3D Printing and Characterization of Metamaterial Composite Structures for Absorbing and Shielding Electromagnetic Waves

Lixian Yin¹*, Xiaoyong Tian²

¹North University of China, Xueyuan Road, Taiyuan, China.
*Corresponding author, E-mail address: a3149387@163.com
²Xi’an Jiaotong University, Xianning West Road, Xi’an, China.

Abstract. Electromagnetic (EM) absorbing and shielding materials possess critical position in defence field. However, traditional absorbing materials failed to achieve a wide absorption band because of the impedance mismatching between absorbing materials and air. And Traditional shielding materials, such as metals, failed to meet the increasing critical needs because of the large density, low corrosion resistance, difficulty in fabrication of complex structures. To solve these problems, a metamaterial composite structures with good performance on EM absorbing and shielding was proposed. The composite structure consists of a metamaterial absorber and a composite shielding structure. The metamaterial absorber is composed of graphene composite metamaterial whose impedance is gradually increased by tailoring the geometric parameter and graphene content. The shielding structure was prepared by continuous carbon fiber (CCF) reinforced composite. The composite structure was fabricated by multi-process 3D printing technology, with which different composites can be fabricated integrally without assembly. Experimental results showed that the absorption bandwidth of the composite structure was 32 GHz (4.5~14.5 GHz, 17~39 GHz), and the shielding effectiveness was larger than 63 dB. The excellent absorbing and shielding performance indicates that the composite holds great potentials in defense and that the design and fabrication method is useful for improving the defence survive ability in complex EM environment and fabricating EM functional structures cheaply, rapidly and faciley.

1. Introduction
With the development of radar detection technology and emergence of electromagnetic (EM) weapons, EM absorbing and shielding technologies become research focuses in the fields of weapon and IT industries[1-2]. Metamaterials are lattice structures designed and fabricated artificially, whose EM response can be faciley controlled by designing the unit cell[3]. It is expected that the integration of functions including EM wave absorption and shielding may be realized by combining metamaterial with composites. For example, Huang et al. prepared C1/PA composite metamaterial and obtained a broad absorption band of 8~18GHz[4]. Yin et al. Prepared αFe/EP composite metamaterial, obtaining wide absorption band of 2.6~40GHz[5]. However, the integration of multifunctions of wave absorbing and shielding can not be achieved by previous design and fabrication methods, which limits the application. In order to prepare multifunctional structure with excellent absorbing and shielding performance, and to fabricate the structure integrally, a novel metamaterial composite structure was proposed and investigated. Based on the 3D printing technology of graphene composite and continuous carbon fiber (CCF) reinforced composite, the design, fabrication and properties of the metamaterial composite structure were studied.

2. Experimental
As shown in Figure1, the metamaterial composite structure for wave absorbing and shielding is composed of two parts. The upper part is a composite metamaterial absorber. The absorber was prepared by graphene composites, which absorbs wave and transforms EM energy into heat. Besides, the absorber possesses gradually increased characteristic impedance from bottom to top, thus the
good impedance matching helps more waves enter the composites. The bottom part was a shielding structure. It was prepared by CCF composite, which has sufficient conductive path for reflecting and shielding EM waves. The matrix of graphene composites and CCF reinforced composite are both polylactic acid (PLA). In order to achieve a composite structure with excellent absorbing and shielding capacity, the composite structure was designed by three steps. First, metamaterial absorbers composed of graphene composite were designed and the one with widest absorption band and light weight was chosen. Second, shielding structures composed of CCF composite were design and the one with shielding effectiveness (SE) larger than 60 dB was chosen. Finally, the metamaterial composite structure composed of the chosen absorber and shielding structure was obtained.

2.1. Design of composite metamaterial absorber
The composite metamaterial absorber with increasing $Z_i$ from the bottom to the top was designed according to the effective medium theory. The absorber is composed of unit cells as shown in Fig.2. The woodpile unit cell is composed of two rods. The length, width and height of the rod are $a$, $w$, $a/2$, respectively. $a$ is a constant, while $w$ is a variable geometric parameter. The effective permittivity of the unit cell can be controlled by manipulating the material permittivity and rod width, as shown in formula (1)(2). The material permittivity is effected by graphene content, hence $Z_i$ is can be controlled by tailoring the graphene content and rod width $w$.

In this research, six composites with graphene content of 0%, 1%, 2%, 3%, 4%, 5% were used to prepare three unit cells with $w$ of 0.8 mm, 1.2 mm, 1.6 mm and $a$ of 1.6 mm. $Z_i$ of all the eighteen unit cells was calculated by the formula (1) to (3). Nine unit cells with $Z_i$ of 90 $\Omega$, 112 $\Omega$, 135 $\Omega$, 169 $\Omega$, 198 $\Omega$, 215 $\Omega$, 230 $\Omega$, 254 $\Omega$, 281$\Omega$ were selected to prepare the metamaterial absorber. The graphene content of the unit cell are 5%, 5%, 5%, 3%, 3%, 2%, 1%, 0%, 0%, respectively. The rod width are 1.6mm, 1.2mm, 0.8mm, 1.2mm, 0.8mm, 0.8mm, 0.8mm, 1.2mm, 0.8mm, respectively. Using the selected unit cells, metamaterial absorbers with gradually increased $Z_i$ from bottom to the top were designed. To investigate the effect of impedance contribution on absorbing performance, seven metamaterial absorbers shown in Table 1 were fabricated by 3D printing process of material extrusion. The reflectivity of the absorber was measured. The absorber with widest absorption band was selected as the upper part in the composite structure for wave absorbing.

\[
\varepsilon_{\text{eff}} = f \varepsilon_c + (1-f)
\]

\[
f = \frac{w}{a}
\]

\[
Z_i = Z_0 \sqrt{\mu/\varepsilon_{\text{eff}}}
\]

where $\varepsilon_{\text{eff}}$ is the effective permittivity of unit cell, $f$ is the volume content of the filling material, $\varepsilon_c$ is the permittivity of the filling material, $w$ is the rod width, $a$ is the unit cell constant, $Z_i$ is the
characteristic impedance of unit cell, $Z_0$ is the impedance of air, 377 Ω, $\mu$ is the permeability of unit cell, 1.

![Figure 2. Woodpile unit cell of metamaterial absorber](image)

**Table 1.** Gradient impedance of metamaterial absorber samples

| Sample | Impedance from bottom to top (Ω) | Number of layers | Thickness(mm) |
|--------|---------------------------------|------------------|---------------|
| A1     | 90, 112, 135                    | 3                | 2.4           |
| A2     | 90, 112, 135, 169               | 4                | 3.2           |
| A3     | 90, 112, 135, 169, 198          | 5                | 4.0           |
| A4     | 90, 112, 135, 169, 198, 215     | 6                | 4.8           |
| A5     | 90, 112, 135, 169, 198, 215, 230| 7                | 5.6           |
| A6     | 90, 112, 135, 169, 198, 215, 230, 254| 8         | 6.4           |
| A7     | 90, 112, 135, 169, 198, 215, 230, 254, 281| 9         | 7.2           |

2.2. Design of composite shielding structure

The composite shielding structure was prepared by CCF reinforced composites. Using the 3D printing process for continuous fiber reinforced composite, the CCFs were configured crossly as shown in Figure 3. The layer thickness and the distance between two adjacent fibers within one layer were 0.5 mm and 1.2 mm, respectively. As the number of CF layer is a critical factor effecting shielding performance, shielding structures with 2, 4, 6, 8, 10, 12 CF layers were prepared, as shown in Table 2. SE of the shielding structures was measured and the one with SE>60 dB and light weight was selected as the bottom part in composite structure.

![Figure 3. Continuous carbon fiber configuration of composites for EM wave shielding](image)

**Table 2.** Shielding structures with different number of layers

| Sample | Number of layers | Thickness(mm) |
|--------|------------------|---------------|
| S1     | 2                | 1.0           |
2.3. Metamaterial composite structure
The metamaterial composite structure is shown in Figure 4. The upper part is the seven-layer metamaterial absorber composed of graphene composites, and the bottom is the shielding structures composed of CCF reinforced composite. The thickness of upper and bottom part are 5.6mm and 4.0mm, respectively. The total thickness of the metamaterial composite structure is 9.6mm.

2.4. Fabrication of metamaterial composite structure
The composite structure composed of a seven-layer metamaterial absorber and a eight layer shielding structure was fabricated by multi-process 3D printing as shown in Figure 5(a). First, the shielding structure of the CCF reinforced composite was fabricated by the extrusion process for continuous fiber reinforced composite. Then the shielding structure was moved on the platform of the 3D printer for extruding the graphene composite, and pasted glue or tape. Finally, the metamaterial absorber composed of woodpile unit cell was printed on the surface of the CCF reinforced composite. The 3D printed metamaterial composite structure is shown in Figure 5(b). The upper part is graphene composite, and the bottom part is CCF reinforced composite.

3. Results and discussions
3.1. Absorbing property of the metamaterial absorber
The reflectivity of absorbers with different number of layers is shown in Figure 6. The absorbers with seven/eight/nine layers have broad absorption band of 10 GHz, wider than that of other absorber. The
seven-layer absorber has the smallest thickness (5.6 mm) and area density (4.64 kg/m²) among the three absorbers with widest absorption band. Hence, the seven-layer absorber was used as the absorbing part of the metamaterial composite structure.

![Figure 6. Reflectivity of metamaterial absorber with different number of layers](image)

**Figure 6.** Reflectivity of metamaterial absorber with different number of layers

3.2. **Shielding property of the metamaterial absorber**

The shielding effectiveness of shielding structure with different number of layers is shown in Figure 7. Composites with layer more than eight realized SE larger than 60dB, which means that the composites with eight to ten layers can be used in the military field. For the composite with eight layers has a low area density and low fabrication cost, it was used as the shielding part of the metamaterial composite structure.

![Figure 7. SE of shielding structures with different number of layers](image)

**Figure 7.** SE of shielding structures with different number of layers

3.3. **Absorbing properties of metamaterial composite structure**

The 3D printed metamaterial composite structure is shown in Figure 8(a). In order to investigate the absorption band of the metamaterial composite structure, the reflectivity of the composite structure in 2~40 GHz was measured, and the result is shown in Figure 8(b). The absorption band was 32 GHz (4.5~14.5GHz, 17~39GHz). There are three absorption peak at 5GHz, 11GHz, 21GHz. The smallest reflectivity was -32.9 dB.
### Figure 8. Reflectivity of metamaterial composite structure

#### 3.4. Comparisons on absorbing properties between other graphene composites and this work

As shown in Table 3, the absorption band of graphene composite in literature are 3~8.6 GHz, while the absorption band of the composite structure in this work is 32GHz. These results indicates that the metamaterial composite structure is by far the graphene composite structure with widest absorption band. The excellent absorption performance is due to the good impedance match with air and the strong absorption ability from graphene composite.

| absorbent                  | matrix | Absorbent content/wt% | thickness/mm | bandwidth/GHz | Reflection peak/dB | ref  |
|----------------------------|--------|------------------------|--------------|---------------|--------------------|------|
| Graphene/Fe$_3$O$_4$/SiO$_2$/NiO | wax    | 25                     | 1.8          | 5.1           | -51.5              | [6]  |
| Graphene/ZnO/Fe$_3$O$_4$    | wax    | 15                     | 5.0          | 5.4           | -35.0              | [7]  |
| Graphene/Fe$_3$O$_4$/CMT    | wax    | 25                     | 2            | 3.6           | -50                | [8]  |
| Graphene/MoS$_2$            | wax    | 10                     | 2.3          | 3             | -50.9              | [9]  |
| Graphene/NiO                | wax    | 8                      | 3.0          | 6.7           | -38.0              | [10] |
| Graphene/FeCo              | wax    | 50                     | 2.5          | 5             | -40.2              | [11] |
| Graphene/BaFe$_{12}$O$_{19}$| PVDF   | 80                     | 2            | 8.6           | -32                | [12] |
| Graphene/FeCoB             | EP     | 30                     | 2            | 2.4           | -22.2              | [13] |
| Graphene/MnFe$_2$O$_4$      | wax    | 5                      | 3.0          | 4.9           | -29.0              | [14] |
| Graphene                   | PEO    | 4.2                    | 1.8          | 4.1           | -38.8              | [15] |
| Graphene                   | PVA    | 0.9                    | 2            | 7.7           | -17.5              | [16] |
| Graphene                   | NBR    | 10                     | 3            | 5.5           | -57.0              | [17] |
| Metamaterial composite structure | PLA  | 1~5                    | 5.6          | 32            | -32.9              | This work |

#### 4. Conclusions

A composite structure with absorption bandwidth of 32 GHz and shielding effective more than 60dB was prepared. The composite structure is by far the graphene composite structure possessing widest absorption band, holding great potentials in defense. The composite structure was fabricated by multi-
process 3D printing method, with which structures composed of different composites can be fabricated integrally without assembly. The fabrication method is expected to be used for preparing multifunctional device facilely, rapidly and cheaply.

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