



Screen-printing high/low resistance using only a single silver nanowire ink: Resistance-gradient metasurface application for broadband microwave absorption and optical transparency

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ARTICLE INFO

Keywords:

Metasurface
Screen printing
Silver nanowire
Broadband absorption
Optical transparency

ABSTRACT

Transparent metasurface absorbers are highly sought after for their diverse applications, but achieving broad absorption bandwidths without sacrificing optical transparency remains a challenge. Traditionally, enhancing absorption involves increasing substrate thickness, which reduces transmittance. We address this by introducing a resistance-gradient metasurface (RGM) that combines broad absorption with high optical transparency. Unlike conventional methods requiring various inks for different resistances, our approach uses a single silver nanowire ink and screen-printing to create multiple resistances. This technique allows for flexible design and multiple resonances within the metasurface, achieving broad absorption even with a thin substrate. The RGM demonstrates an absorption bandwidth from 8.68 to 11.48 GHz with a substrate thickness of just $0.045 \lambda_0$, and optical transmittance of 66.3 % at 550 nm. This innovation promises to enhance both substrate efficiency and bandwidth in transparent metasurface absorbers, broadening their application potential in advanced devices.

1. Introduction

The development of various communication technologies such as wireless local area networks, global positioning systems, Bluetooth, and mobile networks has significantly enhanced our everyday experiences. With the global adoption of smartphones, communication systems have become particularly indispensable. At present, research efforts are not simply confined to the development of current communication systems but also extend to future communication systems such as Wi-Fi 7 and 6G, and advancements are anticipated to continue [1–3]. However, the advancement of communication systems presents both advantages and disadvantages. One major issue is the utilisation of numerous frequency bands, resulting in issues such as unwanted radiations, scattering of electromagnetic waves, and electromagnetic interference [4–6]. Addressing these phenomena is not only critical for measuring the performance of electronic equipment and antennas but also crucial from the perspectives of medical, defence, and security applications [7,8]. Hence, to address these issues, electromagnetic wave absorbers are widely employed to effectively absorb unwanted electromagnetic waves

and minimise electromagnetic interference.

Electromagnetic wave absorbers can be broadly categorised into pyramidal absorbers and metasurface absorbers. Among these, pyramidal absorbers are known for their excellent performance in absorbing electromagnetic waves, particularly at low frequencies, and their effective absorption across a wide frequency range. These attributes of pyramidal absorbers make them ideal for electromagnetic interference and electromagnetic compatibility tests requiring measurements at low frequencies, as well as for antenna performance tests across broad frequency bands. However, the high costs and bulky sizes of pyramidal absorbers limit their practical applications. Metasurface absorbers also known as metamaterial absorbers represent viable alternatives to pyramidal absorbers. First introduced by N. Landy in 2008 [9], metasurface absorbers have garnered significant research attention owing to their ability to change their absorption frequencies by manipulating their effective permittivity and permeability [10–16]. Recently, transparent metasurface absorbers, in particular, have gained traction owing to their promising application potential across various devices and applications [17–20].

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<https://doi.org/10.1016/j.matdes.2024.113451>

Received 27 September 2024; Received in revised form 1 November 2024; Accepted 9 November 2024

Available online 12 November 2024

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Transparent metasurface absorbers are typically designed using transparent conductive materials such as indium tin oxide (ITO) and silver nanowires (AgNWs) or metal mesh materials wherein conductive materials, such as copper and silver, are organized into micro-scale thin wires. Here, ITO is valued for its balanced conductivity and good optical transmittance, while AgNWs are preferred for their low costs and good flexibility [21–24]. Meanwhile, metal mesh materials demonstrate good conductivity and durability [25,26]. Despite the advantages of these materials, achieving broadband absorption in transparent metasurface absorbers remains particularly challenging owing to their reliance on resonant properties.

To overcome this, recent studies have introduced various methods. Among these, one approach involves incorporating chip resistors into the metasurface absorber structure to achieve broadband absorption. For instance, Lee et al. [27] proposed structure achieved a broadband absorption of 7.49 to 10.01 GHz at a thickness of $0.05 \lambda_0$, however it requires eight chip resistor connections per unit cell, which complicates the fabrication process. Another method involves creating patterns with multiple resonances within the metasurface to achieve broadband absorption [28–30]. However, these structures require a substantial substrate thickness to achieve broadband resonant properties, which can limit optical transmittance and hinder practical applications. Therefore, alternative methods that can achieve broadband absorption performance without increasing substrate thicknesses are required.

In this study, we introduce the novel concept of a resistance-gradient metasurface (RGM) exhibiting both broadband absorption and optical transparency. The introduced RGM utilises the concept of AgNW screen-printed resistance gradients. Fig. 1 illustrates the conceptual design of the proposed RGM. The properties of the metasurface vary based on the shape, size, and resistance of each pattern. By optimising resistance values across different metasurface patterns, the performance of metasurface absorbers can be improved. This is particularly effective when applied to patterns within the same layer. Such an approach can increase design freedom.

However, most of them require various types of inks to form different resistances, and it is very difficult to form different resistances on the same layer. The proposed method integrates just single AgNW-based transparent ink with screen printing technology, facilitating the easy creation of patterns with varying resistance values within a single layer.

The proposed method was applied to a metasurface design to maximise absorption performance. Notably, the RGM concept effectively addresses the narrow-band characteristics of metasurface absorbers without increasing substrate thickness. Furthermore, the innovative RGM design endows transparent metasurface absorbers with broadband absorption characteristics without increasing substrate thicknesses, making it a promising solution for a variety of optical and electronic devices.

2. Materials and methods

2.1. Screen printing and post printing

An automatic screen printer (SJ-7320A, SUNGJIN Technology) was used for the screen-printing process. A polyester screen mask equipped with a screen mesh measuring $150 \text{ mm} \times 150 \text{ mm}$ (120 mesh count, a 22.5° mesh angle, and $30 \mu\text{m}$ emulsion thickness) was utilised for creating the cross and square patterns on the top and ground surfaces of the 0.25-mm-thick PET substrate. In total, three screen masks, each with alignment marks, were used to implement the cross and square patterns on the top surface and the ground surface, each with alignment marks for printing alignment. The top and ground surfaces were screen printed onto each 0.25 mm thick PET substrate using a single screen-printable AgNW ink. After printing, the top and ground surfaces were heat sintered in an oven at 140°C for 20 min.

2.2. Characterisation

The optical transmittance of the AgNW pattern after each printing cycle was measured using a colour difference metre (CM-36dG, KONICA MINOLTA), while the electrical properties of the substrates were measured using a split cylinder resonator (N1501AKEAD-710, EM Labs, Kobe). The reflection and transmission coefficients of the fabricated metasurface were measured using a vector network analyser (Keysight FieldFox N9951A) capable of measuring up to frequencies of 44 GHz. We used X-band lens horn antennas (LHA-30-WR90, Antenal) for the transmit and receive antennas. The optical transmittance of the fabricated metasurface was measured using an ultraviolet–visible–near-infrared spectrometer (SolidSpec-3700, Shimadzu).

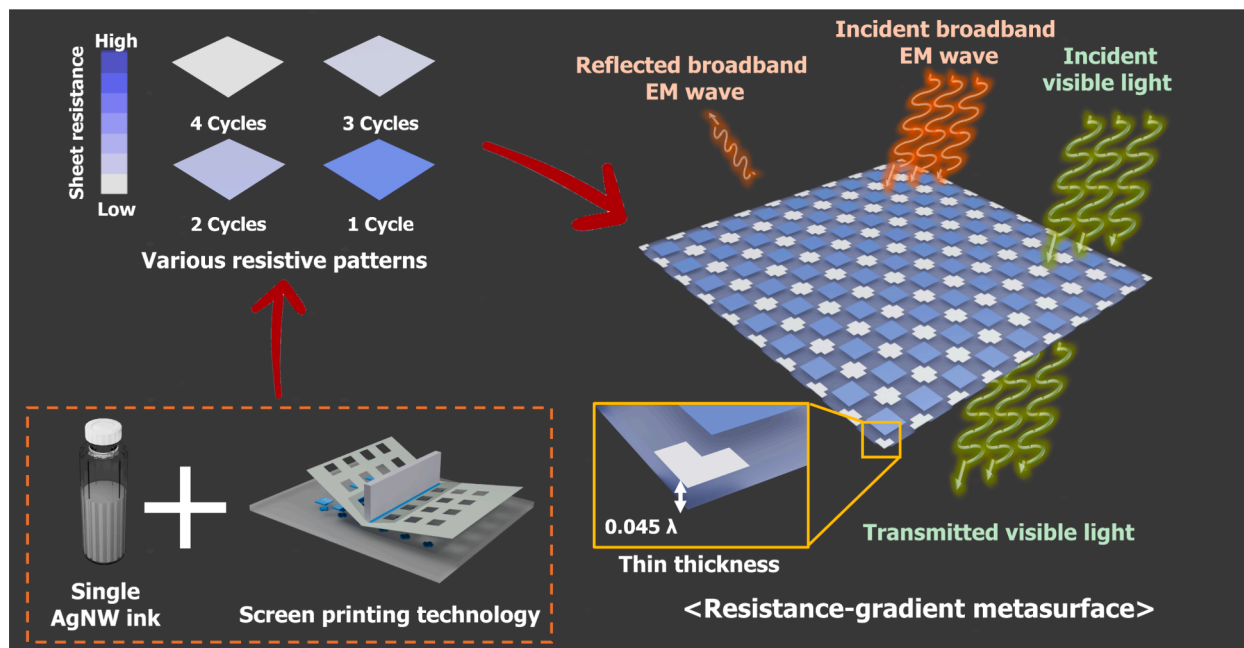


Fig. 1. Concept illustration of the proposed RGM using a single AgNW ink for broadband absorption and optical transparency.

3. Results and discussion

3.1. Proposed RGM concept

Fig. 2(a–d) shows the simulated reflection coefficients of metasurface absorbers with various patterns under changing sheet resistances. We employed the ANSYS high-frequency structure simulator (HFSS) tool for unit structure analyses. Fig. S1 shows the boundary conditions defined within the HFSS. In particular, we utilised master and slave boundary conditions to simulate the unit structure. The substrate thickness was set to 1.55 mm, allowing all four patterns to operate within the X-band. Notably, to achieve an absorption rate of more than 90 %, a reflection coefficient of -10 dB or less is required. Fig. 2(a) depicts the simulated reflection coefficients of the absorber with the square pattern under varying sheet resistances (from 10 to 50 Ω/sq). The results indicate that the reflection coefficient is less than -10 dB up to 20 Ω/sq , with the -10 dB bandwidth decreasing with increasing sheet resistance. Fig. 2(b) shows the simulated reflection coefficients of the square loop pattern under varying sheet resistances (from 5 to 15 Ω/sq). These results indicate that up to 7 Ω/sq , the reflection coefficient is below -10 dB. Furthermore, the -10 dB bandwidth decreases as the sheet resistance increases, similar to the trend observed for the square pattern. This suggests that the square loop pattern requires a lower sheet resistance compared to the square pattern. Fig. 2(c) shows the simulated reflection coefficients of the absorber with the cross pattern under varying sheet resistances (from 10 to 50 Ω/sq). The simulation results show a reflection coefficient value of -10 dB or less up to 20 Ω/sq . Notably, unlike the square pattern, there is little difference in the -10 dB bandwidth for 10 and 20 Ω/sq . Fig. 2(d) shows the simulated reflection coefficients of the absorber with the circular pattern under varying sheet resistances (from 10 to 50 Ω/sq). The results show indicate that the reflection coefficient value remains below -10 dB up to 30 Ω/sq . Unlike the other patterns, the -10 dB bandwidth is wider at 20 Ω/sq compared to 10 Ω/sq . These results indicate that different metasurface absorber patterns require different sheet resistance values. This implies that the characteristics of the resistive ink will constrain the range of designable metasurface absorber patterns. For instance, if the resistive ink exhibits a sheet resistance of 30 Ω/sq , achieving a reflection coefficient below -10 dB

with the current structure is challenging, except for the circular pattern. Conversely, if the resistive ink exhibits a sheet resistance of 10 Ω/sq or less, most patterns meet the required performance criteria. However, the optical transmittance of transparent conductive materials typically decreases as the sheet resistance decreases [31,32]. Therefore, designing transparent metasurface absorbers requires simultaneous considerations of the sheet resistance and optical transmittance, necessitating the selection of an optimised sheet resistance. Fig. 2(e) shows an AgNW film subjected to 1–4 cycles of screen printing. In this study, we used AgNW-based screen-printable transparent inks (DM-SNW-8012S, Dycotec, UK). The figure reveals that the logo becomes increasingly opaque as the number of printing cycles increases. We also measured the sheet resistance and optical transmittance of the screen-printed film. Fig. 2(f) shows the change in sheet resistance with the number of screen-printing cycles. Notably, the sheet resistance decreased from 12.3 Ω/sq after the first printing cycle to 3.5 Ω/sq after the fourth printing cycle. Thus, as the number of printing cycles increased, the sheet resistance gradually decreased. Fig. 2(g) shows the change in optical transmittance with the number of screen-printing cycles. The unprinted polyethylene terephthalate (PET) substrate exhibited an optical transmittance of 92.2 % at 550 nm. At the same wavelength, after the first printing cycle, the film exhibited an optical transmittance of 81.8 %, while after the fourth printing cycle, the film demonstrated an optical transmittance of 65.7 %. Thus, the optical transmittance decreased as the number of screen-printing cycles increased, mirroring the trend observed for the sheet resistance. A metasurface absorber was a structure that combines a pattern on the top surface with a ground-plane bottom surface. To achieve the optimal optical transparency, a high resistance is typically required. However, the results displayed in Fig. 2(a–d) indicate that achieving a reflection coefficient below -10 dB by simply using a high resistance is difficult. To address this limitation, we introduced a novel RGM that utilises different resistances simultaneously.

Next, we predicted the performance of the proposed RGM using electromagnetic simulations. As shown in Fig. 3(a), we designed a metasurface absorber unit structure with three different resistive patterns. Subsequently, we performed electromagnetic simulations assuming that these patterns featured one, two, and three different resistances, respectively. Fig. 3(b) shows the simulated reflection

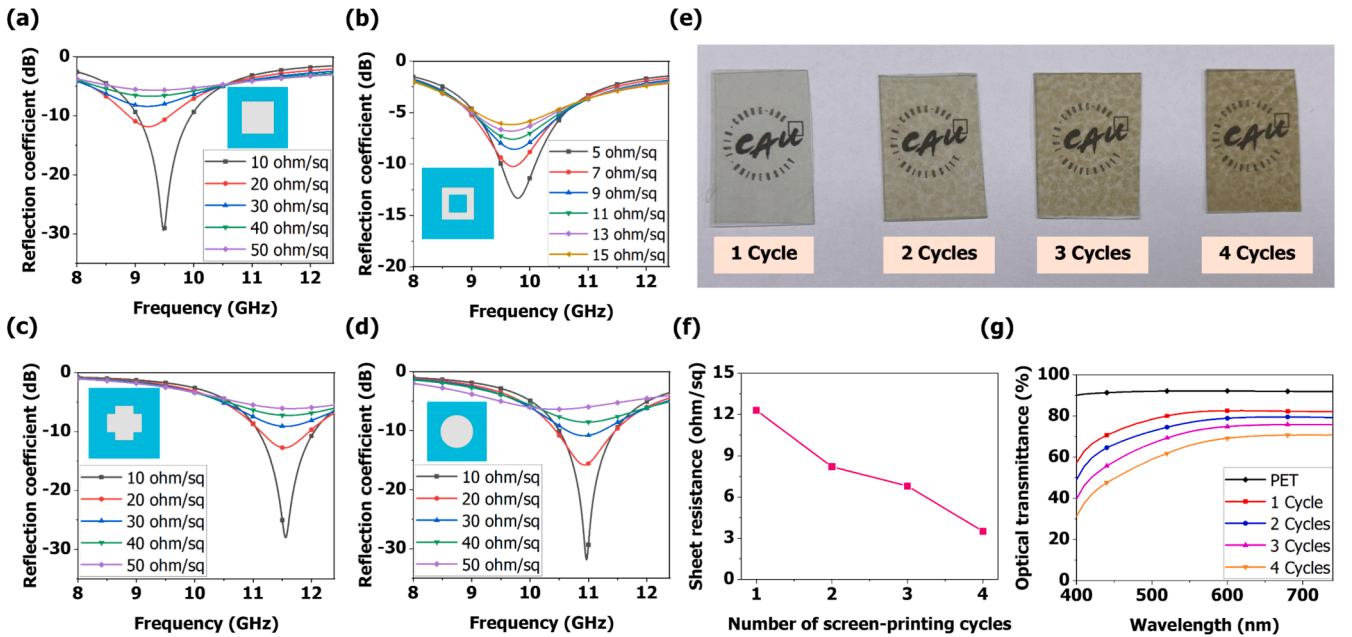


Fig. 2. Simulated reflection coefficients of a typical metasurface absorber with different patterns under varying sheet resistances: (a) square pattern, (b) square loop pattern, (c) cross pattern, and (d) circular pattern. (e) Screen-printed AgNW film subjected to varying numbers of screen-printing cycles. Variations in the (f) sheet resistance and (g) optical transmittance of films with increasing screen-printing cycles.

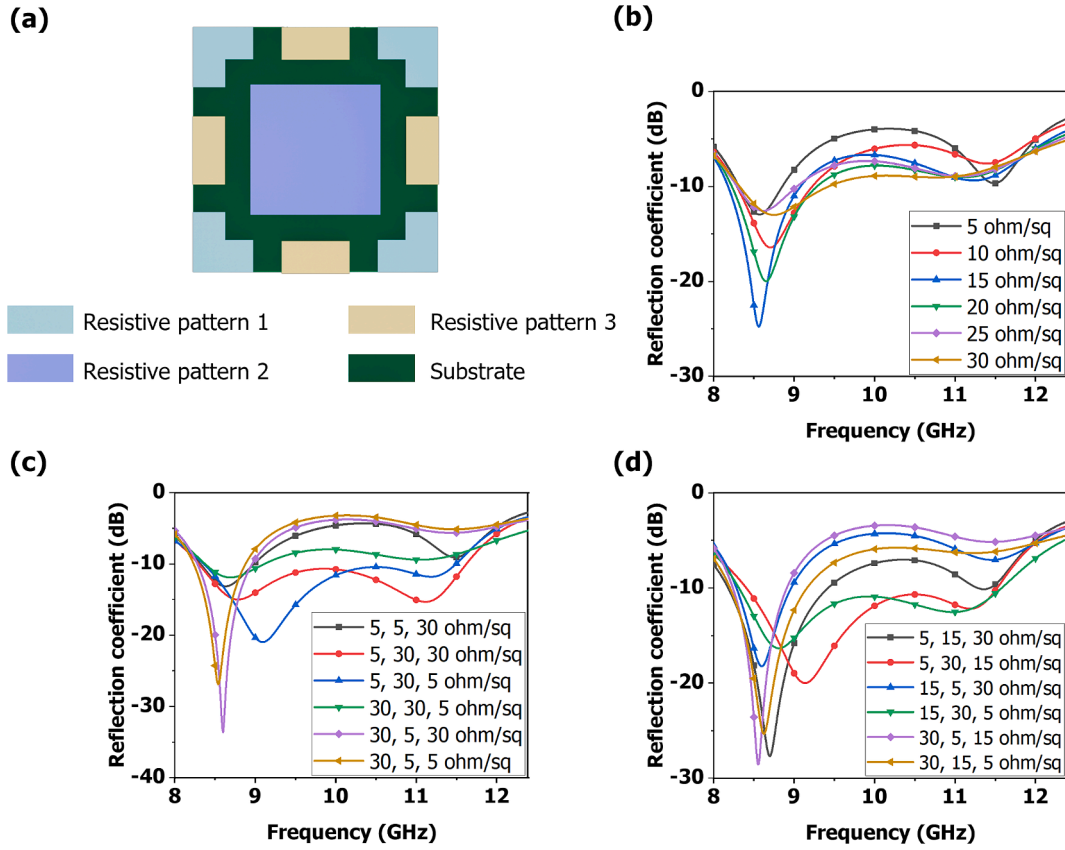


Fig. 3. (a) Metasurface absorber structures with different resistance patterns. Simulated reflection coefficient results for varying number of resistance values: (b) one resistance value, (c) two resistance values, (d) three resistance values.

coefficient results assuming that the three resistive patterns feature only one resistance value. The -10 dB bandwidth shifted toward higher frequencies as the sheet resistance increased. The -10 dB bandwidth was the widest (at 8.32 to 9.43 GHz) when the sheet resistance was 30 Ω/sq . Fig. 3(c) shows the reflection coefficient results simulated assuming that the three resistive patterns feature two different resistance values. The results indicate that when the first, second, and third resistive patterns exhibit sheet resistances of 5, 30, and 30 Ω/sq , respectively, the -10 dB bandwidth ranges from 8.3 to 11.62 GHz. This bandwidth is 2.2 GHz wider than that observed for a single resistance value. Given that the majority of the resistances are relatively high, higher optical transmittance values compared to those under a single low resistance value are expected. Fig. 3(d) shows the reflection coefficient results simulated assuming that the three resistive patterns exhibit three different resistance values. In this case, the widest bandwidth is achieved when the first, second, and third resistive patterns feature sheet resistances of 15, 30, and 5 Ω/sq , respectively, resulting in a -10 dB bandwidth ranging from 8.31 to 11.58 GHz. This bandwidth is similar to that obtained with two resistance values. Thus, when designing a metasurface absorber with a structure featuring multiple resonances, two or more different resistance values are required. This approach is essential to achieve satisfactory broadband absorption performance. Furthermore, a high optical transparency can be anticipated owing to the relatively high value of resistance used.

3.2. Design and analysis of the proposed RGM

Fig. 4(a–d) shows the bird's-eye, top, side, and bottom views of the proposed RGM. Notably, the RGM unit structure was designed as dual-resonant structure combining square and cross patterns. To maximise absorptivity performance, we applied sheet resistances of 30 Ω/sq and 8

Ω/sq to the square and cross pattern, respectively. For the substrate, we used a 0.25-mm-thick PET film (UC224, Hyosung Chemical, South Korea) with a dielectric constant of 3.22 and a loss tangent of 0.0048 at 10 GHz, along with another 0.95-mm-thick PET with a dielectric constant of 2.95 and loss tangent of 0.0059. The total thickness of the substrate used was only 1.55 mm, with an electrical length of $0.045 \lambda_0$. In total, three PET substrates were bonded using an optically clear adhesive (OCA) film (8146–1, 3 M, USA). The ground pattern was designed to exhibit a sheet resistance of 15 Ω/sq to ensure transparency while preventing electromagnetic waves transmission. Notably, patterns with different resistances achieve optimal absorptivity performance and enhance optical transparency. We simulated the reflection coefficient and absorptivity of the proposed RGM. In particular, the absorptivity was obtained using the following formula:

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

where $R(\omega)$ is the reflection coefficient, and $T(\omega)$ is the transmission coefficient. Fig. 4(e) shows the simulated reflection coefficient and absorptivity of the proposed RGM. Notably, the -10 dB reflection coefficient bandwidth of the proposed RGM ranged from 8.83 to 11.64 GHz. It can be seen that it behaves as a double resonance, with resonance peaks at 9.5 GHz and 11.3 GHz. The 90 % absorptivity bandwidth was between 8.85 and 11.63 GHz, similar to the reflection coefficient. This similarity is attributed to the low values of the transmission coefficient. Fig. 4(f) shows the simulated absorptivity of the proposed RGM at varying incident angles. At incident angles θ up to 20° , the absorptivity bandwidth of the RGM remains similar to that at an incident angle of 0° . At incident angles up to 50° , the absorptivity remains above 80 %, decreasing with increasing θ . Fig. 4(g) shows the simulated absorptivity results for different polarization angles of the proposed RGM. Notably, the simulated absorptivity remains unchanged across polarisation angles ranging

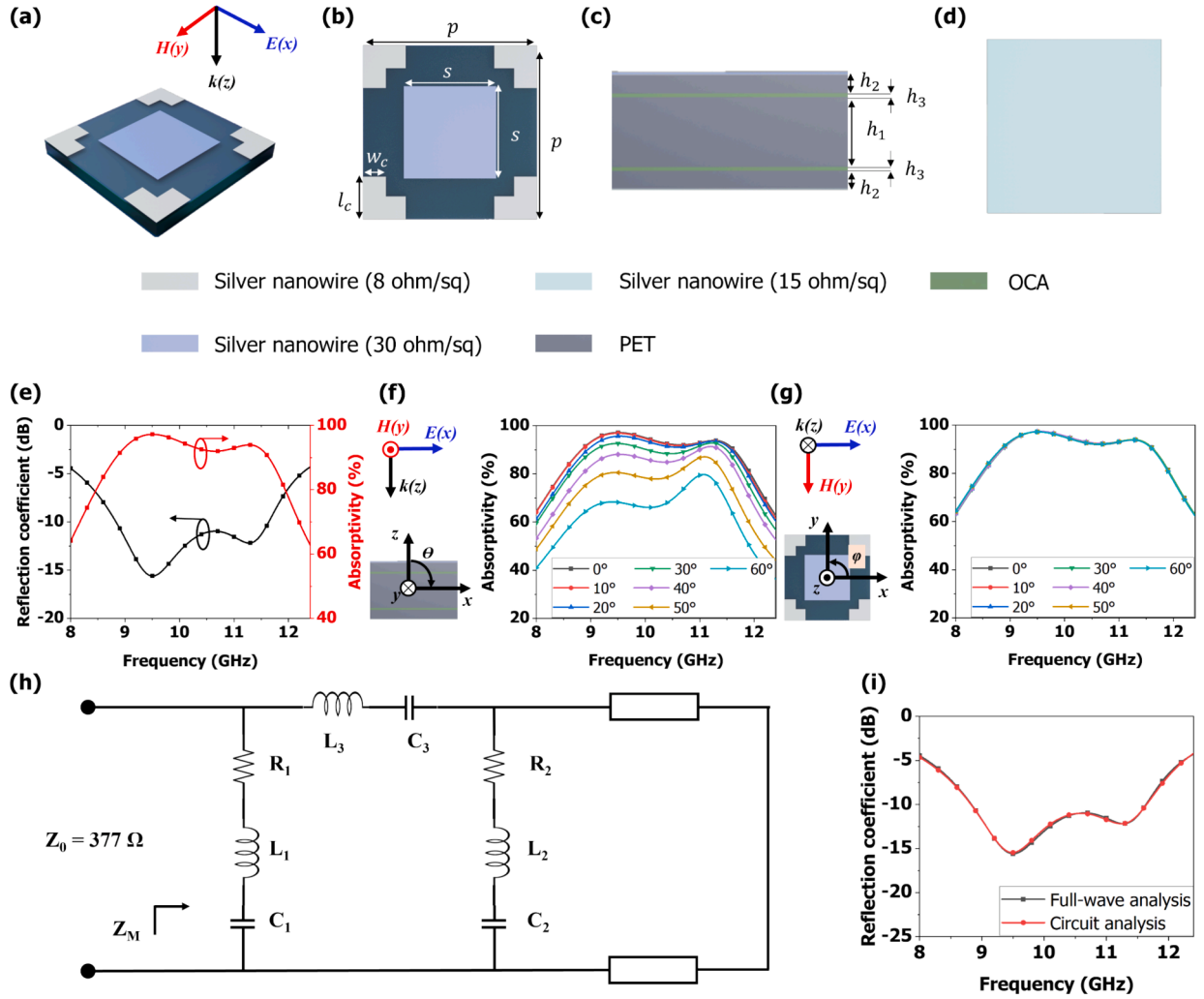


Fig. 4. (a) Bird's-eye view, (b) top view, (c) side view, and (d) bottom view of the proposed RGM ($p = 14.5$ mm, $s = 7.7$ mm, $w_c = 1.9$ mm, $l_c = 3.55$ mm, $h_1 = 0.95$ mm, $h_2 = 0.25$ mm, and $h_3 = 0.05$ mm). (e) Simulated reflection coefficient and absorptivity results of the unit structure of the proposed RGM. Simulated absorptivity results for (f) oblique incidence and (g) each polarisation. (h) Equivalent circuit of the proposed RGM. (i) Comparison of the reflection coefficients obtained from the full-wave analysis and circuit analysis.

from 0° to 60° , owing to the symmetry of the proposed RGM unit structure. Fig. S2 shows the simulated absorptivity results for each pattern, square and cross, in the unit structure of the proposed RGM. For the cross pattern, the 90 % absorptivity bandwidth lies between 11.15 and 12.06 GHz, with a peak absorption at 99.7 %, exhibiting a sharp trend. The square pattern exhibits its peak absorption of 86.5 % at 9.2 GHz. Here, no bands achieve an absorptivity exceeding 90 %, and the variation trend is smoother compared to that observed for the cross pattern. The reason the proposed RGM exhibits broadband absorption characteristics even with a thin thickness is due to the additional coupling phenomenon between the square pattern, which shows a smooth absorption trend, and the cross pattern, which exhibits a sharp trend. Next, we performed a circuit analysis of the proposed RGM to support our claims. Fig. 4(h) shows the equivalent circuit of the proposed RGM. Here, Z_M denotes the impedance of the metasurface absorber, which is defined as follows:

$$Z_M = Z_0 \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}}, \quad (2)$$

where Z_0 denotes the impedance in free space, which is 377Ω . The impedance Z_M of the metasurface absorber is determined based on the reflection and transmission coefficients, and electromagnetic wave

absorption occurs when Z_M approximates the value of the free space impedance Z_0 . The proposed RGM can be interpreted as two series RLC circuits connected in parallel, with LC circuits connected in series between them. The two series RLC circuits represent the square and cross patterns in the unit structure, respectively. Here, L_3 and C_3 denote the parasitic inductance and parasitic capacitance formed between the two patterns. Next, we performed a circuit analysis using the Keysight advanced design system tool to validate the agreement between the full-wave analysis performed using the HFSS tool and the proposed equivalent circuit. Fig. 4(i) compares the reflection coefficients obtained from the full-wave and circuit analyses. The circuit parameters used in the circuit analysis were $R_1 = 250 \Omega$, $L_1 = 26.5$ nH, $C_1 = 0.0117$ pF, $R_2 = 7.2 \Omega$, $L_2 = 4$ nH, $C_2 = 0.02135$ pF, $L_3 = 31.3$ nH, and $C_3 = 0.00615$ pF. The results of the reflection coefficients derived from the circuit analysis were consistent with those obtained from the full-wave analysis results. Both the circuit analysis and full-wave analysis utilized different high and low resistances, showing that both analyses produced similar results.

Next, we analysed the electric field distributions at 9.5 GHz and 11.3 GHz, which are expected to be strong resonance points based on the reflection coefficient results. Fig. 5(a) shows the top view of the surface current distribution at 9.5 GHz. As indicated, the current appears concentrated in the square pattern. Furthermore, the current direction is

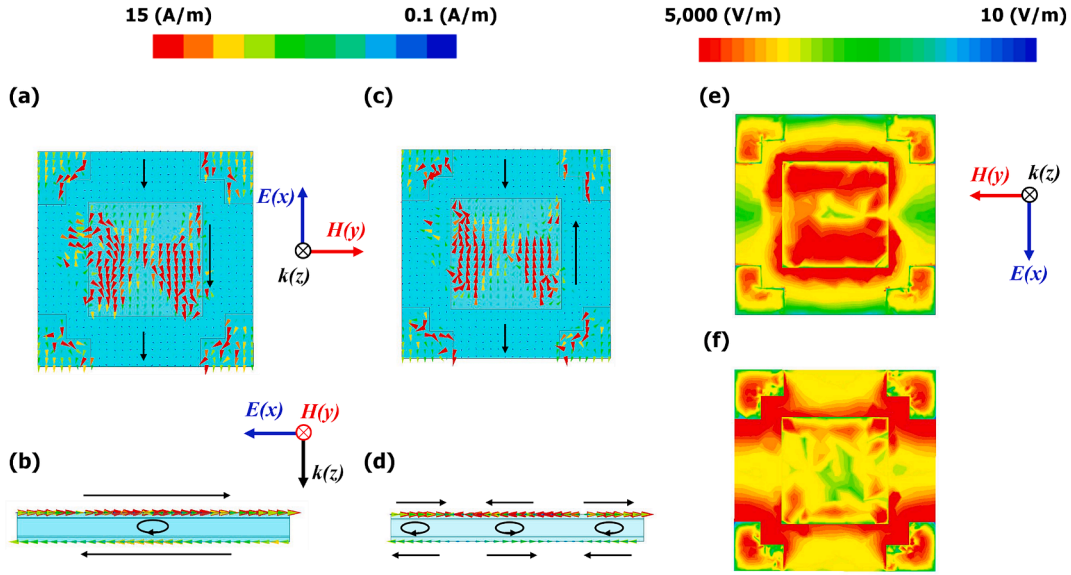


Fig. 5. Simulated surface current distributions: (a) top and (b) side views at 9.5 GHz and (c) top and (d) side views at 11.3 GHz. Simulated electric field distributions at (e) 9.5 GHz and (f) 11.3 GHz.

along the $-x$ axis for both the cross and square patterns. Fig. 5(b) shows a side view of the surface current distribution at 9.5 GHz. Here, the currents at the top and ground surfaces are aligned in opposite directions, inducing a near-field coupling between the top and ground surfaces and thus resulting in magnetic resonance. Notably, this magnetic resonance contributes to the electromagnetic wave absorption at 9.5 GHz. Fig. 5(c) shows a top view of the surface current distribution at 11.3 GHz. Notably, the square pattern exhibits a decreased current intensity compared to that at 9.5 GHz. Furthermore, the current direction is unusual: the cross pattern displays a current directed along the $-x$ direction, while the square pattern displays a current aligned along the $+x$ direction. Fig. 5(d) shows a side view of the surface current distribution at 11.3 GHz. Here, the ground surface current is distributed along the $+x$ direction in the cross-pattern region and in the $-x$ direction in the square pattern region. This induces different near-field couplings, resulting in a double magnetic resonance phenomenon, which contributes to the electromagnetic wave absorption performance at 11.3 GHz. In addition to magnetic resonance, ohmic losses in the resistive pattern of the metasurface also contribute to absorption [33,34]. Fig. 5(e, f) shows the electric field distributions at 9.5 GHz and 11.3 GHz, respectively. As depicted in Fig. 5(e), the electric fields within and around the square pattern are strong, indicating that the square pattern is a key factor in determining the 9.5 GHz resonant frequency. As depicted in Fig. 5(f), the electric fields within the cross pattern and between the cross and square patterns are strong, suggesting that the 11.3 GHz resonant frequency is influenced by both the cross pattern and the parasitic components formed between the patterns.

To understand the effects of parameter variations on the absorption rate of the RGM, we conducted simulations with varying parameters. Fig. 6 shows the absorption performance of the RGM as a function of the parameter length and sheet resistance. Fig. 6(a) shows the simulated absorptivity results for different values of the width w_c of the cross pattern. When w_c was varied from 1.5 to 2.3 mm, the absorption peak in the high-frequency region shifted to higher frequencies as w_c decreased. Conversely, at a higher value of w_c , the absorption peak shifted toward lower frequencies, along with the overall absorption bandwidth. This indicates that the width w_c of the cross pattern affects absorption in the high-frequency region. Fig. 6(b) shows the simulated absorptivity results for various values of the length l_c of the cross pattern. When l_c was varied from 3.15 to 3.95 mm, the absorption peak in the high-frequency region shifted to higher frequencies with decreasing l_c , similar to the trend

observed for w_c . However, the effect of l_c was more pronounced compared to that of w_c at the same length. Thus, similar to w_c , l_c also contributes to high-frequency absorption. Fig. 6(c) shows the simulated absorptivity results for different sheet resistances of the cross pattern. When the sheet resistance was varied from 4 to 12 Ω/sq , the absorption at high frequencies decreased as the sheet resistance increased, and the absorption at high frequencies increased as the sheet resistance decreased. Although the absorption bandwidth increased with decreasing sheet resistance, the change was minimal. For instance, the bandwidths were 8.87 to 11.71 GHz at 4 Ω/sq and 8.91 to 11.53 GHz at 12 Ω/sq . Fig. 6(d) shows the simulated absorptivity results for different values of the width and length s of the square pattern. When s was varied from 7.3 to 8.1 mm, absorption in the high-frequency region was not affected. However, as s decreased, the absorption peak at low frequencies gradually shifted toward higher frequencies. Conversely, as s increased, the absorption peak shifted toward lower frequencies. Unlike the cross pattern, the absorption at high frequencies remained unaffected, while the absorption in the middle band moved to lower frequencies. This indicates that the width and length of the square pattern contribute to low-frequency absorption. Fig. 6(e) shows the simulated absorptivity results for different sheet resistances of the square pattern. When the sheet resistance was 10 Ω/sq , the low-frequency absorption of the RGM remained above 90 %; however, its high-frequency absorption was lower. As the sheet resistance increased, the high-frequency absorption rate tended to increase, beginning from 40 Ω/sq . However, at higher sheet resistances, high-frequency absorption increased, whereas low-frequency absorption tended to decrease.

These results suggest that the bandwidth of the RGM can be adjusted by varying the sheet resistance of the two patterns. Fig. 6(f) shows the simulated absorptivity results for different values of the unit structure size p . As p increases, the cross pattern shifts, increasing the separation between the two patterns. The simulation results indicate that as p decreases, the high-frequency absorption worsens, low-frequency absorption improves, and overall absorption bandwidth shifts to lower frequencies. Conversely, as p increases, high-frequency absorption improves, low-frequency absorption worsens, and overall absorption bandwidth shifts to higher frequencies. Thus, by adjusting the unit structure size p , the two absorption peaks can be adjusted, yielding the optimal absorption bandwidth. Fig. 6(g) illustrates the simulated absorptivity profiles for various thicknesses h_1 of the PET substrate, demonstrating the significant impact of h_1 on the absorption

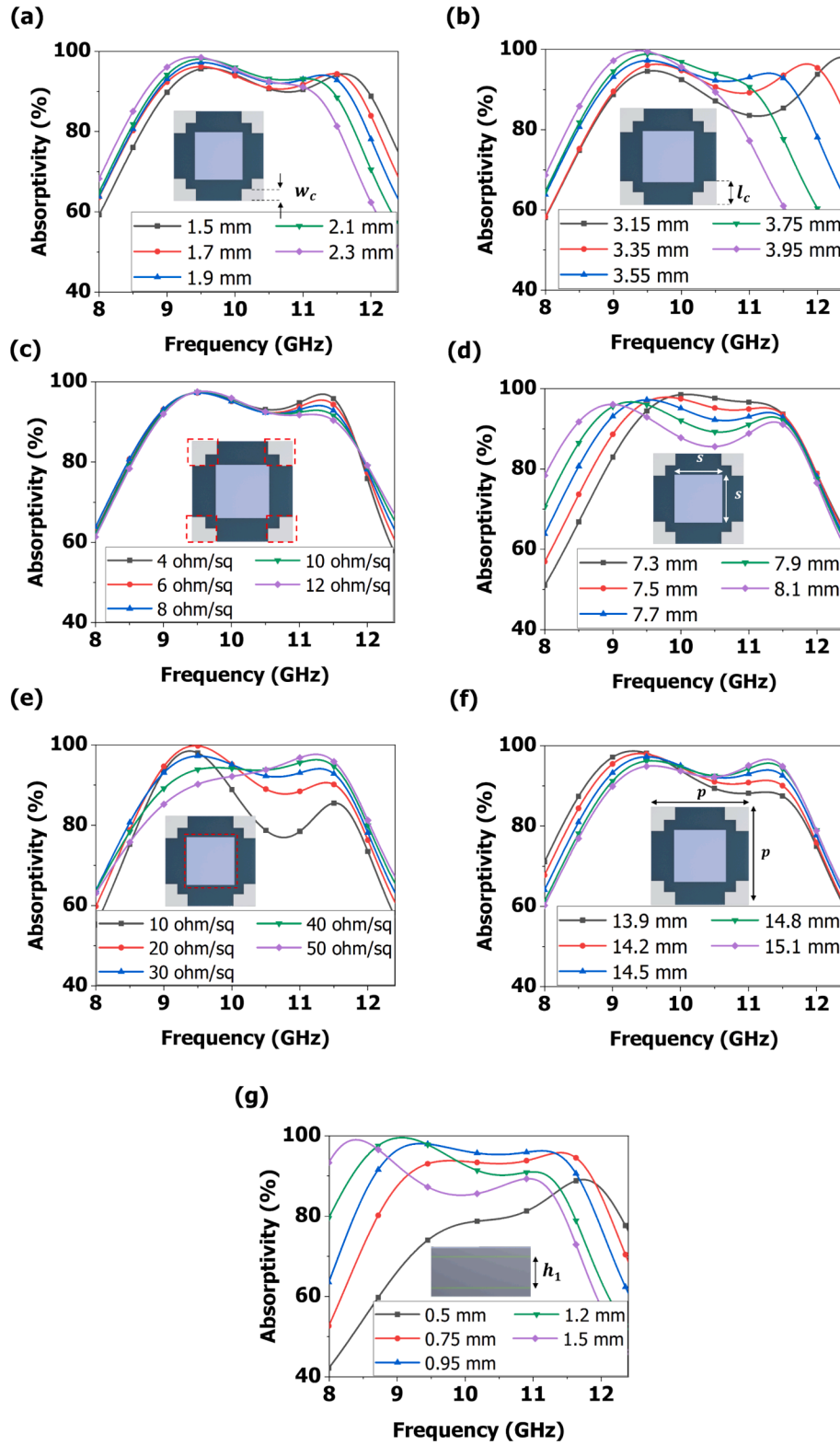


Fig. 6. Simulated absorption results of the proposed RGM under varying parameters: (a) w_c , (b) l_c , (c) sheet resistance of the cross pattern, (d) s , (e) sheet resistance of the square pattern, (f) p , and (g) h_1 .

characteristics. At an initial thickness of 0.5 mm, no frequency bands achieved an absorption level above 90 %, indicating limited resonance within the target frequency range. When h_1 increased to 0.75 mm, two distinct resonance peaks with absorption above 90 % appeared, albeit with a relatively narrow bandwidth compared to that at 0.95 mm. Further increases in h_1 resulted in a noticeable shift of both resonance

peaks toward lower frequencies, while the bandwidth of frequencies maintaining absorption above 90 % continued to decrease. At a thickness of 1.5 mm, high-frequency resonance diminished, falling below 90 % absorption. These findings suggest that the PET substrate thickness h_1 plays a critical role in tuning the resonance frequencies and absorption bandwidth, enabling tailored absorption characteristics through

substrate design adjustments.

3.3. Fabrication and measurement

For performance assessments, we fabricated a 9×9 prototype of the RGM. Fig. 7 illustrates the fabrication process. First, we screen-printed the cross pattern on the top unit structure with AgNW-based transparent ink for three cycles. The printed pattern was then dried on a hot plate for 10 min at 80 °C to prevent possible damage during the subsequent square patterning process. Next, a square pattern was screen-printed on the dried top surface using the same AgNW-based transparent ink. Subsequently, the top surface of the RGM was heat-sintered in a 140 °C oven for 20 min to complete the fabrication. The ground surface was screen-printed using the same AgNW-based transparent ink for two cycles, followed by heat sintering in a 140 °C oven for 20 min. The fabricated top and ground surfaces were then bonded to the top and bottom of a 0.95-mm-thick PET substrate using OCA to fabricate the final RGM prototype. Comparing the fabrication process with the measured sheet resistance results, it can be seen that more printing was done in the actual fabrication. The reason for this is that the printed AgNW patterns were not uniformly distributed. Some areas were clumped together while others were not printed properly. This caused the RGM to operate with a higher sheet resistance than the measured sheet resistance, deviating from the optimised simulation results. Therefore, we solved this problem by adjusting the number of printing iterations to target a slightly lower sheet resistance than initially designed.

Fig. 8(a) shows image of the 9×9 RGM prototype, with the university logo clearly visible in the background. Fig. 8(b, c) compare images without and with the RGM prototype, respectively. Note that the apartment in the background remains clearly visible even with the RGM prototype in place. Fig. 8(d) illustrates the measurement environment for the proposed RGM. We measured the reflection and transmission coefficients of the RGM using the free space measurement method. For the reflection coefficient, the reflected wave from a copper plate of the same size as the fabricated RGM served as the reference, and the

reflected wave from the RGM was measured against this reflected wave. For the transmission coefficient, the received wave to the Rx antenna in free space without the RGM was taken as the reference. Similar measurements were conducted with the RGM in place. Fig. S3 shows measured reflection and transmission coefficient results. The reflection coefficient shifted to a lower frequency by 0.2 GHz compared to the simulated coefficient, but the trend was similar, with two resonance points visible. The transmission coefficient was measured to be less than -20 dB, consistent with the simulation results. Fig. 8(e) shows the measured absorptivity results, calculated from the measured reflection and transmission coefficient results. The measured 90 % absorptivity bandwidth ranged from 8.68 to 11.48 GHz, similar to the simulated results. Fig. 8(f) shows the measured optical transmittance of the fabricated RGM. The optical transmittance of the substrate without the AgNW pattern was 86.2 % at 550 nm. Meanwhile, the optical transmittance values of the fabricated RGM were 66.3 % at 550 nm. The fabricated RGM have an optical transmittance of less than 55 % between 400 nm and 450 nm, owing to the surface plasmon resonance properties of the Ag [35,36].

Table 1 compares the performance of the proposed RGM with previously developed transparent metasurface absorbers utilising thin substrates. The absorber developed by the authors of [27] demonstrated an impressive FBW of 36.8 % and an optical transmittance of 78 % with a thickness of only $0.05 \lambda_0$. However, it required eight chip resistors per unit cell, complicating large-area fabrication. The absorber developed by the authors of [37] exhibited a similar relative thickness compared to the proposed RGM but with an FBW of only 5 %, limiting its bandwidth. Meanwhile, the absorber developed by the authors of [38] achieved an FBW of 36.6 % using a metal mesh, but it was 1.5 times thicker compared to the proposed RGM. The vulnerability to low thickness of absorbers using metal mesh can be seen in the work of [39]. This study used a substrate thickness of $0.015 \lambda_0$, but only achieved an FBW of 1.4 %. In this study, we achieved a relatively wide FBW of 27.8 % with a thin thickness of $0.045 \lambda_0$ and comparable optical transparency. Furthermore, unlike most previous studies that utilised different materials or lumped elements to fabricate metasurfaces, our proposed RGM utilises

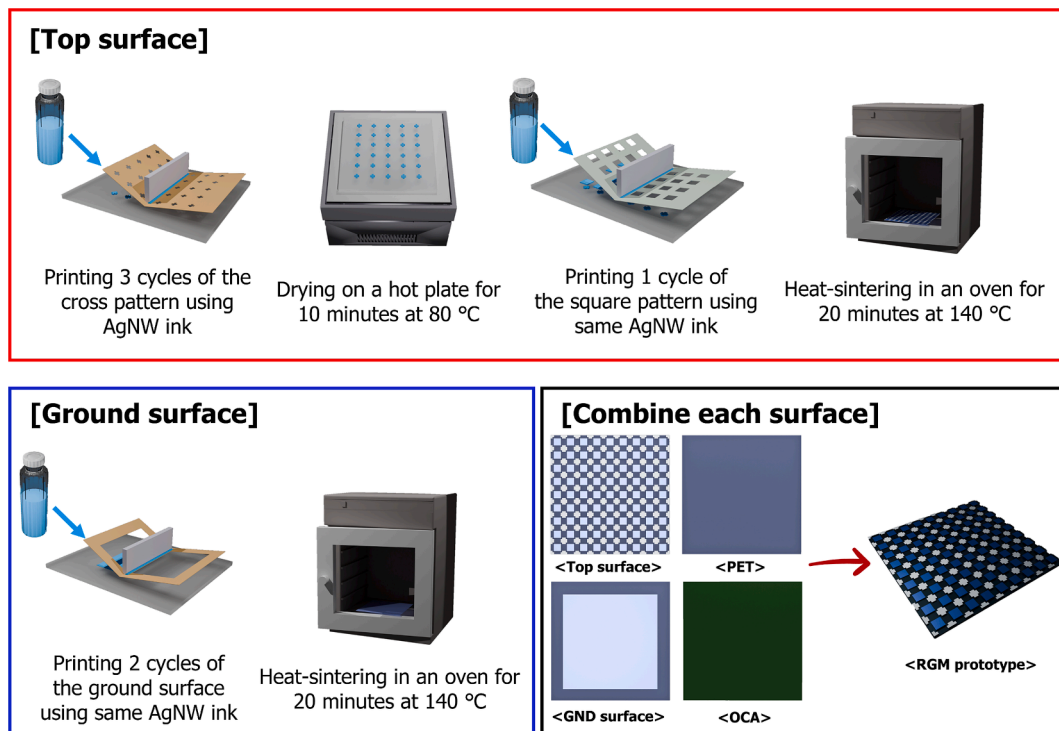


Fig. 7. Fabrication process of the proposed RGM prototype.

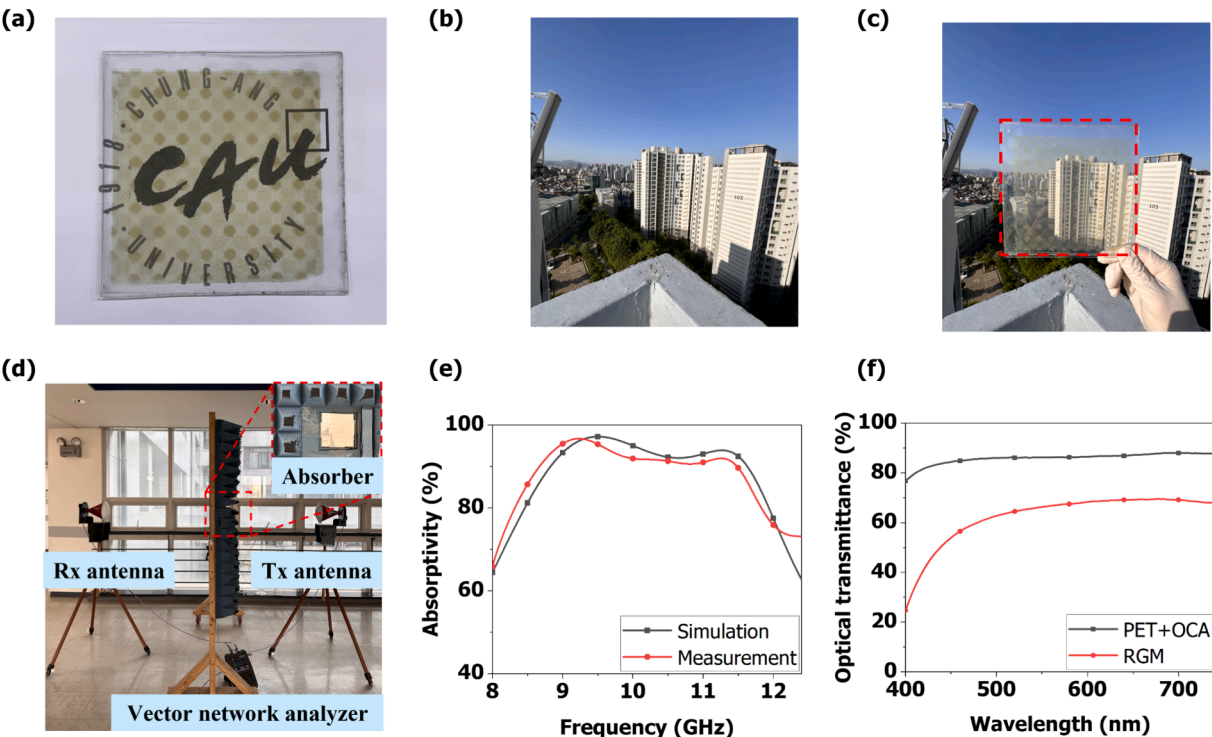


Fig. 8. (a) Fabricated RGM prototype. Photographs (b) without RGM prototype and (c) with RGM prototype. (d) Measurement environment image. (e) Absorptivity and (f) optical transmittance of the RGM.

Table 1
Comparison of the proposed RGM with previous optically transparent metasurface absorbers using thin substrates.

Ref.	Frequency (GHz)	FBW ¹ (%)	Optical transparency (%)	Thickness (mm)	Electrical thickness (λ_0)	Materials
[37]	26.8–28.2	5	N/A	0.5	0.04	ITO, silver
[38]	9.6–13.9	36.6	96.3 (Metal mesh), 90 (ITO)	2.1	0.068	Metal mesh, ITO
[39]	0.915–0.928	1.4	75 (Micromesh)	5.1	0.015	Al micromesh
[27]	7.3–10.6	36.8	78	2.25	0.05	ITO, 8 chip-resistor
This work	8.68–11.48	27.8	66.3	1.55	0.045	Only single AgNW ink

¹ FBW (fractional bandwidth) is defined as $FBW = 2(f_H - f_L)/(f_H + f_L)$, where f_H and f_L are the maximum and minimum frequency of the absorption band, respectively.

only a single screen-printable AgNW ink, addressing process complexity and cost issues.

4. Conclusion

In this study, we proposed a novel concept of a RGM demonstrating broadband absorption and optical transparency with a thin substrate. We generated different resistance values using a single screen-printable AgNW ink and successfully applied to transparent metasurfaces. The proposed RGM demonstrated over 90 % absorption across a broadband spanning from 8.68 to 11.48 GHz with a substrate thickness of only $0.045 \lambda_0$. Its optical transmittance was 66.3 % at 550 nm, indicating high optical transparency. Furthermore, the proposed RGM could be easily fabricated at a low cost using only single screen-printable AgNW ink. Designing transparent broadband metasurface absorbers with a thin substrate has been a longstanding challenge, with limited research. We believe that our proposed resistance-gradient concept will address the limitations of metasurface absorbers and facilitate their use in advanced optical and electronic devices.

CRediT authorship contribution statement

Junghyeon Kim: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation.

Prabhakar Jepiti: Validation, Investigation, Data curation. **Minjae Lee:** Software, Methodology. **Eiyong Park:** Validation, Data curation. **Ratanak Phon:** Visualization, Investigation. **Sungjoon Lim:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (2021R1A2C3005239) and Institute of Information & Communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (RS-2024-00396235).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.matdes.2024.113451>.

Data availability

Data will be made available on request.

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