Controlling Graphene Sheet Resistance for Broadband Printable and Flexible Artificial Magnetic Conductor-Based Microwave Radar Absorber Applications

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Abstract—Current artificial magnetic conductor (AMC) designs use metallic patterns on rigid substrates and focus on shapes and sizes of AMC structures, rather than on material performance, which has hindered operation bandwidth and design flexibility. Here, we introduce printed graphene AMC-based broadband and flexible microwave radar absorbers, which not only redirect but also absorb the incident wave so to broaden the operation bandwidth. Contrasting to other reported works, the phase characteristics of the AMCs are realized through the control of the surface resistance provided by printed graphene laminates. We produced a variety of AMC structures, composed of printed graphene circular ring arrays with exactly the same shape and size, but different sheet resistances. By carefully designing the sheet resistance of printed graphene laminates, the optimized anti-phase reflection cancellation between AMCs can be achieved. With printed graphene AMCs and flexible dielectric substrate, the absorber presented in this work has a broadband effective absorption (above 90% absorptivity) from 7.58 GHz to 18, is polarization insensitive under normal incident, and can work at relatively wide incident angles. Furthermore, this absorber is capable of bending easily with notable performance, which makes it ideal for applications with irregular and uneven shapes.

Index Terms—Artificial magnetic conductor (AMC), flexible microwave radar absorber, printed graphene, sheet resistance.

I. INTRODUCTION

ARTIFICIAL magnetic conductor (AMC) [1] has been widely applied in microwave metamaterial radar absorber designs [2]–[16] to provide high effective absorption and broad bandwidth. A microwave radar absorber based on a combination of AMC and perfect electric conductor (PEC) in a chessboard configuration was proposed in [17]. Its principle of operation was based on scattering cancellation. The reflected energy was mainly scattered into four diagonal directions, leading to dramatic reduction of the radar cross section (RCS) in the normal incident angle. Recently, a radar absorber based on a combination of two different AMC structures has been proposed to further broaden the absorption bandwidth [18].

However, most AMC structures used in radar absorbers are designed with metallic patterns [18]–[27], which means nearly zero absorptivity can be provided by metallic patterns themselves, hindering the operational bandwidth. The phase difference and cancellation of reflections between different AMC structures in these designs were achieved through different shapes [19], [23], [27] or sizes [20], [22], [24], [25] of AMCs, which limited the design flexibility to some extent. Besides, metallic patterns and rigid dielectric substrates in these AMC designs led to poor mechanical flexibility.

Various types of graphene-based absorbers have been proposed in the past decade through applying ferrite–graphene-based magnetic materials [28] and monolayer/multilayer graphene [29]–[32]. Recently, with the development of printed electronics, printable conductive inks [33] have been used to replace conventional conductors in metamaterial absorber designs [34]–[38] due to their extraordinary characteristics in mechanical flexibility and lightweight. Among various conductive inks, graphene ink has incomparable advantages in terms of flexibility, lightweight, high conductivity, and low-cost mass production [39]–[42], which make it a potential candidate for metamaterial radar absorbers.

In this article, we present a fully screen-printed graphene AMC-based radar absorber working at X-band (8–12 GHz) and K$_\text{a}$-band (12–18 GHz). Whereas all AMC patterns have exactly the same shape and size, the desired anti-phase reflection cancellation is achieved by controlling the sheet resistance of the printed graphene AMC patterns. Due to...
the unique property of the printed graphene AMCs, a new design methodology is proposed to obtain the required range of phase difference between the AMCs to achieve effective absorption. The performance of the proposed radar absorber at wide incident angles for both transverse electric (TE) and transverse magnetic (TM) modes and under different bending cases has been investigated. The experimental results are in reasonably good agreement with numerically simulated and calculated ones.

This article is organized as follows. First, the material preparation and method of controlling sheet resistance of printed graphene laminates are introduced. Then, the designs and modeling of unit cells of AMC structures are introduced, which is followed by the analysis of the absorber surface and the investigation of the relationship between magnitude difference and required phase difference to achieve broadband effective absorption. Next, the simulation and experimental results are presented and discussed, including the performances and angular stability analysis under various incident angles and different bending cases. Finally, this work is summarized and concluded with some final remarks.

II. MATERIAL PREPARATION AND ELECTRICAL PROPERTIES

Pristine graphite flakes (Alfa Aesar, >99%) were first dispersed in 400 ml of N-methyl-2-pyrrolidone (NMP; Sigma, >99%) in a concentration of 20 mg ml$^{-1}$. After sonication for 24 h, the mixture was filtered with a 300-mesh stainless steel screen and centrifuged at low speed (500 r/min) for 20 min. Then, NMP was removed from the obtained dispersion through vacuum filtering. In order to achieve appropriate viscosity for screen printing, the collected graphene nanoflakes were re-dispersed in viscous solvent ethylene glycol (Alfa Aesar, >99%) at a concentration of 50 mg ml$^{-1}$.

Screen printing was performed to print graphene patterns on normal A4 printing papers [43]–[46]. The semi-automatic pneumatics screen printer (YICAL4060PV) with pneumatic cylinder (XINGCHEN CQ2B32-20, max press of 0.7 MPa) was used for screen printing. The printer worked at a printing speed of 70–90 mm s$^{-1}$ with a 70° angle squeegee. The printing screen of 49 mesh was specially fabricated and patterned with capillary film (ULANO, EZ50-Orange) to achieve the uniform laminate and resolution. The printed samples were dried in an oven under vacuum environment at 120° for 5 h. Samples with required sheet resistances were obtained through a further rolling compression.

The conductivity of the prepared samples can be obtained through

$$\sigma = \frac{1}{R_s \times t} \quad (1)$$

where $R_s$ is sheet resistance of printed graphene patterns, which can be measured using 4-point probe station (Jandel, RM3000) and semiconductor characterization system (Keithley, 4200C), while $t$ is the thickness of the printed graphene patterns, which can be represented by the average thickness of the printed layers measured based on cross-sectional scanning electron microscopy (SEM) view.

![Fig. 1. SEM images of printed graphene laminates on paper substrate: cross-sectional view of uncompressed (a) Sample 1 (sheet resistance of 36.6 $\Omega$sq) and (b) Sample 2 (sheet resistance of 98 $\Omega$sq) with 500 $\times$ magnification. Top view of (c) uncompressed Sample 1 and (d) compressed Sample 3 (sheet resistance of 8.7 $\Omega$sq) with 100 $\times$ magnification, (e) uncompressed Sample 1, and (f) compressed Sample 3 with 1000 $\times$ magnification.](image)

Fig. 1 displays SEM images of three samples of the printed graphene laminates on paper substrate. Samples 1–3 have sheet resistances of 36.6, 98, and 8.7 $\Omega$sq, respectively. Through controlling the thickness of the printed graphene laminates during the printing and compressing processes, different sheet resistances of graphene laminates can be achieved. With relatively lower printing speed and squeegee pressure, the graphene laminate of Sample 1 was made thicker than that of Sample 2, as shown in Fig. 1(a) and (b), resulting in a relatively lower sheet resistance. Based on the cross-sectional SEM view in Fig. 1(a), the average thickness of Sample 1 (uncompressed sample) is measured to be around 54 $\mu$m. With the measured sheet resistance of 36.6 $\Omega$sq, the conductivity is calculated to be 506 S/m according to (1). To obtain a much lower sheet resistance, rolling compression was applied in preparing Sample 3. Unlike the uncompressed samples with porous structure which limits the conductivity [Fig. 1 (c) and (e)], the graphene laminate of Sample 3 has much denser surface, as shown in Fig. 1(d) and (f). The average thickness of compressed Sample 3 is measured to be 18.7 $\mu$m, and the conductivity is calculated to be $6.14 \times 10^3$ S/m, which leads to a sheet resistance of 8.7 $\Omega$sq. More details of printed graphene electrical properties can be found in [44]–[46].

III. DESIGN AND SIMULATION

The elementary unit cell of AMCs is composed of printed graphene resistive circular ring, two layers of dielectric substrates, and a metal ground plane. CST Microwave Studio has been used to optimize the elementary unit cell design.
Each elementary unit cell, as shown in Fig. 2(a), is modeled as an infinite periodic structure by independently applying periodic boundary condition in x- and y-directions, and Floquet boundary condition in z-direction. A PEC is assumed for the metal ground plane. The supporting dielectric substrate of 3 mm thickness is chosen to be silicone (Polymax, SILON Translucent Silicone Sheet 60ShA FDA) with a dielectric constant of 3.5 and a thickness of 0.1 mm, which is then placed on the top of the silicone substrate. In the full-wave electromagnetic simulation, the printed graphene patterns are simulated as ohmic sheet surfaces with specific resistances in the design.

Fig. 2(b) shows a $4 \times 4$ elementary unit cell array, which constitutes a unit AMC lattice. To investigate the effects of combination of AMC lattices with different sheet resistances, various combinations have been studied numerically. It is revealed that $2 \times 2$ dual AMC lattices, as shown in Fig. 2(c), can provide much wider effective absorption bandwidth than if only uniform AMC lattices (i.e., all rings have the same sheet resistance) are used. Such $2 \times 2$ dual AMC lattices have been used to constitute a functional unit cell of the proposed radar absorber. To verify the novel approach of achieving phase cancellation purely through different sheet resistances of two AMCs, the appropriate sheet resistances for AMC1 and AMC2 which can meet our design requirement were optimized to be 8.7 and 98 $\Omega$/sq through numerical simulation. Fig. 2(d) illustrates the bird’s view of the absorber, which has a chessboard configuration composed of many functional unit cells.

The absorptivity of printed graphene AMC surface can be obtained through the formula $1 - |T(\omega)| - |R(\omega)|$, where $T(\omega)$ is the transmission and $R(\omega)$ is the reflection. Due to the metal ground plane on the back side of the metamaterial surfaces, the transmission is blocked, which means the absorptivity can be calculated by

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

where $S_{11}$ represents the reflection coefficient.

The reflection phase and magnitude of AMC1 (sheet resistance of 8.7 $\Omega$/sq) are shown in Fig. 3(a) and (b), respectively. It resonates at 8.6 and 20.4 GHz, with two narrow effective absorption bands. Fig. 3(c) and (d) shows that, on the other hand, AMC2 (sheet resistance of 98 $\Omega$/sq) resonates at 14.8 GHz. It is worth to point out that although either AMC1 or AMC2 can absorb incident EM wave in some spectrums, neither of them on its own can provide any phase cancellation which can lead to a wideband effective absorption.

To achieve a wideband effective absorption, AMCs with different sheet resistances and phase characteristics (AMC1 and AMC2) are arranged as $2 \times 2$ dual AMC lattices to form a functional unit cell [Fig. 2(c)]. The functional unit cells are then periodically placed in a chessboard configuration, as displayed in Fig. 2(d). The absorption principle of the chessboard metasurface is based on the anti-phase reflection property [17]. When the phase difference of the reflection coefficients between the two AMC lattices is around 180°, the reflected fields interfere with each other destructively, which leads to cancellation of reflected waves. According to (2), the decrease of reflection magnitude results in the increase of absorptivity. Since the AMC structures consisting of printed graphene rings can be very lossy, the phase canceling criteria of 180° ± 37° between two AMCs which were derived for lossless metal patterns with unity reflection magnitude [18] are no longer appropriate for printed graphene surfaces. Thus, a new design guideline is required based on the unique reflection property of printed graphene AMCs.
Here, we use the concept of standard array theory [47], [48] to work out the required phase difference for printed graphene AMCs, which is an approximation approach but useful design guideline. The functional unit cell of the chessboard configuration, consisting of $2 \times 2$ dual AMC lattices (each lattice has $4 \times 4$ elementary unit cells) can be modeled as a $2 \times 2$ array composed of two types of lattices. Since the two lattices occupy the same area of the array surface, the incident power is distributed evenly to each other. Suppose that the incident electric field is $E_{in}$ and there is no coupling between them, then the reflected electric field components can be expressed as

$$E_{rf\_1} = \Gamma_1 \cdot E_{in} = A_1 e^{jP_1} \cdot E_{in}$$

(3)

$$E_{rf\_2} = \Gamma_2 \cdot E_{in} = A_2 e^{jP_2} \cdot E_{in}$$

(4)

where $\Gamma_1, \Gamma_2$ represent reflection coefficients ($A_{1,2}$ and $P_{1,2}$ are the magnitudes and phases, respectively) of AMC1 and AMC2, respectively.

The total reflected electric field is then given by

$$E_{rf\_total} = AF_1 \cdot E_{rf\_1} + AF_2 \cdot E_{rf\_2}$$

(5)

where $AF_{1,2}$ represent the array factors and can be expressed as [48]

$$AF_i(\theta, \phi) = \sum_{n=1}^{N} W_n e^{j k_0 \sin \theta (s_n \cos \phi + t_n \sin \phi)}$$

(6)

where $i = 1 \ or \ 2$, $s_n$ and $t_n$ represent the coordinate of the $n$th element, and $W_n$ is its complex excitation coefficient.

In the radar absorber design, infinite periodic structure is assumed and edge effects are neglected. Since two AMC lattices are arranged anti-symmetrically in the functional unit cell, hence, each of them occupies half area of the chessboard, and the array factors from (6) can be approximated to be $(1/2)$ for both AMCs, which means according to (5), the reflection coefficient of the absorber surface can be approximated by the average reflection coefficients of two AMC structures [26]

$$S_{11} = \frac{A_1 e^{jP_1} + A_2 e^{jP_2}}{2}.$$  

(7)

In order to find the relationship between magnitude difference and required phase difference to achieve effective absorption for two printed graphene AMCs, i.e., lossy AMCs, the magnitude and phase differences between the two lossy AMCs based on the numerically simulated reflection coefficients of the individual AMC lattices were calculated and displayed in Fig. 4(a) and (b), respectively. Since the effective absorption needed by a radar absorber is higher than 90%, we combine (2) and (7) and obtain the required absorption as

$$A(\omega) = 1 - \frac{1}{4} \left[ A_1^2 + A_2^2 + 2A_1A_2 \cos(P_1 - P_2) \right] > 90\%.$$  

(8)

By calculating this inequality in MATLAB with the reflection magnitudes $A_1$ and $A_2$ obtained from CST full-wave numerical simulation, the required phase difference $|P_1 - P_2|$ can be obtained and illustrated in Fig. 5.

In Fig. 5, the gray-shaded area represents the region of phase differences that satisfy the requirement to achieve more than 90% absorption. It can be seen that the required phase difference changes over frequency. From 0 to 5 GHz, because the reflection magnitudes of the two AMC lattices are near unity, the required phase difference is around $180^\circ \pm 37^\circ$, which is consistent with that of metal AMC surfaces [18]. From 5 to 9.5 GHz, the reflection magnitudes of the AMC lattices as well as the difference between them change rapidly over frequency [as shown in Fig. 4(a)], which lead to the steep edge of the gray-shaded region. From 9.5 to 19 GHz, the required phase difference is around $180^\circ \pm 78^\circ$, which has a broader range comparing with that of metal surfaces. This
because the absorption of printed graphene radar absorber counts on not only the cancellation effect of reflections due to the phase difference, but also the absorption of graphene AMC lattices. From 20 to 21 GHz, there is a gap on the required phase difference, which means no such values can satisfy (8). In other words, for the two presented AMCs with fixed dimensions and chosen sheet resistances, the effective absorption (>90%) cannot be achieved within this frequency range no matter how. This gap is caused by the large reflection magnitude difference between the two AMCs.

To further illustrate the effect of the reflection magnitude difference between the two AMC lattices, let us consider an extreme condition that the two AMC lattices have absolutely opposite reflections, which means the phase difference is 180°. Then, (8) can be simplified as

\[ A(\omega) = 1 - \left| \frac{A_1 - A_2}{2} \right|^2 > 90\%. \tag{9} \]

According to (9), when the magnitude difference \( |A_1 - A_2| \) is 0.632, the absorption is 90%. When the magnitude difference \( |A_1 - A_2| \) is greater than 0.632, the effective absorption cannot be achieved even with absolutely opposite reflection phases. In Fig. 4(a), it can be seen from the red solid line that the magnitude difference is greater than 0.632 from 20 to 21 GHz, which leads to the gap in Fig. 5.

Comparing the phase difference (red solid line) in Fig. 4(b) with the required phase difference range (gray area) in Fig. 5, the phase difference between the two AMC lattices satisfies the requirement from 8.5 to 19.8 GHz, which means the effective absorption can be obtained within this frequency band. As shown in Fig. 6, the simulated radar absorption at normal incident (the red line) indicates that the proposed radar absorber can achieve a wide bandwidth from 7.9 to 19.4 GHz. The discrepancies are due to the fact that the simulation results in Fig. 6 are based on the functional unit cell \([2 \times 2\) dual AMC lattices, Fig. 2(c)], whereas the results in Fig. 5 are based on two elementary unit cells of AMCs. The former has taken into account of mutual coupling between the different AMC lattices and the elementary unit cells, while the latter has only simulated coupling between the elementary unit cells.

Radar absorbers with lossless AMC structures depend strictly on phase difference, therefore, normally cannot provide wide bandwidth, especially when the incident angle becomes large [18], [24], [25]. To investigate the performances at various incident angles, the effective absorption bandwidth at different incident angles for TE and TM waves has been studied numerically, and the results are displayed in Fig. 6(a) and (b), respectively. The data indicate that for both TE and TM waves, the absorption and bandwidth decrease gently as the incident angle increases from 0° to 45°. Generally, unlike metal AMCs chessboard absorbers, the printed graphene absorber shows comparatively good performance at wide incident angles for both TE and TM waves.

IV. MEASUREMENTS AND EXPERIMENTAL RESULTS

To verify the simulation results, we have printed the graphene absorber with overall dimension of 210 mm x 240 mm using home-made graphene ink.

Limited by the screen printer, it is difficult to print two AMCs with different sheet resistances on the same paper. The two types of AMC lattices with sheet resistances of 98 and 8.7 Ω/sq (Sample 2 and Sample 3 in Fig. 1) were printed separately on normal A4 sized paper. The photograph of the printing screen used in fabrication is shown in Fig. 7(a). This printing screen was patterned with capillary film (ULANO, EZ50-Orange) and could be used to print two AMC lattices each time. Since the dimension of the ring is too thin for 4-point probe station to measure, rectangles with dimension of 8 mm x 25 mm around the lattices were printed for sheet resistance measurement. The AMC lattices with desired sheet resistances were then cut out [as shown in Fig. 7(b)] and spliced on silicone substrate with adhesive, arranged in chessboard configuration as designed. A thin copper plane with the same size of chessboard surface was placed at the back of the silicone substrate as ground. Fig. 7(c) displays the printed graphene radar absorber.

The printed graphene absorber was measured in the anechoic chamber with the experimental setup as displayed in Fig. 7(d). Two horn antennas (Aaronia AG, PowerLOG 70180) with frequency range of 700 MHz–18 GHz were
connected to the HP8510 vector network analyzer (VNA) as transmitter and receiver, respectively. To obtain a 20 dBm source power from the VNA, power amplifier (5.9–18 GHz, Mini-Circuits, ZVE-3W-183+) was used during the measurement. The time gating function in the VNA was applied to eliminate the noise and the interference between the two horn antennas during the measurement. The experimental results at normal incident are displayed in Fig. 8(a) and (b). Due to the limitations of the experimental conditions, the measurement is conducted only in the range of 6–18 GHz.

Fig. 8(a) shows the measured reflection coefficient between two horn antennas for three cases (copper PCB board, silicone substrate attached on the copper PCB board with blank A4 paper and adhesive on it, and printed graphene radar absorber). From Fig. 8(a), it can be seen that the reflection coefficient of the printed graphene radar absorber is much lower than that of the other two cases, demonstrating high EM absorption of the absorber under normal incident.

From Fig. 8(b), it can be seen that within the measured frequency range, the radar absorber has an impressive performance with an effective absorption from 7.58 to 18 GHz. The simulated data are in reasonably good agreement with the measured although there are discrepancies. There could be various reasons that have caused the discrepancy, such as the variation of the printed sheet resistance deviations, geometric variation of the absorber, uneven surface due to adhesive between the paper and silicone substrates, and so on.

To understand the causes of the discrepancy, uneven distribution of adhesive used to fix the paper on the top of silicone substrate and geometric variation is further investigated. Fig. 7(e) illustrates a kind of air layer induced by the uneven distribution of adhesive. The fabrication deviations in dimensions of AMC lattices vary randomly. The inner diameter of the circular rings is measured to be around $4.7 \pm 0.1$ mm, while the outer diameter is around $6.12 \pm 0.12$ mm, such as the one shown in Fig. 7(f), which should be 6 mm according to the design. The compressing procedure is the main reason which leads to the wider circular rings in fabricated samples.

To further investigate the absorber performance, the absorption at $0^\circ$, $15^\circ$, $30^\circ$, and $45^\circ$ incident angles for TE and TM modes was measured and illustrated in Fig. 9(a) and (b), together with the comparison between measured and simulated results at $45^\circ$. For both TE and TM waves, when the incident angle increases up to $45^\circ$, the absorber can still provide $>85\%$ absorption within the measured frequency range. The results
Fig. 9. (a) Measured absorption at incident angles of 0°, 15°, 30°, and 45°, with simulated absorption at 45° for the TE incidence and (b) TM incidence.

Fig. 10. Two bending cases with bending angles of 148° and 200°, respectively.

A very good absorption performance at wide incident angles.

Measurements for two different bending cases were carried out to investigate the effects of bending of the absorber. The cylinders used in the measurement were wrapped up by foils and have different circumferences of 583 and 432 mm, respectively. During measurement, the transmission coefficient of the cylinder wrapped by foils was measured first. Then, the printed graphene radar absorber was attached to the cylinder wrapped by foils to be measured, as shown in Fig. 10. According to the circumferences of the cylinders, two bending cases have bending angles of 148° and 200°, respectively. The measurement results are illustrated in Fig. 11. The absorber in bending case 1 (bending angle of 148°) provides four effective absorption peaks (>90%) located at 9.4, 11.5, 14.3, and 18 GHz, respectively, whereas in bending case 2 (bending angle of 200°), the absorber can still achieve four effective absorption peaks (>90%) at 9.8, 11.5, 13.3, and 16.8 GHz, respectively. The measurement results demonstrate that even though a single wideband effective absorption (>90%) cannot be provided in these two bending cases, the printed graphene radar absorber can still achieve absorption greater than 70% within most parts of the spectrum from 8 to 18 GHz and greater than 90% in some discrete bands.

V. CONCLUSION

In this work, we have proposed, designed, and screen printed the novel graphene AMC radar absorber with specific sheet resistances. By properly arranging two printed graphene AMC lattices in a chessboard configuration and controlling the sheet resistances of the patterns, we have obtained a desirable printed graphene radar absorber, which has achieved broad effective absorption bandwidth. The absorption mechanism of this new approach relies not only on the reflection cancellation between two AMCs but also on the absorption of the printed graphene patterns. The relationship between reflection magnitude difference and required phase difference of the two AMC lattices to achieve effective absorption has also been investigated thoroughly.

Both simulation and measurement results indicate that the absorption frequency band covers X-band (8–12 GHz) and Ku-band (12–18 GHz). Meanwhile, unlike other reported AMC-based absorbers, the absorber in this work is much less sensitive to incident angles and performs well under various incident angles for both TE and TM waves. The printed graphene radar absorber also has reasonably good mechanical flexibility and can still provide greater than 70% absorption within most parts of the X- and Ku-bands in the two bending cases.

In a word, not only novel screen printed graphene radar absorber based on phase cancellation as well as its absorption has been reported, but new methodology of radar absorber
designs applying dual lossy AMCs with different sheet resistances has also been demonstrated analytically, numerically, and experimentally. This approach could have a wider application as it has provided more degree of freedom in radar absorber designs, i.e., not only the unit cell shapes but also the sheet resistances of the sheets can play a significant part in the design metric.

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