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Miniaturized Metamaterial Absorber Using Three-Dimensional Printed Stair-Like Jerusalem Cross

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ABSTRACT In this paper, we propose a metamaterial absorber using 3-D printing technology. To miniaturize the footprint size of a unit cell, we introduce a 3-D printed stair-like Jerusalem cross (JC) structure. It is demonstrated that the absorption frequency can be decreased by building up one and two stairs from the planar JC. In this paper, the unit cell footprint size of the three-stair JC is reduced by 41% compared with the unit cell footprint size of the planar JC. The proposed metamaterial absorber with 9×9 unit cells is fabricated using a 3-D printer. Poly lactic acid is used as a dielectric material for 3-D printing, and a conductive pattern is realized by applying the silver paste to the 3-D printed dielectric structure. The simulated and measured absorptivity are 99.9% and 99.8%, respectively, at 5.18 GHz. Due to the symmetric unit cell structure, the absorptivity does not change, although the incident polarization gets rotated.

INDEX TERMS Electromagnetic absorber, Jerusalem cross, metamaterial, miniaturization, 3D printing.

I. INTRODUCTION

Metamaterials [1], which have been studied in many fields in recent years, have the advantage that they can artificially adjust the properties of materials by periodically listing the unit structures. These features of metamaterial are used in super lenses [2], invisible cloaking [3], microwave circuits [4], and so forth. Recently, the technology of metamaterial has also been applied to electromagnetic wave absorbers [5]–[8].

Previously, electromagnetic wave absorbers were designed as wedge-tapered absorbers [9] or Jaumann absorbers [10], which are expensive and bulky. On the contrary, as the metamaterial electromagnetic wave absorber is manufactured using a printed circuit board (PCB) [11], it is cheaper than a conventional absorber and has a high absorption rate even with a thin thickness. However, there is a limitation in that absorbers fabricated with metamaterials using PCBs can be designed only in a planar structure. However, a recently introduced 3-dimensional (3D) printed metamaterial absorber can overcome this limitation. Three-dimensional printing can be used to create 3D structures that are difficult to produce with PCBs [12]. In addition, as only a 3D printer is required for production, the absorber can be manufactured at a lower cost than a PCB absorber.

As the metamaterial absorber is designed assuming an infinite periodic structure, the greater the number of unit structures arranged in the actual manufacturing, the greater the errors in the measurement results. Therefore, the footprint size of the unit structure must be reduced so that as many unit structures as possible can be listed within a limited area. However, since the unit area of the unit cell widens as the resonance frequency of the metamaterial absorber decreases, various methods for reducing the unit area at the same resonance frequency have been studied. Representative methods include special design [13], [14], multi-layer design [8], [15], using a chip element [8], [16] and so forth. However, these methods have the disadvantage that they are difficult and expensive. To solve these problems, we propose a metamaterial absorber fabricated by 3D printing. The proposed metamaterial absorber has a three-layer stair-like Jerusalem cross (JC) structure as a unit cell. In general, the resonance frequency of the JC structure, which is the basis of the unit cell of the proposed absorber, decreases as the length is increased [17]. We have designed a stair-like structure so that

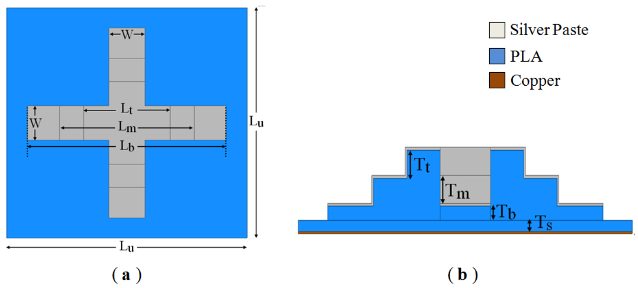

FIGURE 1. (a) Top view and (b) side view of the proposed unit cell: $L_u = 20$, $L_t = 7$, $L_m = 11$, $L_b = 16.5$, $W = 3$, $T_t = 1$, $T_m = 1$, $T_b = 0.5$, and $T_s = 0.4$ (unit: mm).

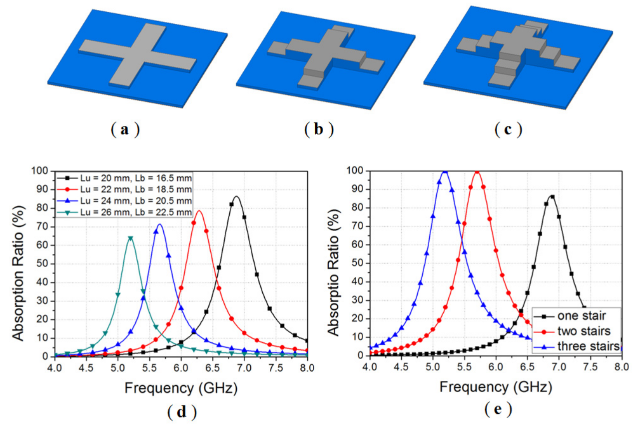

FIGURE 2. 3D view of (a) one-stair, (b) two-stair, (c) three-stair structures and simulated absorption ratio of metamaterial absorber (d) with one-stair unit cell for various values of L_u and L_b and (e) for various numbers of stairs.

the length of the JC in the same unit area can be longer than in a conventional planar structure.

II. DESIGN AND SIMULATION

A. UNIT CELL DESIGN

The proposed absorber is designed based on the JC resonator to intuitively show the effect of the stair-like structure. Fig. 1 shows the design of proposed unit cell. The proposed unit cell has a stair-like JC structure on the substrate and a conductor pattern on the stair-like structure and the bottom ground. We used poly lactic acid (PLA) [18], which is generally used for 3D printing, for the stair-like JC structure and substrate. In order to extract the dielectric constant and loss tangent of the PLA, the resonator is designed at 5 GHz. From measured S-parameter, the extracted dielectric constant and loss tangent of the 3D printed PLA are 1.85 and 0.1, respectively [19]. We used silver paste [20] to form the conductor pattern and a copper plate as the bottom ground. In the top view of the proposed unit structure shown in Fig. 1 (a), the length of the JC appears as Lb. However, as shown in Fig. 1 (b), the length of the proposed JC is the sum of the lengths of Lb, Tt, and Tm since the actual area of the silver paste includes not only the horizontal side but also the vertical side. The values of the parameters in Fig. 1 are $L_u = 20$, $L_t = 7$, $L_m = 11$, $L_b = 16.5$, $W = 3$, $T_t = 1$, $T_m = 1$, $T_b = 0.5$, and $T_s = 0.4$ (unit: mm).

Fig. 2 shows the variation of design and absorption ratio as the number of stairs of the absorber was increased. The proposed unit cell of the absorber is based on a JC as shown in Fig. 2 (a), and it is designed by stacking a stair-like structure as shown in Fig. 2 (b) and Fig. 2 (c). The performance of the proposed absorber was assessed by simulation using a high-frequency structure simulator (HFSS). Fig. 2 (d) shows the simulation result of a different JC unit cell, as shown in Fig. 2 (a), by fixing different parameters and changing the size of the unit area and the length of the JC. Simulation results showed that the resonance frequency decreased from 6.87 GHz to 5.2 GHz when the other parameters of a one-stair JC unit cell were fixed, and L_u was increased from 20 mm to 26 mm, and L_b was increased from 16.5 to 22.5 mm. Fig. 2 (e) shows the simulated changes absorptivity when all the parameters of the JC unit cell were fixed and the number of stairs of the JC were increased. The simulation results show that the resonance frequency decreased as the number of stairs of the JC were increased. It was confirmed that the resonance frequency, which was 6.87 GHz for one stair, decreased to 5.7 GHz for two stairs and 5.18 GHz for three stairs.

To lower the resonance frequency, the method of increasing the unit area and the size of the JC was used for the results shown in Fig. 2 (d), and the method of increasing the number of stairs of the JC structure was used for the results shown in Fig. 2 (e). The unit cell had resonance at 5.2 GHz when the unit area was 26 mm × 26 mm, as shown in Fig. 2 (d), and the unit cell had resonance at 5.2 GHz when the unit area was 20 mm × 20 mm as shown in Fig. 2 (e). Comparing the overall volume of the unit structure when whose resonance frequency at 5.2 GHz, the structure with increased JC size with one stair is 333.4mm and the structure with three stairs is 400mm. The overall volume of the three stairs structure is slightly larger. But comparing the footprint sizes of both unitcells, the three stairs structure is smaller.The results show that the three-stair JC unit cell, which is the proposed absorber structure, has a 41% reduced footprint size in comparison to the one-stair JC structure with the same resonance frequency.

B. SIMULATION RESULT

Fig. 3 shows the simulation results obtained with variation of the parameters of the proposed absorber. Figs. 3 (a) to (c) show changes in the absorption ratio and resonance frequency with changes in the length of the proposed JC of the absorber. Figs. 3 (a) to (c) show the simulation results of the proposed metamaterial absorber when the lengths of the first, second, and third layers of the JC were changed, respectively, while the other parameters were fixed. As seen in the simulation results, the resonance frequency decreased as L_b was increased, and the resonant frequency did not change much when L_m and L_t were increased. The reason for this change

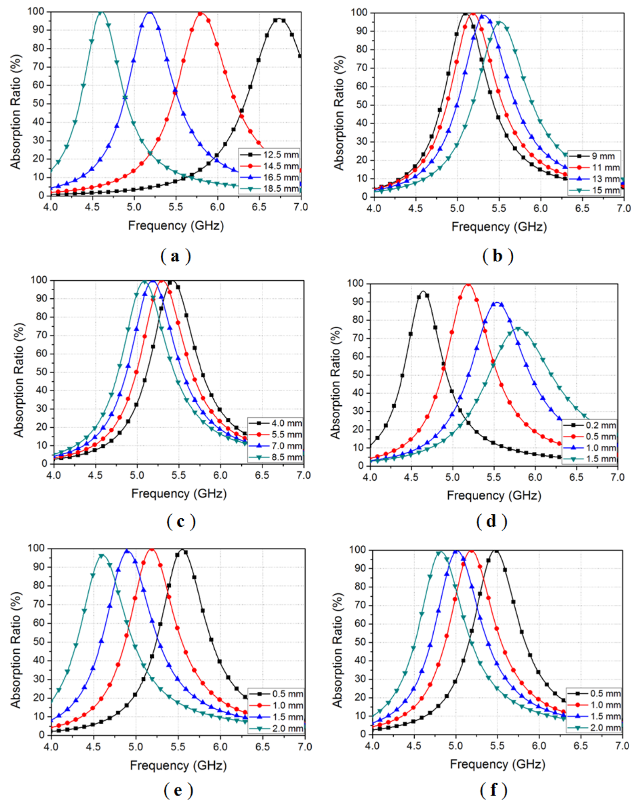

FIGURE 3. Simulated absorption ratio of proposed absorber with variation of (b) L_b, (b) L_m, (c) L_t, (d) T_b, (e) T_m, and (f) T_t.

seems to be that the total length of the stair-like JC increased when Lb was increased, but there was not a large change in the total length of the stair-like JC when Lm and Lt were increased. Figs. 3 (d) to (f) show the simulation results of the proposed metamaterial absorber when the thickness of the first, second, and third layers of the JC were varied, respectively, while the other parameters were fixed. The simulation results in Fig. 3 (d) show that the frequency increased as the thickness of the first layer T_b of the JC was increased. This is because the distance between the conductor pattern and the ground changed as the thickness of the first layer increased. On the other hand, when we changed the thicknesses of the second and third layers of the JC, as shown in Fig. 3 (e) and Fig. 3 (f), the results are the opposite of the simulation results in Fig. 3 (d). In the simulation results, the resonance frequency decreased when T_m and T_t were increased. The reason is that T_b does not affect the total length of the stair-like JC, but the total length of the stair-like JC increases when T_t and T_m are increased.

In general, the metamaterial absorber is working from electric and magnetic (LC) resonance. For instance, the conductive pattern on the top plane creates the electrical response and the magnetic response is generated by the current loop flowing in the top and bottom conductors. In the proposed absorber, Figure 4(a) and (b) shows the magnitude of the electric field where electric response can be demonstrated.

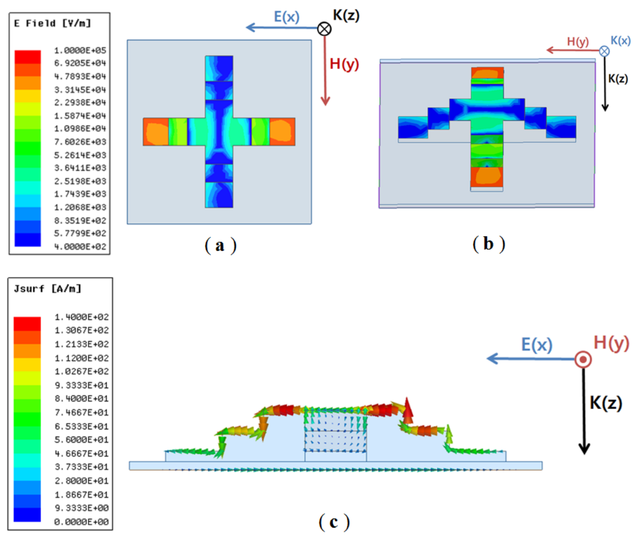

FIGURE 4. (a) Top view and (b) side view of E-field distribution of proposed absorber and (c) side view of surface current distribution of proposed absorber.

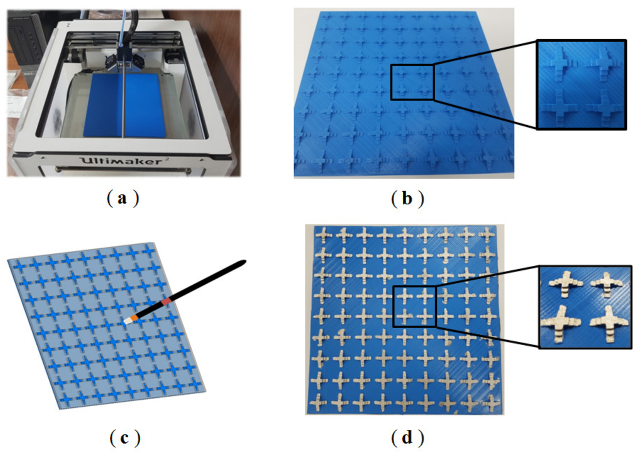

FIGURE 5. Fabrication process of the 3D printed absorber sample: (a) printing substrate using 3D printer, (b) printed substrate of sample (c) painting silver paste using brush, and (d) fabricated sample of proposed absorber.

In addition, the anti-parallel currents on the top and bottom planes generate current loop which can be observed from the electric current distribution as shown in Figure 4(c). Because dielectric loss of a material is enhanced at the LC resonant frequency of the metamaterial absorber, high absorptivity can be achieved with a thin substrate.

III. FABRICATION AND MEASUREMENT

A. SAMPLE FABROCATION

Fig. 5 shows the fabrication of a sample for assessment of the proposed metamaterial absorber. First, the PLA substrate of the proposed metamaterial absorber was formed by 3D printing by an Ultimaker 2 printer as shown in Fig. 5 (a). A sample of the proposed metamaterial absorber was fabricated with a size of 180 mm × 180 mm with 9 × 9 unit

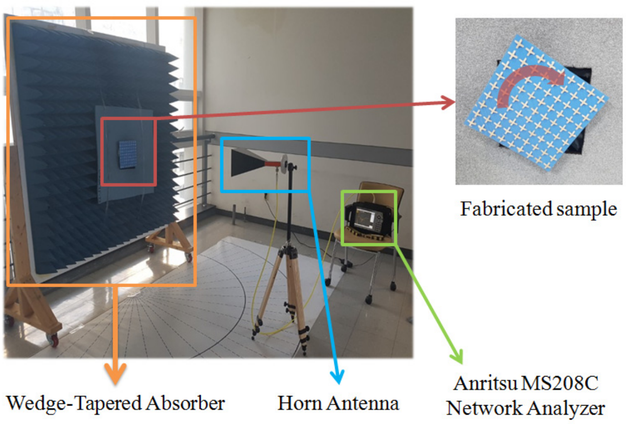

FIGURE 6. Photograph of measurement setup.

cells as shown in Fig. 5 (b). The conductor pattern of the proposed absorber was painted with a commercially available silver paste called ELCOAT. A cover was used to prevent the silver paste from sticking to the outside of the pattern, and silver paste was applied to the substrate using a brush. Finally, the bottom ground was implemented by attaching copper tape to the bottom surface. Fig. 4 (d) shows the sample metamaterial absorber with a stair-like JC structure fabricated by 3D printing.

B. MEASUREMENT SETUP

Fig. 6 shows the measurement setup for assessing the fabricated sample [21]. We measured the absorption ratio with an Anritsu MS2038C vector network analyzer, wedge-tapered absorber, and a horn antenna. The wedge-tapered absorber was installed on the back of the sample to prevent other waves reaching the sample. The horn antenna was positioned 1 m from the sample absorber to satisfy the far-field condition. We measured the absorptivity of the proposed absorber by comparing the signal reflected from the proposed absorber sample and that from a copper plate of the same size as the sample. To assess the absorptivity of the metamaterial absorber, which varies with polarization angle, it was also measured in various polarization environments. To create various polarization angles, we measured the absorptivity by rotating a plastic holder holding the sample.

C. MEASUREMENT RESULT

Fig. 7 shows the measured absorption ratio of the sample proposed absorber. Fig. 7 (a) shows the simulation and measured results of the proposed absorber. The absorption rate of the proposed absorber was 99.9% at 5.18 GHz in the simulation result and 99.8% at 5.18 GHz in the measurement results. As a frequency is farther away from a resonant frequency, difference between simulation and measurement results is observed. It is due to the limitation of our measurement setup. In order to eliminate the undesired signal, we used the time gating in the network analyzer. This calibration is working

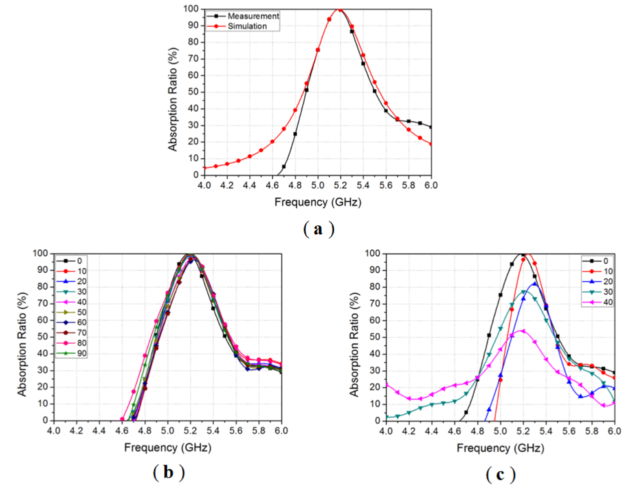

FIGURE 7. (a) Measured and simulated absorption ratio of proposed absorber and (b) measured absorption ratio for various polarization angles and (c) incidence angles.

TABLE 1. Size comparison of the proposed metamaterial absorber with other metamaterial absorbers.

	Freq. (GHz)	Footprint Size: Electrical Size ($\lambda \times \lambda$)	Footprint Size: Physical Size (mm^2)	Overall Volume: Electrical Volume ($\lambda \times \lambda \times \lambda$)	Overall Volume: Physical Volume (mm^3)
[14]	0.4	0.17	3906	0.016	54684
[8]	10.28	0.19	7.29	0.017	4.08
[8]	4.08	0.35	123.6	0.018	123.6
[17]	0.868	0.59	490	0.13	3186
This Work	5.18	0.47	400	0.012	295

Electrical length and volume are calculated at a resonant frequency.

well near a resonant frequency. In addition, lower than 50% absorptivity is difficult to measure due to dynamic range of the given measurement setup. Therefore, the measured absorption ratio is lower than the simulated absorption ratio from 4 – 4.8 GHz.

Fig. 7 (b) shows the measured results of the proposed metamaterial absorber sample with variation of the polarization from 0° to 90° with 10° intervals. The absorptivity and resonance frequency of the proposed metamaterial absorber showed remained the same regardless of polarization angle variation. Figure 7(c) shows the measured absorption ratio of the proposed sample when the incident angle is changed from 0° to 40°. The absorption ratio shows close to 80% until the incident angle is 30°. The incidence angle insensitivity can be improved by using the angle-insensitive unit cell design.

IV. CONCLUSION

In this paper, we proposed a 3D printed stair-like metamaterial electromagnetic absorber. The proposed metamaterial absorber is designed with a three-layered stair-like JC structure so that a longer JC resonator can fit in the same unit cell footprint size. The simulation results demonstrated a 99.9% absorption rate at 5.18 GHz and a 41% unit cell footprint size reduction in comparison to a JC with only one stair. The proposed absorber sample was printed with a 3D printer and painted with a silver paste to form the conductor pattern. The sample of the proposed absorber was assessed under the far-field condition. The measured results demonstrated that the proposed absorber achieves an absorption rate of 99.8% at 5.18 GHz and is insensitive to polarization angle variation. In Table 1, the footprint size and volume of the proposed absorber's unit cell are compared with those of other absorber's unit cells. Due to a stair-like structure, the proposed absorber shows the smallest electrical volume compared with other absorbers. In addition, we can further reduce footprint size by using the stair-like structure as well as the miniaturized unit cell.

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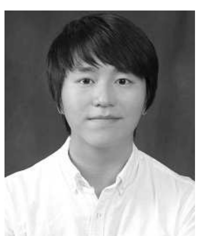

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