

Design of a single-layer broadband absorber based on a simple nested topology of lumped elements

Yuliang Zhao^{1,2}, Wenrong Yang^{1,2}, Ting Chen^{1,2*}, Xian Zhang^{1,2}, Junling Luan^{1,2} and Haoyan He^{1,2}

¹ School of Electrical Engineering Hebei University of Technology, Tianjin 300401, China

² State Key Laboratory of Intelligent Power Distribution Equipment and System, Hebei University of Technology, Tianjin 300401, China

* Correspondence: tingchen@hebut.edu.cn (Chen T)

Abstract

This paper designs a metasurface absorber with a simple nested topology of lumped elements, achieving over 90% absorptivity across the frequency range of 10.15 to 20.91 GHz, demonstrating strong polarization insensitivity, and exhibiting stability for incidence angles of up to 30° and 50° for TM and TE modes, respectively. The designed absorber features a single-layer structure and achieves excellent broadband absorption performance through the superposition of resonant peaks at three distinct frequency points. The absorber comprises an FR-4 dielectric substrate, a metallic resonant structure, eight chip resistors, and a metallic reflective backplate. The absorption performance is analyzed under varying structural parameters, and the electromagnetic wave absorption mechanism is investigated through the surface electric field distribution. Furthermore, a prototype is fabricated, and its absorption characteristics are experimentally validated. Featuring broadband absorption with simple topology, the proposed absorber demonstrates strong potential for applications in electromagnetic shielding, radar stealth, and electromagnetic compatibility.

Keywords: Microwave, Metamaterials, Wave absorber, Broadband

Citation: Zhao Y, Yang W, Chen T, Zhang X, Luan J, et al. 2026. Design of a single-layer broadband absorber based on a simple nested topology of lumped elements. *Wireless Power Transfer* 13: e028 <https://doi.org/10.48130/wpt-0026-0020>

Introduction

Electromagnetic radiation in communication systems can couple into equipment through closed-loop paths during operation, leading to electromagnetic compatibility issues^[1]. Metasurface absorbers have emerged as an effective solution due to their compact size and high absorption rate. By tailoring artificial structures to modify their equivalent electromagnetic parameters, these absorbers exhibit distinct electromagnetic properties and have increasingly been applied in fields such as invisibility cloaks^[2], metamaterial 'perfect' absorbers^[3,4], wireless power transfer^[5], satellite communication, and radar surveillance^[6].

Although some absorbers are designed with flexible structures to accommodate bending applications, this flexibility often results in increased thickness and reduced absorption bandwidth^[7], limiting their performance in complex and dynamic electromagnetic environments. Conversely, absorbers characterized by broad absorption bandwidths and compact geometries demonstrate superior environmental adaptability. During the design process, factors such as cost-effectiveness and manufacturability must also be carefully considered. Under natural resonance, metamaterial absorbers exhibit an inherently narrow absorption bandwidth. To overcome this issue, superior materials and multilayer stacking can be used to broaden the absorption bandwidth. By incorporating materials with favorable electromagnetic properties, such as ITO, PET, VO₂, SiO₂, and PMI^[8–12], the electromagnetic parameters of the absorber can be improved, thereby broadening its absorption bandwidth. Nevertheless, in practical fabrication, materials such as PET and ITO, despite their excellent electromagnetic properties, often require more complex manufacturing processes. This not only significantly increases production costs but also introduces substantial challenges to the overall fabrication process. Therefore, while these

materials enhance broadband absorption, their inclusion requires an economic trade-off. By stacking multilayer materials^[13] or multilayer resonant topologies^[14–19], each layer contributes to absorption in different frequency bands, enabling distinct electromagnetic wave absorption mechanisms and thereby enhancing the overall absorption performance. However, this approach increases the size and mass of the absorber, and the multilayer structure typically requires sophisticated manufacturing processes. The design of each layer has to take into account factors such as interlayer compatibility and material adaptation. Inadequate coupling between layers may weaken absorption in certain frequency bands, limiting bandwidth enhancement or even causing bandwidth contraction, ultimately degrading overall performance and absorption efficiency. Currently, the absorber topology design based on lumped elements offers an effective approach to broadening the absorption bandwidth; for example, symmetric semicircular structures with pin diodes^[20] and open-ring or metal-strip configurations with chip resistors^[21]. Despite these approaches' ability to expand the absorption bandwidth, they often lead to increased structural complexity and thickness^[22]. Therefore, the design of an absorber based on lumped elements should be characterized by both broadband absorption, simplicity of structure, and small thickness.

In this work, a single-layer absorber based on lumped elements is proposed. The proposed absorber achieves over 90% absorption in the frequency range of 10.15–20.91 GHz, corresponding to a fractional bandwidth of 69.3%, with a total thickness of 2.3 mm and an electrical thickness of 0.119 λ_0 , where λ_0 is the wavelength corresponding to the center frequency of the absorber's operating bandwidth. Experimental validation confirms its performance, demonstrating broadband operation, structural simplicity, wide-angle stability, and polarization insensitivity.

Design and simulation

Figure 1 shows the top view, side view, and overall structural configuration of the proposed metasurface absorber unit. The unit consists of a metal resonant layer, a dielectric layer, a metal reflective layer, and chip resistors. The metal resonant unit includes an outer split ring, within which is nested a split square ring, a central metal disc, and eight chip resistors. The eight chip resistors are symmetrically placed at the split gaps of the two rings—four on the outer circular ring and four on the inner square ring—providing conductive bridging across the splits and contributing to the broadband absorption performance. They are loaded at eight splits from the outside to the inside. The resistors on the circular ring are denoted as R_w , and those on the square ring are denoted as R_n . Considering the fabrication cost as well as the fabrication process, FR-4 material with a relative dielectric constant of 4.3 and a loss tangent of 0.025 was selected for the dielectric layer. The metal resonance layer and the reflection layer are made of metallic copper. The size of the resonance unit is 10 mm × 10 mm. The values of the parameters identified in Fig. 1 are $a = 10$ mm, $t = 0.035$ mm, $h = 2.3$ mm, $w = 0.5$ mm, $r_1 = 3.2$ mm, $r_2 = 3.7$ mm, $b = 4$ mm, $r_3 = 2.3$ mm, $c = 0.5$ mm, and $d = 1$ mm.

To obtain the electromagnetic wave absorption performance, the designed broadband metasurface absorber is modeled using CST

Studio Suite. Fig. 2 illustrates the absorption performance of the optimal parameters. The absorption rate is calculated by:

$$A(\omega) = 1 - \Gamma(\omega) - T(\omega) \quad (1)$$

where, $A(\omega)$ is the absorptivity of the absorber, $\Gamma(\omega)$ is the reflectivity of the electromagnetic wave, and $T(\omega)$ is the transmittance of the electromagnetic wave.

Results and discussion

In full-wave simulations, the reflection coefficient of an absorber is primarily determined by its structural and electromagnetic properties; consequently, the unit cell array density has a negligible influence on both the reflection coefficient and the resulting absorption characteristics. Accordingly, in the simulation, unit cell boundary conditions are applied in the x and y directions to enforce periodicity, while an open boundary condition is used in the z direction to model electromagnetic wave incidence from free space. Fig. 2a presents the reflectance coefficient and absorptivity of the absorber in the 10.15–20.91 GHz frequency band, where the reflectance coefficient is below -10 dB, and the absorption rate exceeds 90%. At the two high-frequency resonance points, 18.4 GHz and 20.16 GHz, the attenuation of electromagnetic waves falls below -30 dB, corresponding to an absorption rate above 99% in the vicinity of the high-frequency resonance points. The broadband absorption efficiency is achieved by superimposing the resonant peaks with high absorptivity.

The thickness of the dielectric layer influences the absorption performance of the absorber. Fig. 2b shows the absorption rate of the absorber at different dielectric layer thicknesses, h . As the thickness h of the dielectric layer increases, the absorption band of the absorber is shifted to lower frequencies and the absorptivity between the two high-frequency resonance points decreases gradually. Considering both absorptivity and absorption bandwidth, $h = 2.3$ mm is selected as the optimal parameter. For the design of split

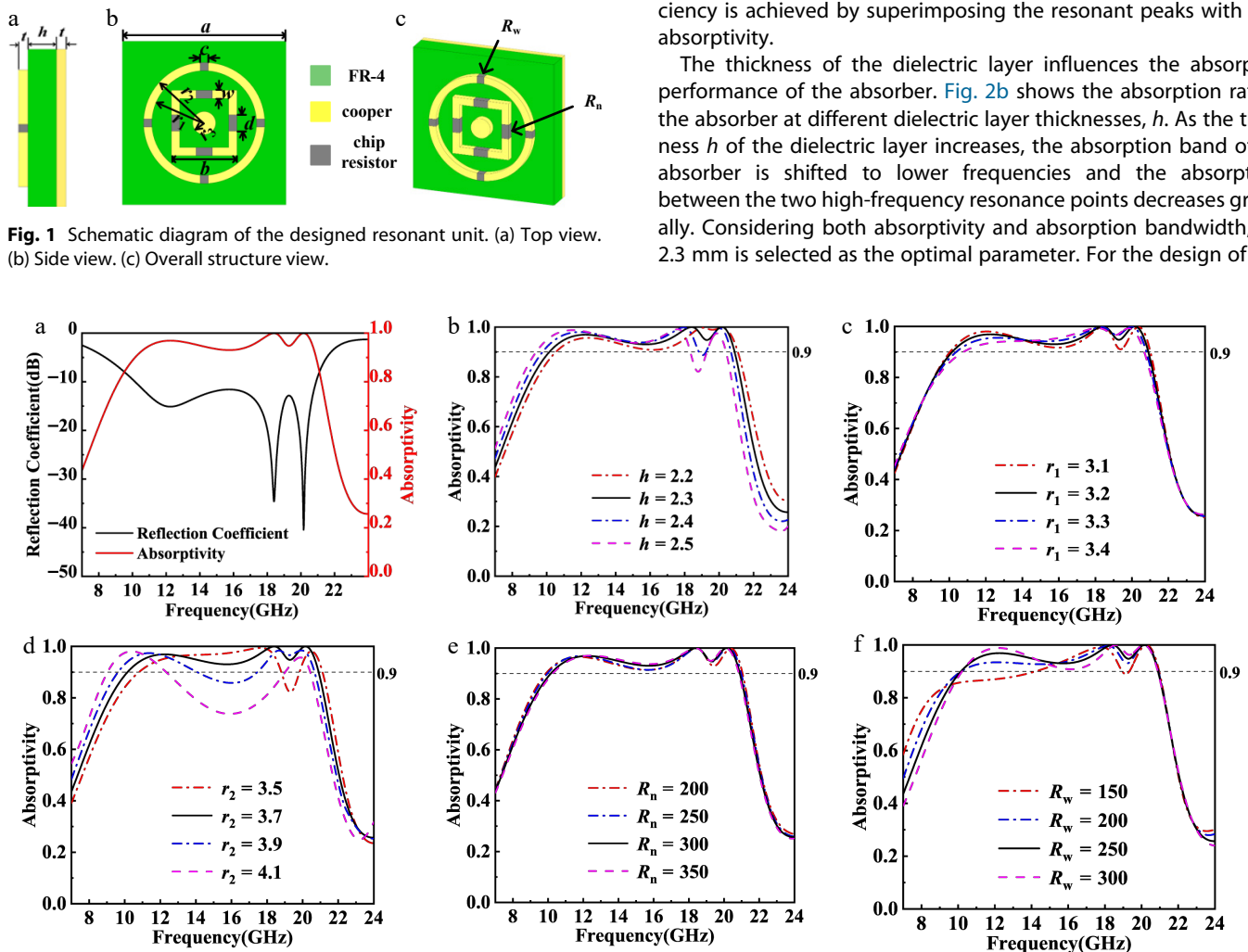


Fig. 2 Reflection coefficient and absorptivity of the absorber at different parameters. (a) Optimized structural parameters, (b) h , (c) r_1 , (d) r_2 , (e) R_n , and (f) R_w .

rings, the inner and outer diameters are two crucial parameters. It is important to ensure that the designed absorber exhibits broadband absorption. Fig. 2c and d show the variation in absorptivity of the absorber as the inner diameter r_1 and outer diameter r_2 of the split ring are varied, respectively. As r_1 increases, the absorptivity in the low-frequency band decreases, and the corresponding resonance peak no longer exists when r_1 is 3.4 mm. However, in the mid- and high-frequency bands within the broadband range, the absorption improves as the inner diameter r_1 increases. For the outer diameter r_2 , an increase leads to a significant reduction in absorptivity in the mid-frequency band, while the low-frequency resonance peak shifts toward lower frequencies. When $r_2 = 3.5$ mm, the low-frequency resonance peak vanishes, and at $r_2 = 4.1$ mm, the two high-frequency resonance peaks merge into one. To ensure that the absorber has a better broadband absorption effect, r_1 and r_2 are chosen to be 3.2 and 3.7 mm, respectively. Furthermore, the addition of chip resistors has an effect on both the absorption bandwidth and absorptivity. The absorptivity of the absorber by varying the resistances of the chip resistor R_n at the square ring split and the chip resistor R_w at the circular ring split is shown in Fig. 2e and f, respectively. The effect of R_n on the absorptivity is mainly concentrated in the mid-frequency band. As R_n increases, the absorptivity increases, and the low-frequency resonance point is slightly shifted toward the high frequency. However, increasing the R_n from 300 to 350 Ω does not significantly enhance the absorptivity, so 300 Ω is chosen as the optimal value for R_n . In contrast, changes in resistance R_w on the absorber have a more pronounced impact. Near the low-frequency resonance point, an increase in R_w significantly improves the absorption performance. When R_w reaches 150 Ω , the low-frequency resonance effect diminishes, disappearing completely at 200 Ω . Between the two high-frequency resonance points, the absorptivity increases further as R_w increases. However, in the mid-frequency band, the absorptivity decreases as R_w increases. In order to ensure broadband absorption, 250 Ω is selected as the optimal resistance value for R_w .

Polarization angle and incidence angle insensitivity is also an important property of metasurface electromagnetic wave absorbers. Fig. 3 shows the absorptivity of electromagnetic waves at different polarization angles, as well as the absorptivity at various angles of incidence in transverse electric (TE) and transverse magnetic (TM) modes.

Fig. 3a depicts the polarization characteristics of the absorber at 0°–90° polarization angles. It is clearly demonstrated that the absorptivity remains above 90% in the range of 10.15 to 20.91 GHz across all polarization angles, indicating excellent polarization insensitivity. All of the above analyses are performed under normal-phase incidence of the electromagnetic wave. The absorption behavior of absorbers varies with different incidence angles. Fig. 3b and c shows the absorptivity under oblique incidence in TE and TM modes, respectively. In TE mode, the overall absorption bandwidth of the absorber decreases with the increase of the incident electromagnetic wave angle. However, when the incident angle is less than 50°, the absorber maintains an absorptivity greater than 80% over the 10.86–20.88 GHz range. In the TM mode, the absorber exhibits greater sensitivity to the incident angle, with absorptivity exceeding 80% over the 9.27–19.62 GHz range.

In order to further visualize the performance of the designed absorber, Fig. 4 shows the electric field distribution in the vicinity of each of the three resonance points. The electric field distribution at 12.24 and 18.4 GHz is shown in Fig. 4a and b, respectively. It is evident that the high electric field regions are mainly distributed around chip resistors as well as at the edges and tips of the unit cells. The chip resistor causes an interruption in the electric field, resulting in strong local electric field gradients. A portion of the electromagnetic wave energy is lost through ohmic dissipation in the chip resistors. The other part of the electromagnetic wave energy loss is related to the distribution of the high electric field regions at the edges and tips of the resonant cells. In this case, the absorber undergoes localized surface resonance, leading to dielectric losses and further absorption. Fig. 4c illustrates the electric field

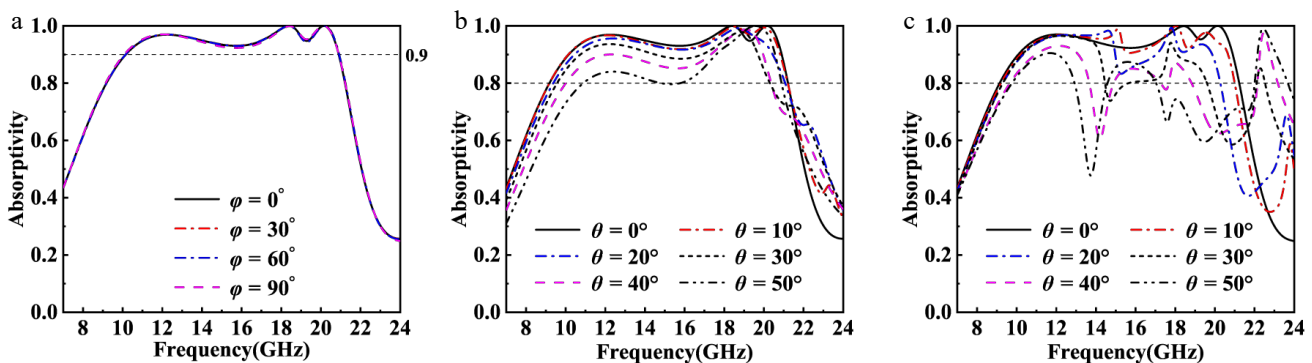


Fig. 3 Absorptivity of the absorber at different (a) polarization angles, (b) incidence angles in TE mode, and (c) incidence angles in TM mode.

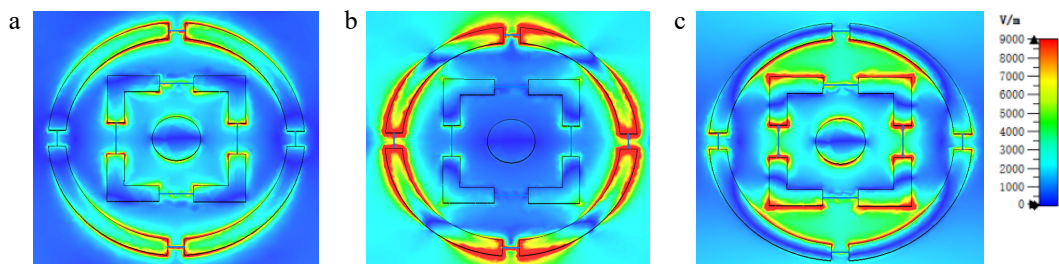


Fig. 4 Electric field distribution at three resonance frequencies. (a) 12.24 GHz, (b) 18.4 GHz, and (c) 20.16 GHz.

distribution at 20.16 GHz, where the high electric field regions are mainly distributed at the tips of the resonance unit as well as at the edge position of the ring. In this case, the absorber undergoes mainly localized surface plasmon resonance, where the electromagnetic energy is captured by the locally enhanced electric field and converted into thermal energy through dielectric losses. It is the coexistence of multiple dissipation modes that provides the absorber with good broadband absorption.

In addition, in order to further analyze the absorption effect of the designed absorber, the surface electric power of the absorber at the resonance frequency point was further simulated and calculated. The surface current density distribution of the absorber near the three resonance points is shown in Figs 5 and 6.

At 12.24 GHz, as shown in Figs 5a and 6a, the current direction of the resonant layer of the absorber is opposite to that of the metal backplate. This means that magnetic field coupling is formed in the upper and lower current loops, indicating that the main resonance mode at this frequency point is magnetic resonance. As shown in Fig. 5b and c, at 18.4 and 20.16 GHz, the current direction of the outer ring is opposite to that of the inner square ring and metal disc, thereby exciting electrical resonance on the surface metal layer. This results in new resonance peaks in the mid-frequency and high-frequency regions, which is conducive to the formation of wide-band absorption, and the distance between the mid-frequency and high-frequency resonance points is relatively close. As shown in Fig. 6b, at 18.4 GHz, the surface resonant structure can be regarded as a two-dimensional metal grating, forming a guided mode resonance at this frequency point. The current in the metal backplane is divided into three regions, with the upper and lower regions carrying current upward and the middle region carrying current downward. The currents between adjacent regions remain oppositely parallel. Meanwhile, as shown in Figs 5c and 6c, the current direction on most of the metal resonant surface and the metal backplate surface is parallel. The direction of the surface current is opposite to the direction of the electric field applied by the incident electromagnetic wave, and no magnetic field coupling of closed-loop current is formed. This indicates that electrical resonance also exists at this frequency point. Additionally, due to the requirements of the

electromagnetic parameter extraction work for the absorber, tiny perforations were made in the metal ground plane without affecting the absorption characteristics^[23]. Consequently, the surface current on the metal backplane of the absorber accumulates around the perforations, which is considered a normal phenomenon.

Experimental validation

To verify the effectiveness of the designed absorber, the physical prototype was fabricated, and its reflection coefficient was experimentally measured. Fig. 7a and b show the physical sample of the absorber and the measurement setup in a microwave anechoic chamber, respectively. A 30 × 30 cm absorber sample consisting of a 30 × 30 unit-cell array was fabricated, ensuring that most of the electromagnetic energy was confined to the sample surface. This configuration helps to reduce the diffraction deviation of electromagnetic waves and improves the reliability of the measured reflection coefficient. Chip resistors in package size 0402 are used. During testing, two horn antennas are symmetrically positioned at various angles to simulate electromagnetic wave incidence at different angles. To minimize near-field effects, the distance between the antenna and the absorber is maintained at 1.875m, as calculated using Eq. (2). Under these conditions, the reflection coefficient is measured using a vector network analyzer:

$$r_a = \frac{D^2}{\lambda} \quad (2)$$

where, D is the aperture of the antenna, and λ is the wavelength corresponding to the highest operating frequency of the antenna.

As shown in Fig. 7c–g, the reflection coefficients of the absorber are measured and simulated at incident angles of 0° and 30° in TM mode, and 0°, 30°, and 50° in TE mode. Minor discrepancies are observed between the measured and simulated reflection coefficients. These deviations arise due to variations in the FR-4 substrate electromagnetic properties, manufacturing tolerances, and edge effects from the finite absorber size. Experimental results validate the effectiveness of the proposed design. The comparison with other representative absorbers is shown in Table 1, demonstrating

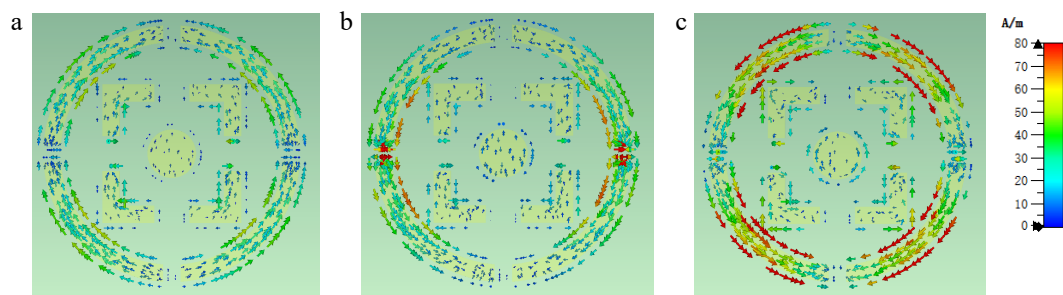


Fig. 5 The surface current density distribution (a) 12.24 GHz, (b) 18.4GHz, and (c) 20.16 GHz.

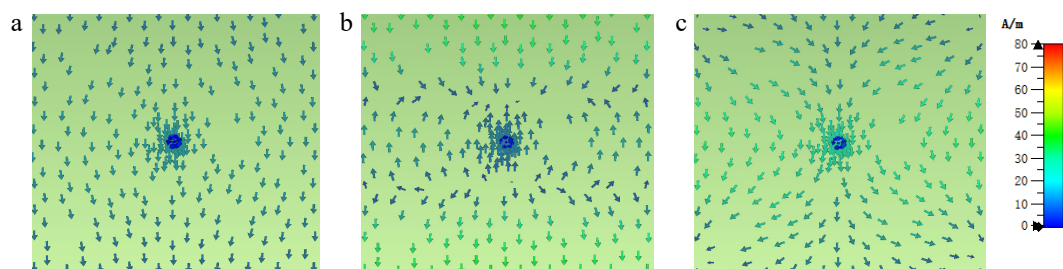


Fig. 6 The backplane current density distribution (a) 12.24 GHz, (b) 18.4 GHz, and (c) 20.16 GHz.

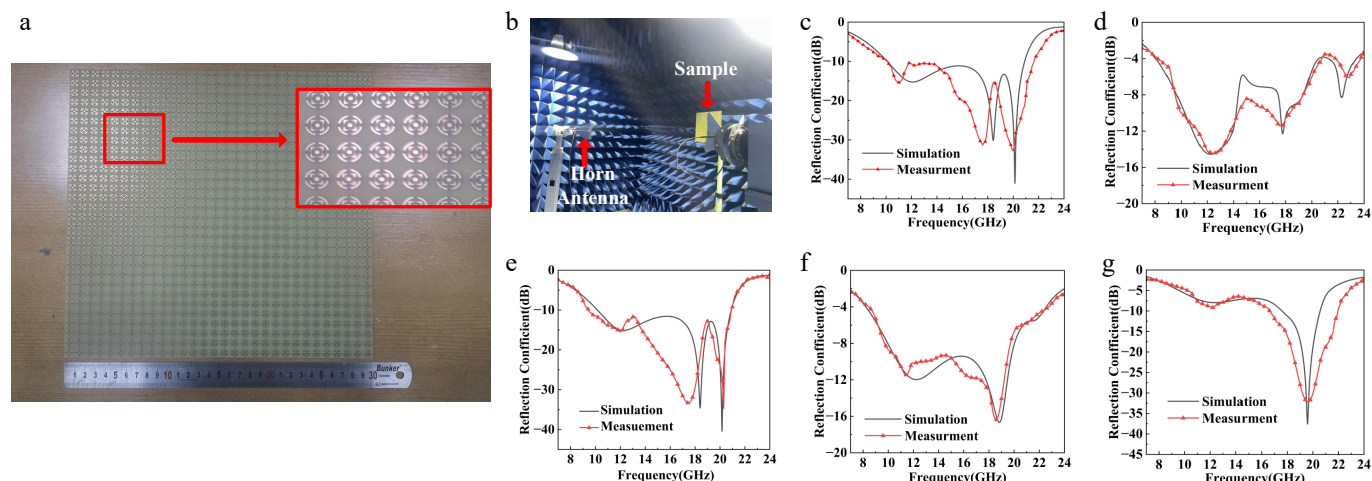


Fig. 7 Experimental tests and results; (a) absorber sample, (b) experimental setup, (c) 0° angle of incidence in TM mode, (d) 30° angle of incidence in TM mode, (e) 0° angle of incidence in TE mode, (f) 30° angle of incidence in TE mode, and (g) 50° angle of incidence in TE mode.

Table 1. Comparison of broadband absorbers.

Ref.	Bandwidth (GHz)	FBW (%)	Oblique incidence		Thickness (mm)	Electrical thickness	Structural materials	Fabrication features
			TE	TM				
[24]	11.4–20	54.8%	50°	50°	1.6	$0.084\lambda_0$	FR-4 and metal	Single layer
[27]	4.3–11.1	88.3%	60°	60°	9.48	$0.243\lambda_0$	PVC/ITO/OCA/PET	Double-layer
[28]	5.10–14.07	94%	N/A	N/A	6.6	$0.211\lambda_0$	Rossler chaos surface	Chaotic units
[25]	12.35–14.65	17%	45°	45°	2	$0.09\lambda_0$	FR-4 and metal	Single layer
[26]	8.9–14.0	44.5%	50°	60°	1.6	$0.061\lambda_0$	ITO and substrate	Single layer
This work	10.15–20.91	69.3%	50°	30°	2.3	$0.119\lambda_0$	FR-4 and metal	Single layer

that the designed absorber exhibits favorable broadband performance and incident angle stability.

Conclusions

In summary, this paper presents a wideband electromagnetic absorber based on a simple topology utilizing an FR-4 substrate and chip resistors, significantly reducing fabrication complexity and cost. According to Eq. (3), the absorber achieves a fractional bandwidth (FBW) of 69.3% and exhibits structural symmetry, resulting in excellent polarization insensitivity. In both TE and TM modes, the absorber maintains an absorption rate above 80% when the incidence angle is less than 50° and 30°, respectively, demonstrating robust angular stability. Experimental measurements of the reflection coefficient validate its absorption performance. Table 1 shows that the proposed unit cell uses conventional FR-4 and copper in a simple sandwich configuration, which is relatively low-cost and easy to fabricate compared with multilayer or functional-material designs. Compared with studies by Araújo et al.[24], Pham et al.[25] and Lei et al.[26], which also uses single layer, the proposed absorber achieves a wider fractional bandwidth. Compared with Jiang et al.[27] and Yuan et al.[28], the proposed absorber has a lower electrical thickness. Thus, the proposed design combines fabrication economy with broadband absorption performance and shows promising potential for applications in electromagnetic compatibility, electromagnetic shielding, and radar stealth technologies.

$$FBW = \frac{2(f_{\max} - f_{\min})}{f_{\max} + f_{\min}} \times 100\% \quad (3)$$

where, $f_{\max}$ and $f_{\min}$ are the upper and lower frequencies of the 90% absorption band, respectively.

Author contributions

The authors confirm their contributions to the paper as follows: conceptualization: Zhao Y, Chen T, Yang W, Zhang X; methodology, writing – original draft preparation: Zhao Y, Chen T, Yang W; principle analysis: Zhao Y, Chen T, Luan J, He H; platform construction and experimental testing: Zhao Y, Chen T, Yang W, Zhang X, Luan J, He H; funding acquisition, writing–review and editing: Chen T, Yang W, Zhang X; validation: Chen T, Yang W; project administration: Chen T, Yang W, Zhang X. All authors reviewed the results and approved the final version of the manuscript.

Data availability

The data presented in this study are available on request from the corresponding author due to the funder's privacy policy.

Acknowledgments

This work is supported in part by the National Natural Science Foundation of China (52307009); the Hebei Province Yan Zhao Golden Terrace Talent Gathering Plan Key Talent Project (B2024011); and the Science Research Project of Hebei Education Department (CXZX2026074).

Conflict of interest

The authors declare that they have no conflict of interest.

Dates

Received 8 February 2026; Revised 2 April 2026; Accepted 17 April 2026; Published online 8 October 2026

References

- [1] Li Y, Cao W, Zuo P, Li Y, Gao Z, et al. 2019. Analysis of multilayer structure near- and far-field radiation by the coupled PP-PEEC and field-equivalence principle method. *IEEE Transactions on Electromagnetic Compatibility* 61:495–503
- [2] Zhang G, Qi P, Wang X, Lu Y, Li X, et al. 2006. Selective etching of metallic carbon nanotubes by gas-phase reaction. *Science* 314:974–977
- [3] Culhaoglu AE, Osipov AV, Russer P. 2013. Mono- and bistatic scattering reduction by a metamaterial low reflection coating. *IEEE Transactions on Antennas and Propagation* 61:462–466
- [4] Lim D, Lim S. 2019. Ultrawideband electromagnetic absorber using sandwiched broadband metasurfaces. *IEEE Antennas and Wireless Propagation Letters* 18:1887–1891
- [5] Zhang Z, Zhang B, Deng B, Wei X, Wang J. 2018. Opportunities and challenges of metamaterial-based wireless power transfer for electric vehicles. *Wireless Power Transfer* 5(1):9–19
- [6] Barde C, Choubey A, Sinha R, Mahto SK, Ranjan P. 2020. A compact wideband metamaterial absorber for Ku band applications. *Journal of Materials Science: Materials in Electronics* 31:16898–16906
- [7] Yoo M, Kim HK, Kim S, Tentzeris M, Lim S. 2015. Silver nanoparticle-based inkjet-printed metamaterial absorber on flexible paper. *IEEE Antennas and Wireless Propagation Letters* 14:1718–1721
- [8] Wang Y, Wu G, Zhang J, Wu X, Yuan G, et al. 2024. Genetic algorithm-enhanced design of ultra-broadband tunable terahertz metasurface absorber. *Optics & Laser Technology* 170:110262
- [9] Liujia E, Liu Z, Zhang J, Xu Z, Yuan Z, et al. 2023. Realization of an ultrathin absorber with fragmented magnetic structure at L-, S-, and partial C-bands. *Journal of Applied Physics* 134:223105
- [10] Sheokand H, Singh G, Ghosh S, Ramkumar J, Ramakrishna SA, et al. 2019. An optically transparent broadband microwave absorber using interdigital capacitance. *IEEE Antennas and Wireless Propagation Letters* 18:113–117
- [11] Yi J, Wei M, Lin M, Zhao X, Zhu L, et al. 2022. Frequency-tunable and magnitude-tunable microwave metasurface absorbers enabled by shape memory polymers. *IEEE Transactions on Antennas and Propagation* 70:6804–6812
- [12] Zhou FK, Tan RY, Fang W, Fu YF, Ji JD, et al. 2021. An ultra-broadband microwave absorber based on hybrid structure of stereo metamaterial and planar metasurface for the S, C, X and Ku bands. *Results in Physics* 30:104811
- [13] Shou H, Feng J, Qi B, Qiao L, Niu T, et al. 2023. A wideband absorber working in the L- and S-bands based on magnetic materials. *Applied Physics Letters* 122:251703
- [14] Ran Y, Shi L, Wu S, Li J, Jin X, et al. 2022. Optically transparent ultrawideband electromagnetic stealth metasurface for microwave absorption and scattering. *IEEE Antennas and Wireless Propagation Letters* 21:2412–2416
- [15] Ghadimi A, Nayyeri V, Khanjarian M, Soleimani M, Ramahi OM. 2021. Design and simulation of a wideband, wide-angle and polarization-insensitive microwave absorber based on pattern optimization of resistive films. *Journal of Physics D: Applied Physics* 54:055102
- [16] Malik S, Sharma A, Srivastava KV. 2021. Resistive ink based microwave absorber for S and C-band with 99% absorption. *Proc. 2021 IEEE Indian Conference on Antennas and Propagation (InCAP), Jaipur, Rajasthan, India, 13–16 December, 2021*. USA: IEEE. pp. 677–680 doi: [10.1109/incap52216.2021.9726447](https://doi.org/10.1109/incap52216.2021.9726447)
- [17] Zheng J, Zheng H, Pang Y, Qu B, Xu Z. 2023. Transparent broadband absorber based on a multilayer ITO conductive film. *Optics Express* 31:3731–3742
- [18] Ge J, Zhang Y, Li H, Dong H, Zhang L. 2023. Ultra-broadband, tunable, and transparent microwave meta-absorber using ITO and water substrate. *Advanced Optical Materials* 11:2202873
- [19] Ding F, Cui Y, Ge X, Jin Y, He S. 2012. Ultra-broadband microwave metamaterial absorber. *Applied Physics Letters* 100:103506
- [20] Li J, Jiang J, He Y, Xu W, Chen M, et al. 2016. Design of a tunable low-frequency and broadband radar absorber based on active frequency selective surface. *IEEE Antennas and Wireless Propagation Letters* 15:774–777
- [21] Du Z, Liang J, Cai T, Wang G, Deng T, et al. 2022. Designing an ultrathin and wideband low-frequency absorber based on lumped resistance. *Optics Express* 30:914–925
- [22] Yuan W, Cheng Y. 2014. Low-frequency and broadband metamaterial absorber based on lumped elements: design, characterization and experiment. *Applied Physics A* 117:1915–1921
- [23] Ye D, Wang Z, Xu K, Li H, Huangfu J, et al. 2013. Ultrawideband dispersion control of a metamaterial surface for perfectly-matched-layer-like absorption. *Physical Review Letters* 111(18):187402
- [24] de Araújo JBO, Siqueira GL, Kemptner E, Weber M, Junqueira C, et al. 2020. An ultrathin and ultrawideband metamaterial absorber and an equivalent-circuit parameter retrieval method. *IEEE Transactions on Antennas and Propagation* 68:3739–3746
- [25] Pham TS, Zheng H, Chen L, Khuyen BX, Lee Y. 2024. Wide-incident-angle, polarization-independent broadband-absorption metastructure without external resistive elements by using a trapezoidal structure. *Scientific Reports* 14:10198
- [26] Lei X, Li Y, Huo S, Sun Z, Yu H, et al. 2022. Design and analysis of a novel compact metamaterial absorber based on double-layer ITO resistive film for improving signal integrity. *IEEE Access* 10:24067–24079
- [27] Jiang H, Yang W, Li R, Lei S, Chen B, et al. 2021. A conformal metamaterial-based optically transparent microwave absorber with high angular stability. *IEEE Antennas and Wireless Propagation Letters* 20:1399–1403
- [28] Yuan X, Zhang C, Chen M, Cheng Q, Cheng X, et al. 2019. Wideband high-absorption electromagnetic absorber with chaos patterned surface. *IEEE Antennas and Wireless Propagation Letters* 18:197–201



Copyright: © 2026 by the author(s). Published by Maximum Academic Press, Fayetteville, GA. This article is an open access article distributed under Creative Commons Attribution License (CC BY 4.0), visit <https://creativecommons.org/licenses/by/4.0/>.