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Additively manufactured metastructure design for broadband radar absorption

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Abstract

Background: Recent advances in material science and electronics led to the rapid development of communication devices and radar detection techniques resulting in an ever-increasing demand for improved stealth performance of air vehicles during scouts. Absorber design employing metastructure concept has recently become a popular approach to improving radar stealth performance. Metastructure permits the realization of desired absorption characteristics by careful design of geometrical structures and material compositions. In this study, a metastructure designed based on graphite SLS composite for radar absorption has been demonstrated. The unit cell of the proposed structure is simulated by COMSOL Multiphysics to determine the frequency-dependent absorption characteristic of the structure. It is fabricated by using a low-cost selective laser sintering technique of additive manufacturing technology.

Results: The prototype, while measured, shows effective absorption bandwidth of 1.04 GHz that is in reasonable agreement with the simulated response of 2.08 GHz. The optimized structure exhibits ≤ -10 dB reflectivity within a broad frequency range extending from 7.60 GHz to 18.00 GHz under normal incidence in both TE and TM polarizations. Furthermore, the absorption performance under different polarizations and incident angles has been investigated. Results indicate that the absorber displays polarization indifference and exhibits a wide-angle of incidence tolerance of up to 45° in TE polarization and 30° in TM polarizations.

Conclusion: In this paper, the feasibility of using graphite SLS material to design and 3D print a metastructure design for radar absorbing has been established as confirmed by the simulation and the measurement results. The advantages of low cost, ultra-broad operating band, wide-angle of incidence feature, and polarization insensitivity qualifies the proposed absorber for stealth and electromagnetic shielding applications.

Keywords: Broadband, Graphite SLS, Metastructure, Radar, Wide-angle

1 Background

Recent advances in material science and electronics have led to the rapid development of communication devices and radar detection techniques. This has compounded the electromagnetic (EM) interferences and radiation problems. Also, there is pressing demand for improved stealth performance of air vehicles during the scout. In an attempt to find a solution to these problems, there has been extensive research interest in EM absorbing

materials in the last few years. Current researches are aimed at developing EM absorbers with the properties of thinner thickness, lower density, wider angle of incidence tolerance, better polarization insensitivity, and stronger and broader bandwidth absorption [1]. Though improvement to these properties can hardly be met simultaneously, there is a need to develop absorbers with optimal property mix that is peculiar to the area of application such as radar stealth [2–4], electromagnetic compatibility [5], energy harvesting [6], and so on. Recently, absorber design employing metastructure concept has become a popular approach [7–9] for improving radar stealth performance as it permits realization of

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desired absorption characteristics by carefully manipulating the geometry of the structure and/or material composition. Metastructures (MS) are artificially engineered subwavelength units that can effectively manipulate the propagation of electromagnetic waves resulting in unique electromagnetic features that are unattainable in conventional materials, such as near-zero or negative refractive index.

Additive manufacturing technology, which is also known as 3D printing, is a promising processing technology for fabricating structures and devices with different geometries using computer-aided design [10]. It offers high efficiency, convenience, and a low-cost fabrication process that involves printing successive layers of a given material on top of each other. Lately, 3D printing systems have been utilized to manufacture metamaterial absorbers (MMAs) of different structural designs and material bases [11–17]. However, the main hindrance for the fabrication of broadband MMAs using 3D printing technology is the limited range of materials compatible with 3D printers [18, 19]. Most of the available 3D printing materials are fully insulating or have low conductivity values [11], which limits their usage in 3D printing of EM absorbing metamaterials. To enhance the dielectric performance of the common 3D printing polymers, organic materials such as carbon, carbon black, carbon nanotubes, and graphite are loaded to the polymers as hitherto demonstrated in non-3D printing polymeric composites [20, 21]. Nowadays, commercially available conductive filaments like conductive PLA, conductive ABS, and graphene are being explored for the development of EM absorbers and devices using 3D printing [11–19, 22]. However, none of the existing reports reviewed have considered graphite SLS 3D printing material.

Therefore, a cross-block patterned broadband metasurface absorber for radar absorption at X and Ku bands manufactured using low-cost 3D printing technology is presented in this work. The graphite SLS material is introduced in the design of the absorber for the first time. A preliminary designed structure is 3D printed via selective laser sintering (SLS) technique and its absorption performance measured afterward. Good agreement between measured and simulated results of the preliminary absorber is observed. By optimizing the dimensions of the cross-block patterned preliminary absorber resonator unit cell, an ultra-broad absorption band with a reflectivity of below -10 dB (absorptivity of higher than 90%) is realized over the range of 7.6 to 18 GHz radar spectrum as indicated in the simulation results. Moreover, the angular acceptance of the absorber in transverse electric (TE) and transverse magnetic (TM) mode are investigated, likewise, absorber polarization dependency is simulated. Results indicated wide angles of

incidence tolerance for both polarization modes and polarization insensitivity at normal incidence. These exceptional promising features of the present metastructure absorber design qualifies it to be used for different applications in radar frequencies, such as low-cost electromagnetic interference shielding, electromagnetic compatibility, and stealth technology.

2 Theory

The electromagnetic absorption behaviour of a structure can generally be determined by using Eq. (1) where the frequency-dependent parameters $A(\omega)$, $R(\omega)$, and $T(\omega)$ represent the absorption, reflectance, and transmittance, respectively.

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

where $R(\omega) = |S_{11}|^2$ and $T(\omega) = |S_{21}|^2$

Due to the ground plane in the designed structure, $T(\omega)$ can be neglected. Therefore, Eq. (1) reduces to Eq. (2).

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

Using scattering parameter (S_{11}) from the simulations, the absorptivity of the RAMS is calculated using Eq. (2).

The wave equation of the propagating electric field “ E ” based on the Maxwell equation is given by Eq. (3).

$$\nabla \times \mu_r^{-1} (\nabla \times E) - k_0^2 \left(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0} \right) E = 0 \quad (3)$$

where μ_r represents the relative permeability, k_0 the free space wavenumber, ϵ_r the relative permittivity, σ the conductivity, ω the angular frequency, and ϵ_0 the permittivity of free space.

In COMSOL, the S-parameters describing the reflection and transmission of the wave are defined as follows:

$$S_{11} = \frac{\int_{\partial\Omega} (E - E_1) \cdot E_1}{\int_{\partial\Omega} E_1 \cdot E_1} \quad (4)$$

$$S_{21} = \frac{\int_{\partial\Omega} E \cdot E_2}{\int_{\partial\Omega} E_2 \cdot E_2} \quad (5)$$

Then, the S_{11} parameter evaluated from Eq. (4) is subsequently substituted into Eq. (2) in COMSOL software to calculate the magnitude of the absorptivity of the incident wave. Based on transmission line theory, impedance encountered by EM waves at layer “i” is defined as [23]:

$$Z_{in^i} = Z_i \frac{Z_{in}(i+1) + Z_i \tanh \gamma_i d_i}{Z_i + Z_{in}(i+1) \tanh \gamma_i d_i} \quad (6)$$

where Z_i and γ_i can be represented as $Z_i = \sqrt{\frac{\mu_{r,i}}{\epsilon_{r,i}}}$ and $\gamma_i = j2\pi f \sqrt{\epsilon_{r,i} \mu_{r,i}}$, respectively.

The magnitude of EM wave absorption represented by the reflectivity of an absorber backed by a perfect

Fig. 1 Designed unit cell radar-absorbing metamaterial with three-layer cross-block structure. **a** Model of periodic unit. **b** Model size. $l_1 = 4.0$ mm, $l_2 = 2.6$ mm, $w = 1.8$ mm, $e = 0.6$ mm, $d_1 = 0.8$ mm, $d_2 = 0.8$ mm, $d_3 = 2.6$ mm

electrical conductor (PEC) ground plate can be written as Eq. (7).

$$R = 20 \log \left| \frac{Z_{in} - 1}{Z_{in} + 1} \right| \quad (7)$$

where R is reflectivity and Z_{in} is surface layer input impedance.

The reflectivity of the three-layered RAMS can be calculated from Eqs. (6) and (7) using the FEM formulation.

3 Method

3.1 Design of the structure

The proposed absorber is a three-layer structure consisting of a cross-shaped surface structure, square block middle layer, and conventional single slab bottom layer as revealed in Fig. 1. The material used in the design of the absorber layers is Graphite SLS, exclusive material from a UK-based Graphite Additive Manufacturing company. It was obtained from the mixture of a Nylon 12 (PA) powder and graphite powder, to enhance the dielectric performance of the material. As graphite SLS assumed the property of graphite, the measured complex

Fig. 2 Complex permittivity of graphite SLS material

Fig. 3 Additively manufactured radar-absorbing metastructure

permittivity of graphite [24] used in this work is shown in Fig. 2, while the loss tangent of the graphite is 0.52. A copper film of 0.04 mm thickness is used in the design as a ground plane to prevent transmission of the waves beyond the structure. The schematic of the unit cell of the proposed radar-absorbing metastructure (RAMS) shown in Fig. 1 is simulated by using the frequency domain solver of COMSOL Multiphysics environment based on finite element method (FEM) to investigate its absorption characteristics.

3.2 Simulation approach

FEM is used in this study to investigate the EM absorbing property of the proposed design. In FEM, the simulation domain is discretized into sub-elements called mesh

elements. Tetrahedral mesh element is selected with a maximum element size of one-tenth of the minimum wavelength ($\frac{1}{10}\lambda_{\min}$) of the input wave to obtain reasonable accuracy of the simulation results within a reasonable computation resource in the COMSOL. The complete mesh consists of 16688 domain elements, 2294 boundary elements, and 276 edge elements. The boundaries of the simulation domain along x and y axes were simulated as a perfect magnetic conductor (PMC) and perfect electric conductor (PEC) boundary conditions as shown in Fig. 1b. This method sets tangential fields to zero [1] respectively to mimic an infinite periodic structure arranged in the x and y directions. A periodic port boundary in the radio frequency (RF) module of COMSOL was used to generate plane-polarized electromagnetic wave excitations along the z -axis plane. With this boundary condition, the magnitude of the reflection loss can be assessed. Impedance boundary condition (IBC) which treats any material behind the boundary as being infinitely large is chosen for the ground plane. It is used at boundaries where the field is known to penetrate only a short distance outside the boundary. This penetration is approximated by the IBC to avoid the need to include another domain in the model. The IBC is represented in Eq. (8).

$$\sqrt{\frac{\mu_0\mu_r}{\epsilon_0\epsilon_r - \frac{j\sigma}{\omega}}} \mathbf{n} \times \mathbf{H} + \mathbf{E} - (\mathbf{n} \cdot \mathbf{E}) \mathbf{n} = (\mathbf{n} \cdot \mathbf{E}_s) \mathbf{n} - \mathbf{E}_s \quad (8)$$

In Fig. 2, the measured dielectric properties of graphite SLS material [24] are shown. Together with the loss

Fig. 4 Schematic of a typical SLS setup [31]

Fig. 7 Measured and simulated reflectivity plots at 10° incidence of TE-polarized wave

tangent of material recorded as 0.52, these material parameters are used in the simulation to evaluate the absorption behaviour of the proposed structure.

3.3 Fabrication and measurement

We used the services of UK based graphite additive manufacturing company for the fabrication of the proposed designed RAMS model. The RAMS was built using selective laser sintering (SLS) process and a partially enlarged picture of the 3D printed radar-absorbing metastructure is presented in Fig. 3.

Selective laser sintering (SLS) is an additive manufacturing process that allows the building of complex 3D parts by solidifying successive layers of powder material deposited on top of each other [25]. A wiper deposits a

thin layer of powder particles (typically 0.1–0.3 mm thickness) on a fabrication bed, laser scans over the particles in the shape of the desired object as calculated from a CAD model causing the particles to melt and fuse. The final part is built by repeatedly depositing and sintering successive powder layers. A schematic overview of the SLS process is depicted in Fig. 4. No support structures are needed and allow rapid production of complicated geometries parts in one step process. Suitable materials for SLS include polymers, ceramics, and metals.

The fabricated absorber structure performance was measured at ABS techniques [26] laboratory to verify the rationality of the Comsol Multiphysics design. NRL Arch measurement procedure was adopted to obtain the

Fig. 8 Simulated reflectivity plots of the optimized structure at normal incidence for TE and TM polarizations

absorber reflection loss (RL). Measurement of RL at a near-normal incidence of 10° for each antenna versus the normal on the reflective metal plate for TE polarized incident wave was carried out from 2.0–18 GHz. The schematic of the measurement setup is indicated in Fig. 5 and the detailed measurement method as per IEEE std 1128/1998 is given in [27].

3.4 Geometric Dimension Optimization

The measured and simulated results of the 3D printed RAMS demonstrate below -10 dB reflectivity in the 10–12 GHz range only. To obtain broad absorption in the X and Ku bands of radar spectrum satisfying the below -10 dB reflectivity, the unit cell geometric dimensions are optimized by using Comsol Multiphysics' in-built Nelder-Mead method to get the desired absorption property.

4 Results

4.1 Additively manufactured RAMS

The measured reflectivity result of the 3D printed absorber at an incident angle of 10° for TE-polarized wave

is shown in Fig. 6, and the simulated reflectivity is plotted alongside the measured reflectivity in Fig. 7 for comparison.

4.2 Geometric dimension optimized RAMS

The optimized dimensions obtained which result in broadband absorption characteristics of the designed absorber are $l_1 = 15.0$ mm, $l_2 = 3.5$ mm, $w = 4.2$ mm, $e = 1.6$ mm, $d_1 = 1.2$ mm, $d_2 = 0.6$ mm, $d_3 = 3.2$ mm. The simulated reflectivity of the optimized structure at normal incidence for both TE and TM polarizations is presented in Fig. 8.

Absorber angle of incidence tolerance is evaluated to assess its suitability for practical application which demands a wide angle of incidence performance. Simulations were carried out for TE and TM modes under different angles of incidence varying from 0° to 45° at steps of 15° . Absorber reflectivity and absorptivity responses under different angles of incidence for TE mode of the optimized design are displayed in Fig. 9, while absorber's angle of incidence responses for TM

Fig. 12 Calculated real effective impedance plots of metastructure absorber and flat absorber

mode are depicted in Fig. 10. Another useful characteristic of an EM absorber is the ability of the absorber to respond well in different polarization angles. Therefore, the metastructure's response to different polarization angles is investigated in this paper and revealed in Fig. 11.

When the impedance of an absorber matches that of air, reflection is minimized which results in near-unity absorbance. For comparison, the real and imaginary parts of the impedance of the metastructure and single-layer flat designs were calculated from the simulated complex S parameters using $Z_{\text{eff}}(\omega) = \sqrt{\frac{(1+S_{11})^2}{(1-S_{11})^2}}$ and plotted in Figs. 12 and 13. To explore the physical absorption mechanism of the proposed RAMS, current density, power loss density, and E field distributions were simulated at two absorption peaks of 9.0 and

15.4 GHz when the incident angle is 0° , and results are revealed in Fig. 14.

5 Discussions

Considering the additively manufactured RAMS, there is a favourable agreement between the simulation and measurement curves. The effective absorption bandwidth is 1.04 GHz for measured and 2.08 GHz for simulated. Effective absorption bandwidth is often defined as the corresponding frequency range in which reflectivity is ≤ -10 dB. Deviations between simulated and measured results are observed, which can be attributed to the imperfections resulting from the fabrication and measurement processes.

The geometric dimension optimization has greatly improved the effective absorption bandwidth of the RAMS,

Fig. 13 Calculated imaginary effective impedance plots of metastructure absorber and flat absorber

covering almost the entire frequency range of interest (X and Ku bands) as shown in Fig. 8. The new optimized absorber thickness is 5.0 mm only as against the 4.2 mm of the printed absorber. The reflection coefficient curves for the TE and TM polarizations are observed to overlapped at normal incidence. Moreover, it can be seen from Fig. 9a that as the angle of incidence increases to 15°, the effective bandwidth is unchanged which slightly decreases as the incident angle increase to 45°. Absorption levels are observed to diminish as the incident angle increases as

depicted in Fig. 9b. For TM polarization, the effective bandwidth is similarly unchanged as the angle of incidence increases to 15° while it decreases as the incident angle is varied to 45° according to results from Fig. 10a. Absorption levels are observed to be greater than 90% for normal and 15° incidences, greater than 80% at 30°, and greater than 70% at 45° when TM wave interacts with the RAMS as depicted in Fig. 10b. It is, however, worth mentioning that the absorption level is greater than 70% in the X and Ku bands for all the incident angles considered

Table 1 Comparison of – 10 dB absorption bandwidth range between radar-absorbing metastructure of this work and previous works

Reference	Material	Frequency range (GHz)	Effective absorption bandwidth	Thickness (mm)
[13]	Conductive ABS	4–12	5.43	3.50
[17]	Graphene/nano-Fe ₃ O ₄ /PLA	12.4–16.0	3.60	3.00
[18]	Conductive ABS	3.9–12.0	8.10	9.37
[19]	Conductive PLA	6.0–8.50	2.50	5.04
This work	Graphite SLS	7.6–18.0	10.40	5.00

either for TE wave or TM wave while the absorption level is said to generally decrease with the increase of angle of incidence.

Simulation results for polarization angles varying from 0° to 60° indicated polarization independence behaviour as shown in Fig. 11. The curves are observed to overlapped over one another which is attributed to the fourfold symmetry of the structural design of the absorber unit cell. It is a fact that structures exhibiting fourfold symmetry demonstrate polarization insensitivity absorption behaviour [28–30]. Concluding, the designed RAMS is said to exhibit a wide-angle of incidence property and polarization-insensitive behaviour.

It can be spotted from Figs. 12 and 13 that the designed metastructure's effective impedance is much closer to matching air impedance than the single-layer flat design, though both are designed from the same material and thickness. The real part impedance of the metastructure design from Fig. 12 is close to unity in most of the absorber working frequencies. From Fig. 13, the imaginary part of the effective impedance is observed to be near zero in most of the absorber's working frequency bands. This illustrates the effectiveness of the novel metastructure design for broadband radar spectrum absorption.

As depicted in Fig. 14a, the current density at the 9.0 GHz absorption peak is concentrated at the middle layer and topmost part of the surface layer. At 15.4 GHz, the current density distribution is dominant at the cross-shaped surface layer and the surface of the bottom layer according to Fig. 14b. Remarkably, the power loss distribution coincides well with the current density distribution as revealed in Fig. 14c, d, indicating that the current density plays a vital role in radar absorption which is mainly caused by ohmic losses. The electric field distribution shown in Fig. 14e, f is similar to that of the current density and power loss distribution.

Table 1 is a comparison of the designed absorber in this paper with some other absorbers fabricated by 3D printing. Compared with other absorbers in the literature listed in Table 1, the RAMS reported in this paper has a wider effective bandwidth at 10.40 GHz. It also yields a good thickness at 5.0 mm, better than the

absorber thickness obtained in [18, 19]. Moreover, Graphite SLS was for the first time introduced in this paper as can be observed from Table 1.

Finally, the present metastructure design can be described as a low-cost polarization-independent radar absorber with a wide-angle of incidence characteristics for X and Ku bands applications.

6 Conclusion

In this paper, we demonstrated the feasibility of using graphite SLS material to design and fabricate a metastructure for radar absorption using 3D printing as confirmed by the simulation and measurement results. The simulation results obtained from the optimized RAMS show that the structure can realize the below – 10 dB reflectivity in the 7.6–18.0 GHz frequency band at normal incidence of waves for TE and TM waves. This property is maintained at an oblique incidence until 45° in TE wave and 15° in the TM wave. However, the reflectivity is below – 5 dB (more than is 70% absorptivity) at 45° incidences for TM wave. The metastructure absorber contributes to impedance matching to air that ensures minimized reflection and subsequent broadband absorption. Moreover, the proposed RAMS demonstrate polarization insensitivity and cost-effectivity as it is made from commercially available 3D printing material and technology thereby making it to be a practically viable candidate for stealth and electromagnetic interference shielding applications.

Abbreviations

EM: Electromagnetic; 3D: Three-dimensional; MMAs: Metamaterial absorbers; SLS: Selective laser sintering; TE: Transverse electric; TM: Transverse magnetic; RAMS: Radar-absorbing metastructure; FEM: Finite element method; PEC: Perfect electric conductor; PMC: Perfect magnetic conductor; IBC: Impedance boundary condition

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Authors' contributions

M.H. Ali conceived the idea, gives directives, suggested the fabrication method, and corrected the manuscript. M.B. Abdullahi carried out the design

and the simulation and drafted and organized the manuscript. The authors have read and approved the final manuscript.

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