately with permittivity variation, but the absorption remains above 90% within the target band. In addition, simulation results reveal a resonance frequency sensitivity of approximately 3.5 GHz/ ϵ , indicating that the absorptivity peak is moderately affected by the variations in the dielectric constant.

III. MATERIALS AND METHODS

A. SIMULATIONS

All the numerical simulations were performed via the Ansys high-frequency structure simulator (HFSS). To simulate the periodic boundary conditions of unit cells, master/slave boundaries and Floquet ports were utilized.

Material coefficients were calibrated to match the absorptivity curves of the experimental and simulation data, by grid-searching the PLA loss tangent in the range of 0.03-0.06, step = 0.005, relative permittivity for PLA 2.5-2.8, step = 0.05, silver paste resistance from 0.2 to 3 Ω in 0.4 Ω increments. The grid-search results were sorted by MSE (Mean Square Error), standard deviation, maximum absorptivity frequency difference.

An equivalent circuit was determined based on the calibrated material coefficients, with values of 0.01 pF, 20.49 nH, and 75.7 Ω for effective capacitance (CC), inductance (LC), and resistance (RC), respectively.

B. FABRICATION

A Sindoh PLA printer was utilized to fabricate the absorber. Layer settings were set to: layer height = 0.1 mm, initial layer height = 0.1 mm, all width factors as 100%, wall thickness = 0.8 mm, top/bottom thickness 0.2 mm. Print temperature was set to 200°C, while the bed temperature was set to 55°C. Print speed was set to 80 mm/s for infill and top/bottom, 10 mm/s for the initial layer, and 40 mm/s and 80 mm/s for the outer and inner walls, respectively. The travel speed of the nozzle was set to 130 mm/s. No support was used, yet a raft was utilized. Silver paste (Dycotec DM-SIP-2002) was applied by hand on the Jerusalem cross structure printed in relief, after which the MMA was dried in a 60°C oven for 24 hours. Manual application of silver paste may affect uniformity. Nevertheless, the effect is negligible since only 6 out of 144 unit cells (4.16%) deviate more than 0.5 mm, which does not severely alter the absorbance quality. Fabrication errors caused by the 3D printer may affect performance of the MMA. Changes in the absorptive properties of the MMA due to variations in b_w are provided below.

To evaluate the effect of geometric tolerance during 3D printing, Fig. 13 shows simulation results for unit cell widths

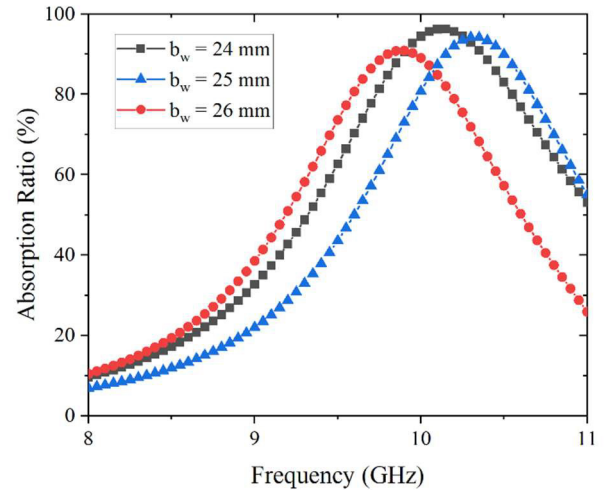


FIGURE 13. Simulation results based on variations in b_w .

$b_w = 24$ mm, 25 mm, and 26 mm. Simulated absorption ratios were 96.25%, 94.16%, and 90.88%, and their resonance frequencies were 10.15 GHz, 10.30 GHz, and 9.90 GHz, respectively. Variations in unit cell size introduce observable resonance shifts, underlining the importance of dimensional precision in fabrication.

C. MEASUREMENT

An X-band lens horn antenna (LHA-30-WR90) was used to measure the plane wave absorptivity of the MMA, as depicted in Fig. 10(a). In addition, a vector network analyzer N9951A (VNA) was used for the measurements.

As shown in Fig. 11(b), the measured absorption is higher than the simulated result across the 8–11 GHz frequency range. This discrepancy is primarily attributed to the non-ideal conditions of the experimental setup illustrated in Fig. 11(a). In particular, part of the incident wave energy is likely scattered or reflected within the measurement environment and not fully received by the horn antenna connected to the VNA. This underestimation of received reference power causes the measured absorption to appear artificially higher than in simulation, which assumes ideal plane-wave excitation and perfect energy confinement. Nevertheless, the measured absorption remains within a practically acceptable range and confirms the expected performance of the designed MMA. For enhanced measurement accuracy and closer agreement with simulation, future experiments should be conducted in a fully anechoic chamber with a larger absorber sample and a more uniform plane wave source. These improvements would help eliminate multipath interference and signal loss, thereby providing a more precise assessment of absorption characteristics.

IV. CONCLUSION

Utilizing the Jerusalem Cross structure, we designed a metamaterial unit cell and verified its absorption characteristics through electromagnetic simulation using HFSS

and experimental fabrication via 3D printing. Resonance was observed at 10.0 GHz with a reflection coefficient of -26.58 dB. A 12×12 array of these unit cells was fabricated to form an MMA sample, and its absorption performance was measured using a vector network analyzer (VNA), yielding a peak absorption of 99.84% at 10.33 GHz. The proposed design achieved a 61.31% reduction in total weight and a 66.22% reduction in PLA material volume compared to the initial unperforated model. In addition, the fabricated MMA exhibited a 90% absorption bandwidth from 10.00 GHz to 10.65 GHz, corresponding to a fractional bandwidth of 6.3%. These results demonstrate that the structurally optimized MMA can significantly reduce material usage and overall mass while maintaining excellent broadband absorption performance.

ACKNOWLEDGMENT

(Junhyuk Ahn and Heeju Jwa contributed equally to this work.)

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