A polarization-insensitive ultra-wideband absorber based on hybrid structure

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May 29, 2023

Abstract

As detection technology continually advances, the survivability of targets on the battlefield is significantly challenged. Therefore, microwave absorbers with stealth capabilities have become a focal point of research in modern military science. To address the issues of narrow bandwidth and complex structures in existing absorbers, we propose a model for an ultra-wideband absorber based on a hybrid structure. In this study, we design, manufacture, and characterize a polarization-insensitive ultra-wideband absorber (PIUWA), which demonstrates impressive absorptivity of over 90% across a range of 4-24.53GHz (a fractional bandwidth of 144%). This is achieved by inducing multiple resonance peaks within the hybrid structure. Moreover, the subwavelength periodicity of the PIUWA theoretically contributes to its angular stability under full-wave polarizations. We observed that absorption performance remains stable under incident conditions within 45 degrees. Furthermore, the operational mechanism of the PIUWA is elucidated through an equivalent circuit model, with design validity confirmed via experimental measurements. This study paves the way for the design and fabrication of ultra-wideband microwave absorbers that offer high absorptivity, robust angular stability, and simpler assembly processes, thereby broadening the potential for application in other absorber types.

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Introduction: The deployment of advanced detection technologies underscores the urgency of minimizing the detectability of military equipment in contemporary battlefields. Metamaterials, owing to their robust electromagnetic (EM) regulation abilities across various domains, have emerged as promising candidates for crafting stealth materials [1-3]. In recent times, microwave absorbers have garnered considerable attention for their superior performance over conventional frequency selective surfaces (FSS) in reducing the radar cross section (RCS) of multi-station radars. These absorbers achieve this by dissipating incident EM power, thereby enhancing device survivability, as illustrated in Fig.1[4-6]. Early proposals for microwave absorbers included the Salisbury screen and the Jaumann absorber. However, their real-world application has been hindered by constraints such as narrow bandwidths or excessive thickness [7,8]. In light of the evolving requirements of stealth systems, wideband absorbers have gained significant interest. Consequently, circuit analog absorbers (CAAs) were introduced to pave the way for thinner microwave absorbers with broader bandwidths [9].

Broadly, wideband absorbers fall into two structural categories: planar [9-14] and three-dimensional [15-19]. Planar metamaterial absorbers typically achieve broadband absorption through the employment of FSS loaded with lumped resistors [10-12], or by using High Impedance Surfaces (HIS) as lossy layers [13,14]. These lossy layers are typically positioned a quarter-wavelength above the metal plate to optimize absorption. The first case often involves using a Square-Loop-Array (SLA). However, the design of an SLA absorber necessitates numerous lumped resistors; for example, the designs in [10] and [11] each require eight resistors per unit, while [12] requires sixteen lumped resistors per element. The utilization of an SLA is primarily aimed at generating multiple resonances to broaden the absorption bandwidth. However, as shown in [10-12], a single-layer SLA can only produce a maximum of three resonance points. To induce additional resonance points, it becomes necessary to either add more square patterns to the same plane or to incorporate more resonant layers in a unit. Regrettably, these methods not only increase the period or thickness of the absorber but also complicate the manufacturing process. Another approach, which involves the use of high impedance materials such as resistive inks with the appropriate surface resistance as a lossy layer, offers a very limited absorption bandwidth. As seen in [13] and [14], only two or three resonances exist within the absorption band with fractional bandwidths of 112% and 92%, respectively. Moreover, the application of large quantities of resistive ink, which is challenging to spray evenly, can negatively impact the absorption performance in practice. Recently, wideband 3D absorbers, grounded in cavity theory [15-18] or radiation pattern synthesis[19], have drawn the attention of many researchers. However, the assembly process of 3D absorbers is cumbersome due to their complex structure, and some of them can only facilitate fixed-polarization absorption [16,18].

(a) (b)

Fig. 1 *Comparation of FSS and microwave absorber in the presence of multi-station radars. (a) FSS. (b) microwave absorber and the 4×3 PIUWA units.*

Drawing from the above discussion, it's clear that there are areas for improvement in ultra-wideband (UWB) absorbers. For two-dimensional structures, the goal is to generate more resonances within a limited number of layers. For 3D absorbers, the complex fabrication and assembly process necessitated by their intricate structure warrants simplification. Against this backdrop, we propose an ultra-wideband absorber based on a hybrid 2D and 3D structure in this study. The 3D upper layer of the hybrid structure naturally forms a cascade transmission line between the dipoles, leading to an increased number of resonance peaks and a subsequent widening of the absorbing bandwidth. The proposed PIUWA exhibits a broad absorption band from 4 to 24.53GHz, representing a fractional bandwidth (FBW) of 144%, all while maintaining a compact size of $0.10\lambda_L\times 0.10\lambda_L\times 0.11\lambda_L$ (where $\lambda_L$denotes the wavelength at the lowest cut-off frequency). The proposed PIUWA offers several advantages: 1) In comparison to 2D structures, the PIUWA provides a wider absorption bandwidth without the need for additional materials to support the lossy layer and backplane. 2)When contrasted with 3D structures, the PIUWA has a simpler structure that facilitates easier design and installation. 3) The subwavelength periodicity of the PIUWA is theoretically advantageous for maintaining angular stability and avoiding grating lobes [20].

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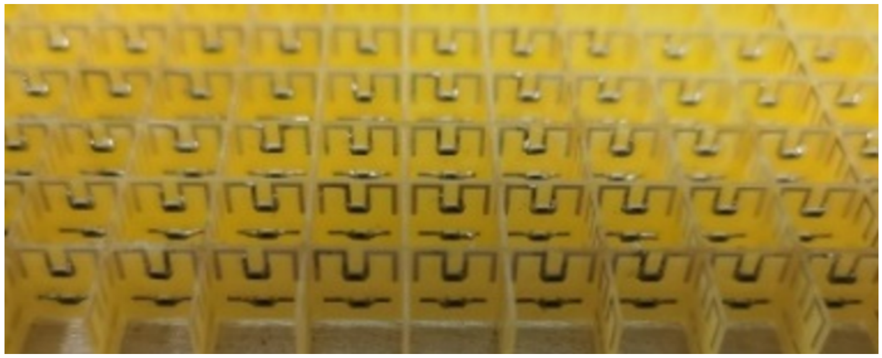

(a) (b)

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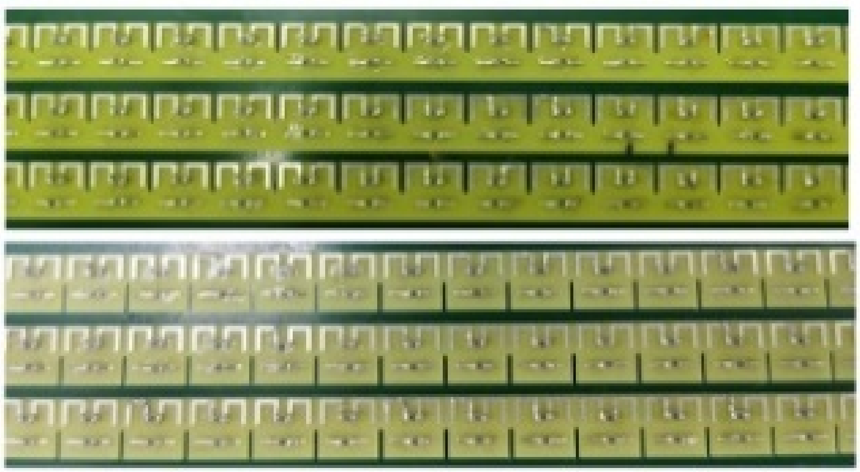
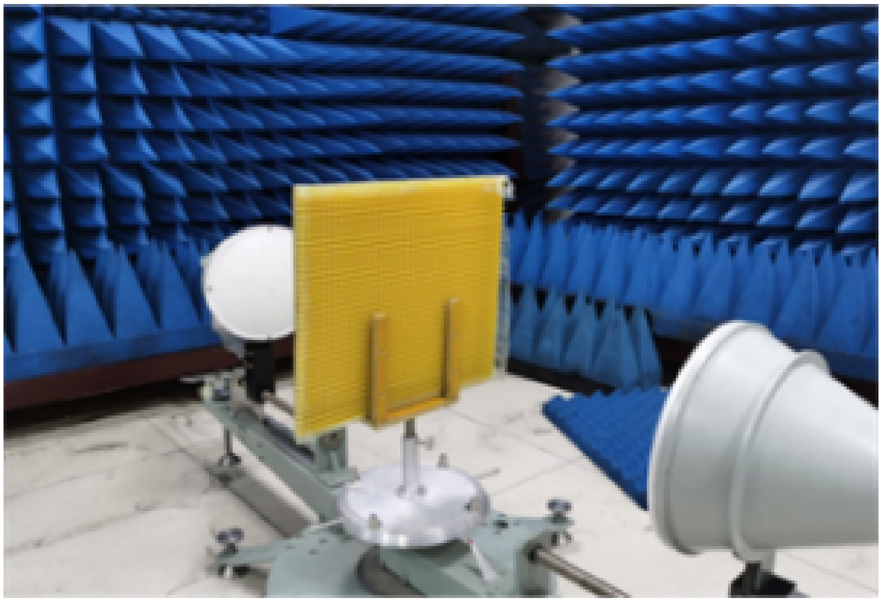


(c) (d)



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(e) (f)

Fig. 2 *(a) δνφιγυρατιον οφ τηε ΠΙΥΩΑ υνιτ. (β) Τηε μανυφαςτυρεδ ΠΙΥΩΑ αρραψ. (ς) Φροντ ιεω οφ τηε υνιτ. (δ) Δεταιλεδ ασσεμβλψ στρυςτυρε οφ τηε 3Δ λαψερ. (ϵ) Τηε ΠΙΥΩΑ σαμπλε ιν τηε μιςροωαε ςηαμβερ. (φ) Σιμυλατεδ ανδ μεασυρεδ αβσορπτιον ρατε υνδερ νορμαλ ινςιδεντ ατ TE μοδε. *Δεταιλεδ γεομετριςαλ παραμετερς αρε ας φολλοως:* β=8μμ, η=8.3μμ, $\Lambda_{\lambda 1}$=2.2μμ, $\Lambda_{\lambda 2}$=2.5μμ, $\Lambda_{\lambda 3}$=1.8μμ, $\Lambda_{\lambda 4}$=3.5μμ, Λ_{η}=2.8μμ, ω_1=ω_2=0.5μμ, η_1=2μμ, η_2=2.2μμ, P_{Λ}=120Ω, P_H=85Ω.

(a)

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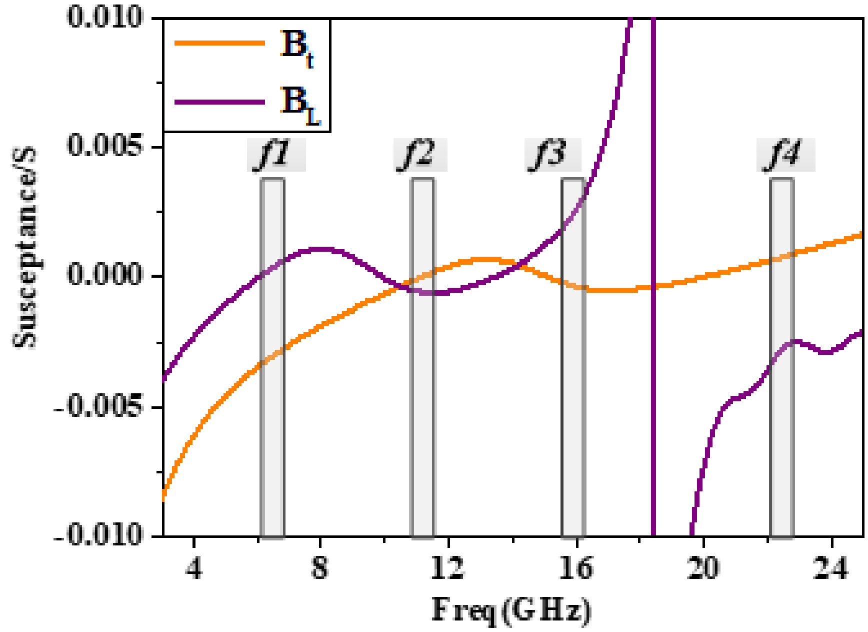

(b) (c)

Fig. 3 *(a) Equivalent circuit model of the proposed PIUWA. (b) Simulated reflection coefficient under HFSS and ADS of the proposed PIUWA under normal incidence. (c) Simulated susceptance of* Y_L *and* Y_t*.*

Configuration and Results: The theoretic model of the proposed PIUWA composed of 3-D lossy layer and planer backplate is depicted in Fig.2(a). The 3D structure of the PIUWA is designed based on a hollow cube made of FR4 substrate with a thickness t of 0.4mm and relative dielectric constant of 4.4. On the two adjacent faces of the cube, two sets of dipoles loading with lumped resistors are printed for obtain full-wave polarizations. As shown in Fig.2(c), the top meander dipole commands the low-frequency absorption and the bottom shorter dipole mainly acts on the high-frequency incident EM waves. Here we useD_L and D_H to represent the top and bottom dipole, R_L andR_H on behalf of the resistors welded on them. By employing the two dipoles, multiple resonances are generated to expand the absorption bandwidth.

The manufactured prototype of the proposed PIUWA is shown in Fig.2(b). The upper 3D layer is processed into two types of long strips with cutting slots in opposite direction for easy assembly, as shown in Fig.2(d). The width of the cutting slots is equal to the thickness of the FR4 substrate so that the strips with different gaps can be inserted and fixed. During our numerical simulations using (High Frequency Structure Simulator) HFSS, the simulated absorbing rate under normal incidence at TE polarization is presented in Fig.2(f). As observed, the proposed PIUWA exhibits a wide absorption band of 144% from 4.0-24.53GHz with a good performance of absorptance over 90% within a wide working band. For validation, the proposed PIUWA consisting 40×40 units has been tested in the microwave anechoic chamber, as shown in Fig.2(e). The detailed measurement procedures can be referred to [21]. Fig.2(f) shows the comparison between the simulated and tested results. As we can see, except for some frequency offset caused by machining errors and experimental environment, the tested result is reasonable compared to the simulation.

Equivalent Circuit and Mechanism Analysis: For the purpose of understanding the physical mechanism of the wideband absorption performance with greater depth, an illustration based on the equivalent circuit theory of the proposed PIUWA is demonstrated in this section. As shown in Fig.1(b), when the incident wave is perpendicular to the PIUWA, the electric field component is parallel to the dipoles, which is the same as CAA absorbers. Therefore, the proposed hybrid structure can be analysed using the equivalent circuit model.

Considering the symmetry of the structure, we choose TE polarization for illustration. The proposed PIUWA can be expressed as two series RLC circuits connected with two sections of transmission lines as shown in Fig.3(a). We use$R_L L_1 C_1$ to represent D_L and$R_H L_2 C_2$ forD_H . Between D_L andD_H is a cascaded transmission line with the length of h_2 representing the vertical substrate between the two dipoles. In addition, the short-circuited transmission line section with the length of h_1 represents the conductor-backed substrate below the short dipole.Z_L and Z_H are the approximate impedances of the top and the bottom dipole.Z_t represents the total impedance of the rest part below the top dipole. Based on the above illustration the transmission line matrix of the proposed PIUWA can be expressed as follows:

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(1)

Z_L and Z_H are the approximate impedances of D_L andD_H respectively. $Z_t$represents the total impedance of the lower part of the PIUWA.

Where

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(2)

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(3)

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(7)

On the basis of the above mentioned, the reflection and transmission coefficient of the PIUWA can be obtained as follows:

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(8)

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(9)

Where *A11, A12, A21, A22* are the members of the PIUWA's transmission line matrix. Then the absorption of the PIUWA can be calculated by the following relation:

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(10)

For proving the validity of the above equivalent circuit model, the simulated reflection coefficient of the proposed PIUWA for TE polarization under HFSS and ADS (Advanced Design System) are depicted simultaneously in Fig.3(b). As shown in the picture, the circuit model agrees well with the calculated results of HFSS. The value of R_L andR_H is optimized in HFSS for achieving desire absorbing performance. And the final value of the equivalent circuit parameters is obtained by tuning and optimizing in circuit simulation, here we use C_1 =0.073pF,L_1 =5.9nH, C_2 =0.036pF,L_2 =2.5nH, Z_1 =94Ω,$\beta_1\eta_1$ =90@17.5GHz,Z_2 =285Ω,$\beta_2\eta_2$ =110@14.1GHz. Different from the three resonances in most wideband absorbers, the proposed PIUWA generates four resonances in the absorption band which across 4.0 to 23.4GHz with a fractional bandwidth of 142%. The four resonance peaks are represented by $f_{(i)}$ (i =1,2,3,4). To prove that the added resonance is owing to the presence of the cascaded transmission line between the two dipoles, here we simulated the model without the vertical substrate in the middle of the two dipoles for comparison, as shown in Fig.3(b). We can see that the comparative model only creates three resonance points within the absorption band from 4.5 to 21GHz with FBW of 129.4%. From the results above, we know that the existence of the cascaded transmission line between the two dipoles generates another resonant peak, at the same time the absorption bandwidth increased.

To get insight understand of the four resonant peaks, we give the susceptance curves for the different constituent parts of the proposed PIUWA, as depicted in Fig.3(c). From (2) we know that the admittance of the PIUWA can be calculated as follows:

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(11)

Where:

(a) (b)

Fig. 4 *Simulated reflection coefficients of the proposed PIUWA under different incident angles. (a) TE polarization. (b) TM polarization.*

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(12)

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(13)

It is known that the circuit resonates when the imaginary part of Y_{in} is equal to zero, that is:

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(14)

Figure 3(b) shows the susceptance of Y_L and Y_t. It can be concluded from (11) that there are two cases in which resonance occurs. The first circumstance is that the susceptance of Y_L equals to the negative value of the susceptance of Y_t , that is when B_L =-B_t . As shown in Fig.3(b), three resonance points correspond to this case, and they are f_1 , f_3 and f_4 respectively. Under the above resonance points, the value of the susceptance for Y_L counteracts the susceptance for Y_t . In the second case, the susceptance of Y_L equals to the susceptance of Y_T equals to zero, that is when B_L =B_t =0. As observed in Fig.3(b), resonance point f_2 corresponds to this situation. Compared to the three resonant points in other absorbers, the proposed PIUWA has an extra resonance for B_L =-B_t . It is because an impedance jump occurs when the shorter dipole and the conductor-backed vertical substrate goes through the cascaded transmission line h_2 . The impedance jump makes B_L produce another negative point to cancel out B_t and creates a new resonant point at the high frequency thus expanding the bandwidth of the PIUWA. As for the five resonance points of the dual polarization model in Fig.4, the addition of a resonance is due to the interaction of the two sets of resonant units on the two adjacent surfaces.

Finally, the polarization dependence and oblique incidence stability of the proposed PIUWA are investigated. The simulated PIUWA reflection coefficients at different incidence angles are shown in Fig.4. It can be seen from the figure that despite for some deteriorates at large angle incidence for the high frequencies above 20GHz, the proposed PIUWA shows a good angular stability under full-wave polarizations over an ultrawide absorption band within 45° while maintaining S11[?]-10dB which means a good absorptance batter than 90%.

Conclusion: This paper introduces a novel methodology for designing an ultra-wideband circuit analog (CA) absorber. Utilizing this approach, we have designed a compact ultra-wideband absorber. The proposed PIUWA exhibits a broad absorption band ranging from 4 to 24.53GHz and maintains a small footprint of $0.10\lambda_L \times 0.10\lambda_L \times 0.11\lambda_L$(where λ_L denotes the wavelength at the lowest absorption frequency). A prototype of the PIUWA was subsequently fabricated and tested. The experimental measurements effectively corroborated the simulated results of the designs, thereby validating our approach.

Acknowledgments: This work is supported by National Key Research and Development Program of China (No. 2020YFB1806405), National Natural Science Foundation of China (No. 12004258), Shanghai Science and Technology Innovation Action Plan (No. 21511101403) and Major Key Project of PCL (No. PCL2021A17).

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