

A Dual-Band Metamaterial Absorber Using Square Loops With Transmission Capability

Vinícius A. Barros, Tadeu N. Ferreira, and Mauricio W. B. Silva

Abstract—This paper presents the design, fabrication, and characterization of a dual-band metamaterial absorber that utilizes square-loop frequency-selective surfaces on FR-4 substrates. In contrast to traditional absorbers that rely on a solid ground plane, the innovative design features patterned loops in both the ground and front layers, allowing for targeted absorption while still permitting some transmission. Simulations conducted in CST Microwave Studio predicted absorption peaks of 76.9% at 3.47 GHz and 77.6% at 5.63 GHz, with adequate absorption levels of 70.9% at 3.5 GHz and 59.1% at 5.8 GHz. Measurements were performed using a Keysight N5232A vector network analyzer, along with horn antennas, inside an anechoic chamber. This setup confirmed absorption peaks at frequencies close to the desired frequencies, each with magnitudes exceeding 56%, which are sufficient to be used as a chipless identification tag and detect by a reader. The proposed approach highlights the viability of square-loop metasurfaces to achieve compact, tunable, and efficient absorbers with transmission capabilities that are suitable for microwave applications.

Index Terms—Metasurface, absorber, square loop resonator, dual-band absorber.

I. INTRODUCTION

METAMATERIAL absorbers are structures that interact with electromagnetic waves, enabling controlled manipulation of wave properties, such as absorption, reflection, and transmission. These absorbers are composed of unit cells, whose dimensions and materials must be carefully selected to achieve the desired goal. As a result, metamaterial absorbers have found extensive applications

in various technological domains, including stealth technology, wireless communication systems, sensor technology, thermal emitters, and photovoltaic systems [1], [2]. A distinct advantage offered by these structures lies in their significant design flexibility, enabling efficient and highly customizable solutions tailored to specialized electromagnetic applications [3].

Frequency-selective surfaces (FSSs) represent critical advancements in electromagnetic device design, providing precise spectral filtering capabilities. While acting as spatially selective filters, these structures modulate the transmission or absorption of electromagnetic waves at predetermined frequencies. Integrating FSS concepts into metamaterial frameworks markedly improves polarization selectivity, angular stability, and spectral resolution, thereby broadening the functional scope and efficiency of metamaterial-based systems [4], [5]. Recently, dual-band metasurfaces have emerged as an area of substantial research interest due to their inherent ability to resonate simultaneously at two discrete frequency bands, significantly enhancing the operational versatility of multifrequency systems [6], [7].

Dual-band metasurfaces specifically address the critical requirements of advanced electromagnetic applications that demand simultaneous performance at multiple distinct frequencies. Recent studies have introduced diverse methodologies to achieve effective dual-band absorption, including the use of graphene-integrated metasurfaces and metallic or dielectric patch arrays, demonstrating robust performance in the terahertz and mid-infrared spectral regimes [8], [9]. Liu et al. proposed a dual-band terahertz absorber based on graphene metasurfaces, achieving near perfect absorption combined with polarization insensitivity [10]. Similarly, Issah et al. demonstrated efficient dual band absorption using metal-insulator metasurface architectures [7].

Extensive research on electromagnetic wave ab-

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DOI: <https://doi.org/10.14209/jcis.2026.12>.

Submission: 2025-10-17, First decision: 2026-01-05, Acceptance: 2026-07-14, Publication: 2026-07-23.

sorbers highlights the extraordinary adaptability and performance capabilities of metamaterials throughout the electromagnetic spectrum. Watts et al. reviewed various configurations capable of achieving near-unity absorption, underscoring their applications in sensors, thermal emission, stealth technology, and wireless communications [11]. Moreover, successful miniaturization efforts have been reported, enabling practical implementations in lower frequency bands, such as VHF (very high frequency), with ultrathin structural profiles conducive to integration within advanced devices [9].

Recent advances in dual-band and multiband metamaterial absorbers have focused on innovative designs and streamlined fabrication processes [12], [13], [14]. The application of advanced circuit modeling has significantly improved design optimization, enabling the development of high-performance dual-band absorbers. Sellier et al. provided a resonant circuit model elucidating the resonant absorption mechanisms in planar metamaterials, emphasizing impedance matching and resonant circuit analogies to refine absorber efficiency [15]. Consequently, dual-band metamaterial absorbers represent a transformative advancement in electromagnetic device engineering, offering compact, efficient, and highly versatile solutions.

In conventional metamaterial absorbers, a continuous metallic ground plane is commonly employed to suppress transmission by reflecting the incident electromagnetic energy, thereby maximizing absorption. While it is effective in this regard, such an approach inherently inhibits transmission through the structure, limiting its functional versatility. In contrast, the use of patterned ground planes based on square-loop resonators enables controlled manipulation of reflection and transmission. This strategy enables specific frequency bands to be strongly absorbed, while others are partially transmitted, thereby significantly expanding the operational capabilities of the absorber. In this context, this paper proposes a dual-band metamaterial absorber employing square loop FSS to achieve controlled transmission windows, targeting RF-based presence detection and chipless sensing applications, similar to those reported in [16], [17], [18].

II. DESIGN AND METHODOLOGY

The metamaterial absorber design utilized was a square loop configuration, which was chosen

because of its feasibility in setting geometric parameters to achieve the desired frequency response, their ability to remain unaffected by polarization, and their strong stability across various angles [19]. The primary considered geometric parameters included periodicity P , track width w , and spacing between adjacent loops g . The structure was optimized to operate at target frequencies of 3.5 GHz and 5.8 GHz. The frequencies were selected due to their significance for sub-6 GHz 5G systems, Internet-of-Things (IoT) implementation, and ISM (Industrial, Scientific and Medical) band wireless sensing and identification applications [20], [21], [22].

The proposed configuration employs square-loop resonators integrated into the ground plane, enabling frequency-selective absorption while allowing partial transmission at specific bands. The resonant behavior of the square loops induces strong surface currents at the target frequencies, resulting in enhanced absorption performance of the metamaterial absorber. Owing to their geometric simplicity, square-loop resonators provide a high degree of tunability, as the resonant frequencies and bandwidth can be adjusted by modifying the loop dimensions, periodicity, or by incorporating additional resonant elements. This design flexibility enables precise tailoring of the absorber response, making the proposed structure suitable for applications such as electromagnetic shielding. Similar geometric tuning and impedance-matching strategies have been reported to achieve near-perfect dual-band absorption in frequency-selective surfaces [23].

The structure consists of multiple layers, which is a widely used configuration [24], with patterned copper loops located in the middle and on the back face, corresponding to the ground plane. As illustrated in Fig. 1(a), the middle section incorporates three copper square loops: l_1 with a side length of 7.31 mm and track width w_1 of 1.25 mm, l_2 with a side length of 11.5 mm and track width w_2 of 0.5 mm, and l_3 with a side length of 25.7 mm and track width w_3 of 1 mm. The ground plane contains two square loops configured with side length l_{g1} of 9.5 mm and track width w_{g1} of 0.3 mm, and side length l_{g2} of 13.95 mm and track width w_{g2} of 0.3 mm, as shown in Fig. 1(b). The proposed structure uses a low-cost FR-4 substrate with a thickness of 2.4 mm, dielectric constant of 4.4 and loss tangent of 0.02, as illustrated in Fig. 1(c). The geometrical dimensions h_1 and h_2 were

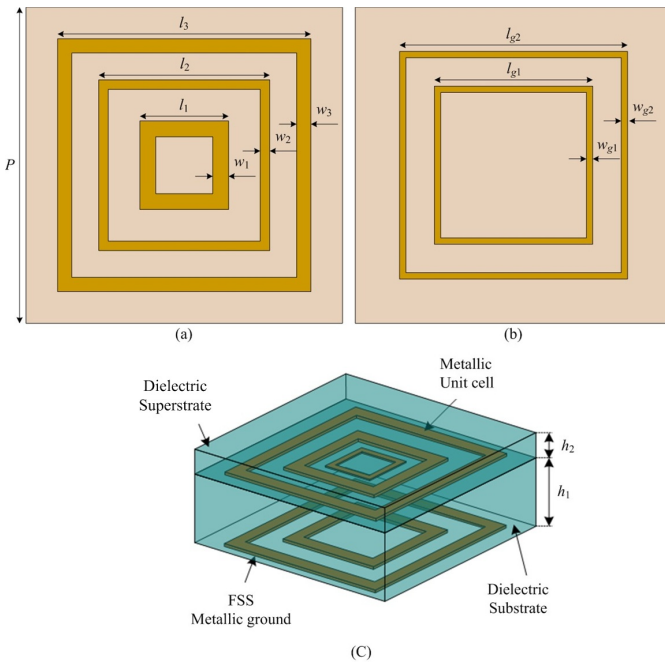


Fig. 1. Front element: (a) View of the Front FSS Element Array, (b) View of the Ground Plane FSS Element Array and (c) Top view of the FSS, where the substrate is rendered opaque to emphasize the loops.

initially defined based on commercially available substrate sizes and manufacturing constraints. In the early stage of the design process, a free-standing model was simulated to estimate the resonance behavior and identify suitable initial dimensions for the metallic patterns. Subsequently, the dimensions were adjusted and optimized considering both the substrate characteristics and the desired absorption response. Different absorption bands can be achieved by modifying the dimensions and the number of resonant metallic loops since the resonance frequencies are directly related to the effective electrical length of the structures. The addition of new loops and the adjustment of their dimensions are effective approaches for introducing or boosting absorption bands. The complete structure features a layered configuration composed of an FR-4 superstrate, an FR-4 substrate containing the patterned metallic layer and a ground plane at the bottom. FR-4, which is a commonly used dielectric material in electronic circuits, plays a significant role in enhancing coupling effects and achieving efficient absorption. The front face of the assembly includes a plate of FR-4 superstrate with a thickness h_2 of 0.8 mm, as illustrated in 1(c), which is crucial for the absorber's performance. This FR-4 superstrate

acts as a key component of the proposed structure, since its dielectric properties, combined with the interaction with the metallic elements, modify the overall impedance of the system. This modification facilitates electromagnetic coupling and tunes the resonance frequencies, ultimately improving both coupling efficiency and absorption. The spacing between adjacent loops, i.e. gap, was defined as 0.3 mm on the front face and 12.05 mm on the back face. The periodicity P of the unit cell arrangement was set to 26 mm, ensuring a repetitive and consistent structure. The plates are positioned so that the middle face serves as the patterned resonating surface, while the back face functions as a reflective ground plane only at the desired frequency. Using a square loop in the ground plate allows efficient absorption, adjusting the properties of the square loop elements, which allows transmission between the structure and the ground plate, unlike a full copper ground plate. The chosen thickness of the plates and arrangement of the loops contribute to the overall effectiveness of the metamaterial absorber across the targeted frequency range.

All metallic layers were modeled with a thickness of $t_m = 0.035$ mm, ensuring proper electromagnetic transmission through the metasurface. This configuration is a foundation for the development of the absorber presented in this work. The final unit cell geometry and the corresponding design stages are illustrated in Fig. 1(c).

III. NUMERICAL MODELING AND ANALYSIS OF THE METASURFACE UNIT CELL

Numerical simulations were conducted to model the electromagnetic behavior of the proposed metasurface unit cell, following the design and methodology outlined in the previous section. The following section provides a comprehensive description of the simulation setup, boundary conditions, material parameters, and the process for extracting the relevant scattering parameters to characterize absorber performance.

A. Frequency-domain unit cell analysis

The performance of the proposed metamaterial absorber was evaluated using CST Microwave Studio. The CST's "Metamaterial - Unit Cell" template, available under the periodic structures and frequency-selective surfaces (FSS) category, was

employed. All numerical simulations were performed assuming an infinite periodic array, implemented through periodic boundary conditions and Floquet-modes with plane-wave excitation. The unit-cell boundary condition enforces periodic replication of the modeled structure in the transverse directions, effectively extending it to infinity. As illustrated in Fig. 2, the simulation domain used for the analysis includes the unit-cell geometry, periodic boundary conditions applied in the transverse directions, and excitation ports defined along the propagation axis.

The frequency range for the analysis was defined from 0.1 GHz to 10 GHz. A broadband frequency sweep was adopted to identify spurious resonances, higher-order modes, and unintended transmission bands beyond the targeted frequencies. A frequency-domain solver was utilized with two ports, each one is configured to support two modes, allowing for the assessment of both co-polarization and cross-polarization effects. The immediate goal of the simulation was to extract the S-parameters S_{11} and S_{21} in the Co-polarization and Cross-polarization, which characterize its reflection and transmission properties, respectively. Co-polarization refers to the field component that is measured in the same polarization as the incident wave, while Cross-polarization denotes the field component that is measured in a polarization that is orthogonal to that of the incident wave. The absorption was calculated according to the following. Absorption A is calculated from reflectivity R and transmittance T as [25]:

$$A(\omega) = 1 - R(\omega) - T(\omega). \quad (1)$$

For a two-port periodic unit cell, these quantities are obtained from the S-parameters:

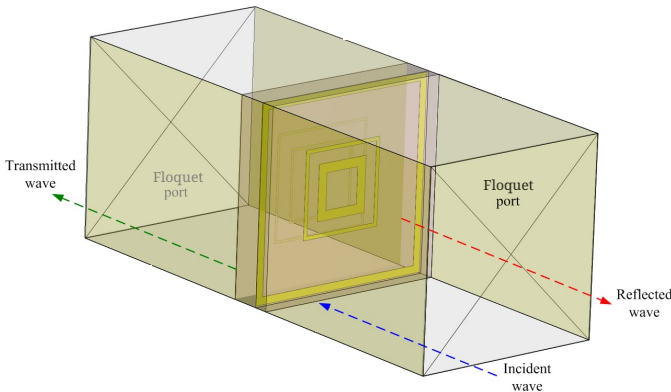


Fig. 2. Boundary conditions for modeling the unit cell in CST.

$$R = |S_{11_{xx}}(\omega)|^2 + |S_{11_{xy}}(\omega)|^2, \quad (2)$$

$$T = |S_{21_{xx}}(\omega)|^2 + |S_{21_{xy}}(\omega)|^2. \quad (3)$$

In (2) [25], $S_{11_{xx}}(\omega)$ denotes the co-polarized reflection and $S_{11_{xy}}(\omega)$ represents the cross-polarized reflection. In (3) [25], $S_{21_{xx}}(\omega)$ denotes the co-polarized transmission and $S_{21_{xy}}(\omega)$ represents the cross-polarized transmission. Here, ω denotes the angular frequency of the excitation; all quantities are evaluated at ω for measured and simulated responses.

Simulation is a critical step in validating design decisions and predicting the response of the absorber under various operating conditions. By analyzing the S-parameters, the structure can be optimized before fabrication, thereby reducing development costs while ensuring efficient performance. Furthermore, the ability to test multiple configurations through simulation enables rapid iteration and refinement, ultimately leading to a more effective metamaterial absorber within the intended frequency range.

The simulation setup consists of a single unit cell positioned along the positive z -axis, aligned with waveguide ports. This port serves as the excitation source, enabling the unit cell to be irradiated by electromagnetic waves during the simulation process. In the model, the $z_{\min}$ boundary of the unit cell is oriented toward the ground plane, which is defined as zero and treated as open in the z direction. Periodic boundary conditions are applied in the x - and y -directions, while open boundary conditions are imposed along the z -axis. To evaluate the performance and electromagnetic response of the proposed design, the scattering parameters were analyzed, with particular attention given to the reflection coefficient S_{11} and the transmission coefficient S_{21} .

To define the bandwidth, the initial and final frequencies were determined based on the -10 dB criterion applied to the reflection coefficient. In the reflection coefficient S_{11} response, three prominent resonance peaks were identified: the first one at 2.77 GHz, with a bandwidth of 532.5 MHz; the second one at 3.493 GHz, with a bandwidth of 92.9 MHz; and the third one at 5.81 GHz, with a bandwidth of 347.7 MHz, as illustrated in Fig. 3. Similarly, for the transmission coefficient response

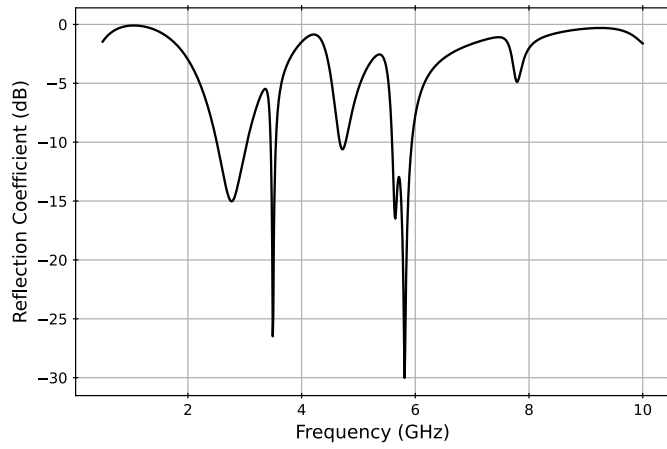


Fig. 3. The simulated co-polarization reflection curves of the proposed absorber.

S_{21} , the passbands were defined considering transmission levels between 0 dB and -3 dB, whereas the stopbands were characterized by transmission levels below -10 dB. And three prominent resonance peaks were also observed: the first one at 1.04 GHz, with a bandwidth of 785.49 MHz; the second one at 4.25 GHz, with a bandwidth of 277.5 MHz; and the third one at 9.35 GHz, with a bandwidth of 1.3853 GHz, as shown in Fig. 4.

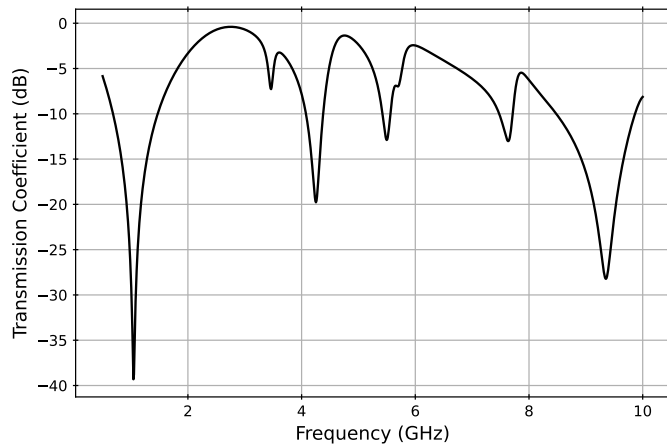


Fig. 4. The simulated co-polarization transmission curves of the proposed absorber.

Tab. I summarizes the results obtained for the resonance frequencies and their corresponding bandwidths, represented by the valleys of the reflection and transmission curves shown in Fig. 3 and Fig. 4.

Based on the simulated data, the absorption was calculated and shown in Fig. 5. The simulation results revealed two distinct absorption bands at approximately 3.5 GHz and 5.8 GHz, with respec-

TABLE I
RESONANCE FREQUENCIES AND BANDWIDTHS.

Parameter	Frequency (GHz)	Bandwidth (MHz)
Reflection S_{11}	2.77	532.5
	3.49	92.9
	5.81	347.7
Transmission S_{21}	1.04	785.49
	4.25	277.5
	9.35	1385.3

tive bandwidths of 92.9 MHz and 347.7 MHz. The recorded absorption levels were 70.91% at 3.5 GHz and 59.15% at 5.8 GHz.

Due to the alteration of the ground plane, a decrease in the absorber's effectiveness is expected. However, simulations show that the absorption still exceeds 50%, which indicates that the structure can still operate as a chipless tag since, chipless tags are decoded through their spectral response rather than requiring perfect absorption [26]. Despite the decrease in absorption, the possibility of allowing partial transmission in specific frequency bands opens new avenues for practical applications. Therefore, by maintaining an appropriate level of absorption, the structure retains its usability, while also gaining additional functionality through controlled transmission.

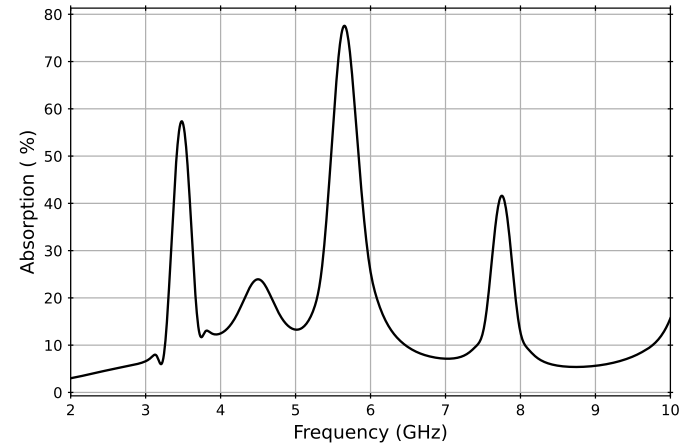


Fig. 5. Predicted absorption behaviour of the simulated structures.

TABLE II
RESONANCE FREQUENCIES AND CORRESPONDING ABSORPTIONS.

Frequency (GHz)	Absorption (%)
3.47	76.86
5.63	77.59
3.5	70.91
5.8	59.15

Further analysis of the simulated data identified two prominent absorption peaks: the first peak at 3.47 GHz, corresponding to an absorption rate of 76.86% and the second peak at 5.63 GHz, with an absorption rate of 77.59%. Overall, at the frequencies of interest, the absorption levels achieved were 70.91% at 3.5 GHz and 59.15% at 5.8 GHz. Tab. II summarizes the results for both the absorption peaks and the absorption levels at the specified frequencies.

B. Effect of the dielectric loss tangent and metal thickness validation

A parametric analysis was performed to examine the influence of dielectric and conductor losses on the simulated absorption response. The analysis considers variations in the dielectric loss tangent of the structure and evaluates the simulated absorption of the metasurface. In addition, the contributions to power dissipation from both the metallic and dielectric layers were analyzed, enabling the characterization of loss-related effects within the structure.

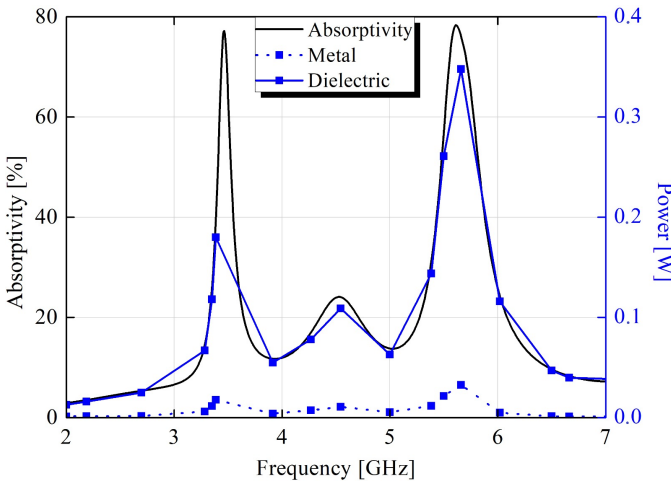


Fig. 6. Simulated contributions of the metallic and dielectric layers to power absorption at a fixed excitation level.

In this article, to verify the influence of materials on absorption, the power loss per material on the absorptivity response was analyzed. The simulation results are shown in Fig. 6, considering an input signal with 0.5 Watts of power. As can be observed, almost all the energy is absorbed within the lossy substrate, and the loss tangent of FR-4 plays an important role in absorption. As expected, most of the incident wave is absorbed within the substrate. This behavior is shown in Fig. 7, which highlights

the influence of the simulated loss constant on absorptivity. Analysis of the curve shows that less than 25% of the energy is absorbed when the dielectric is lossless [$\text{Im}(\epsilon_r) = 0$], and all the absorbed energy is consumed in the metal. As the loss tangent increases to approximately 0.025, the absorptivity also increases, reaching values above 77% at both frequencies. Furthermore, for values of $\text{Im}(\epsilon)$ above the optimum value, absorption decays and remains at a constant value of about 44%. It is concluded, therefore, that values far from $\text{Im}(\epsilon) = 0.025$ ($\tan \delta \ll 0.025$ or $\tan \delta \gg 0.025$) imply a reduction in absorption at both frequencies.

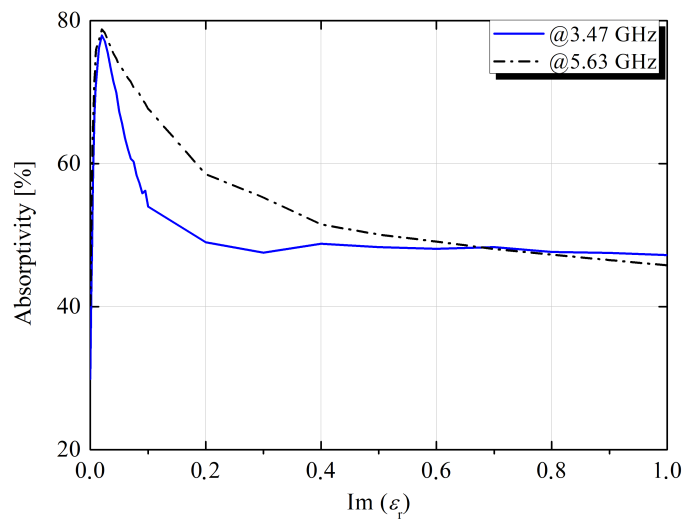


Fig. 7. Simulated absorption at the two selected resonance frequencies as a function of the dielectric loss tangent, illustrating how substrate losses affect the absorption behavior of the proposed metasurface.

IV. FABRICATION PROCESS

Two fabrication techniques were employed for the development of the front loops and the ground plane. The front loops were produced using an LPKF ProtoMat S103 PCB milling system, while the ground plane was fabricated through a photolithographic process involving photosensitive ink and ultraviolet (UV) exposure. The selection of the fabrication method significantly influences the resolution and accuracy of the conductive tracks. The LPKF milling system enables the production of fine conductive traces with minimal spacing, which makes it suitable for designs that require high resolution and geometric complexity. Following the milling step, the fabricated substrate was coated with a protective enamel layer and subsequently

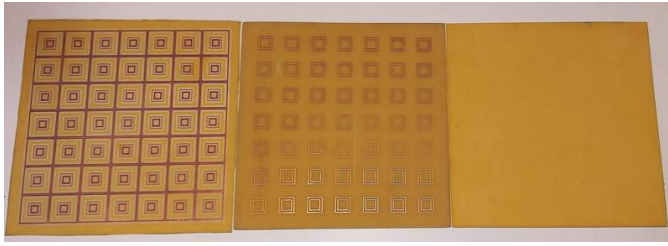


Fig. 8. Fabricated substrates boards arranged side by side.

subjected to a chemical etching process using ferric chloride. This additional etching stage removes residual exposed copper, further refining circuit definition and minimizing the number of drilling operations. In contrast, the photolithographic method involves the application of a photosensitive ink layer onto the copper-clad substrate. The circuit layout, prepared in a mirrored format, is transferred through controlled UV exposure. The irradiated regions polymerize and remain intact, while the unexposed areas are removed during a chemical development stage. Subsequently, ferric chloride etching dissolves the unprotected copper regions, resulting in the final circuit pattern. Although this method is cost-effective and widely adopted, its resolution is inherently constrained by factors such as UV light dispersion and the quality of the photomask during exposure.

The LPKF method was chosen for the middle layer due to its loop array needing features with higher resolution and closely spaced traces. In the photolithographic technique, such narrow spacings can result in defects during the development process, which can cause inadequate ink adhesion or incomplete removal of ink in the thinnest features.

At the end of the fabrication process, the substrates are cut to the required dimensions to complete the production. As shown in Fig. 8, the three fabricated substrates are displayed side by side, clearly illustrating the final result of the prototyping process. The structure measures 182 mm on each side and consists of 49 loops arranged in seven columns and seven rows. The fabricated boards exhibit good quality and consistent sizing. Fig. 9 illustrates the alignment of the boards in a configuration similar to the expected arrangement of the final prototype.

In Fig. 9, the FR-4 substrate is located in the front, the loop layer is located in the center of the structure, the ground plane is positioned at the

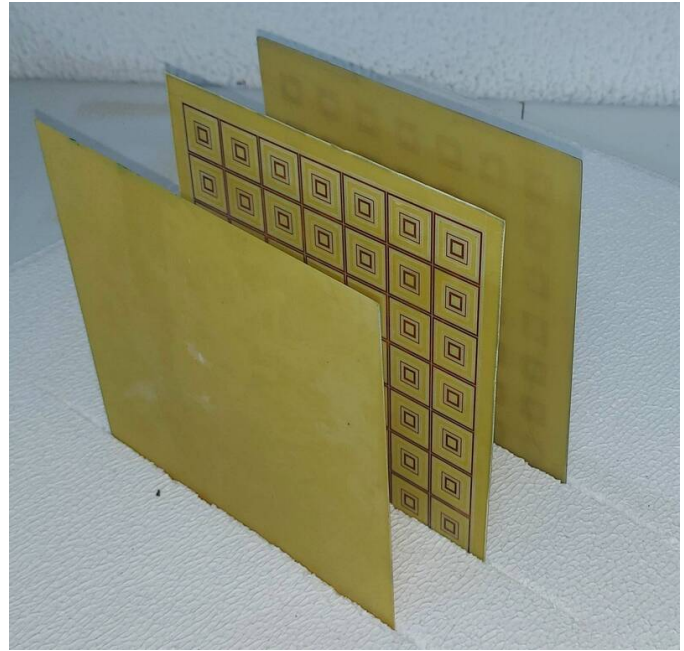


Fig. 9. Alignment of the fabricated boards in the expected configuration of the final prototype.

bottom, clearly displaying its corresponding loop pattern. Fig. 9 effectively illustrates the anticipated alignment of the layer and the structural arrangement of the proposed design.

V. MEASUREMENT SETUP

For a complete understanding of the structure and making precise comparisons with simulation results, it is crucial to establish a measurement setup that aligns with the proposed structure. For the proposed structure, measurements were performed in an anechoic chamber to reduce environmental reflections and electromagnetic interference, contributing to more reliable experimental results. All measurements were performed using a Keysight N5232A Vector Network Analyzer (VNA).

Two different measurement setups were developed using Dual-Ridged Horn antennas (COM-

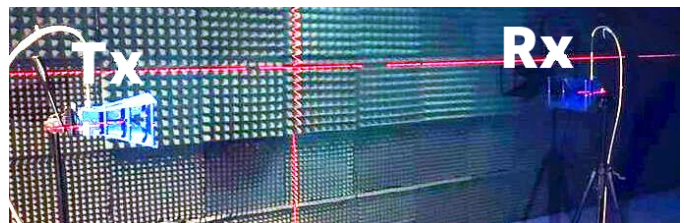


Fig. 10. Free-space transmission measurement calibration setup using horn antennas.

POWER AH-18 model). In this setup, the antennas were positioned facing each other, with a separation distance of 4 m, while the prototype structure was placed at the center of the propagation path between them, as shown in Fig. 10. This configuration was designed to measure the transmission coefficient of the structure and is a widely used measurement method [27], [28]. To guarantee a precise alignment, the antennas were positioned using a laser level, as illustrated in Fig. 11. The same alignment procedure was then applied to the prototype to ensure exact positioning along the measurement axis.

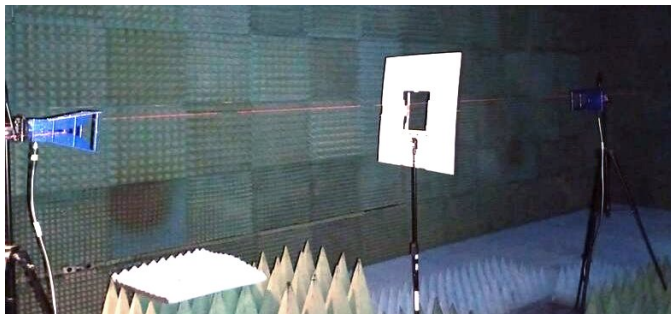


Fig. 11. Antenna alignment procedure using a laser level.

The setup for the final transmission measurement is illustrated in Fig. 12, where the prototype structure is visible. To obtain reliable results, the structure was surrounded by a square protective material, approximately 60 cm wide and 45 mm thick, designed to minimize direct transmission between the horn antennas. This arrangement effectively suppresses unwanted coupling, ensuring that the measured signal corresponds primarily to the transmission through the proposed absorber.

The second configuration was designed to measure the reflection coefficient using an NRL arch with a radius of 1.2 m, thereby allowing angular positioning of the antennas during measurements. For this setup, the antennas were positioned along a curved support, allowing for changes in the angle of incidence, as shown in Fig. 13. Measurements were made at 0° , 15° and 30° incidence angles. To avoid direct coupling between the transmitting and receiving antennas, which could compromise the reflected signal, a shielding material was placed between them, as shown in Fig. 14, to ensure that the signal reflected by the absorber was primarily captured. In Fig. 14 the antennas were positioned with an incidence angle of 15° relative to the normal direction of the structure surface.

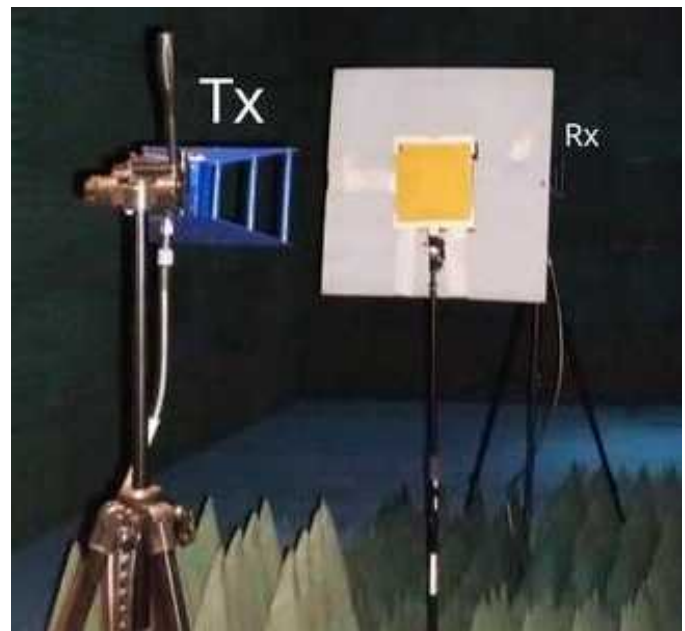


Fig. 12. The setup for transmission measurement in an anechoic chamber.

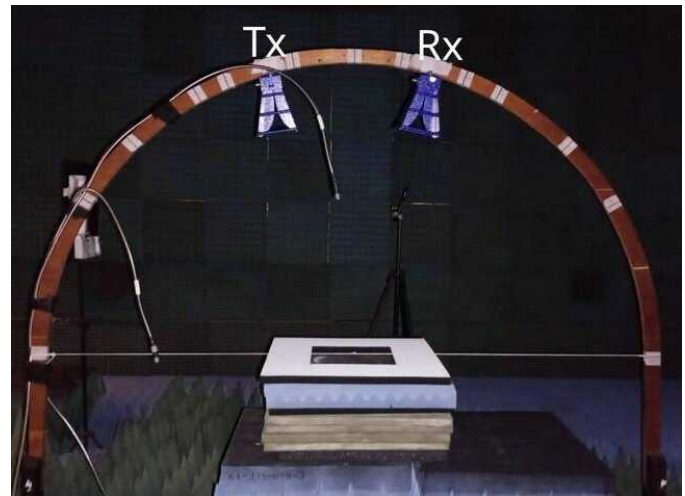


Fig. 13. Reflection measurement configuration with antennas mounted on the NRL arch.

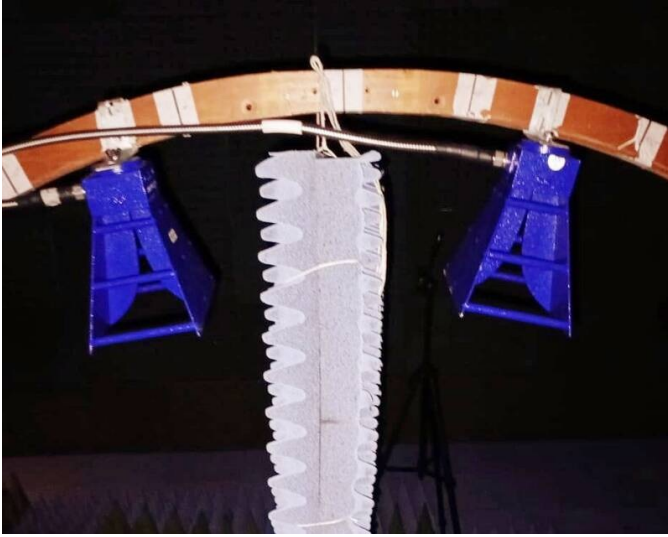


Fig. 14. Reflection measurement configuration with shielding material placed between the antennas.

VI. EXPERIMENTAL RESULTS AND DISCUSSION

To evaluate the functional effectiveness of the suggested design, measurements were performed as described in Section V. In the analyzer, a frequency sweep from 2 GHz to 10 GHz was configured in the analyzer, covering all expected operational bands of the metasurface. In order to evaluate the absorption metrics consistently with the simulations, the S-parameters of the fabricated prototype were measured. Furthermore, to analyze performance variation under different incidence conditions, a parametric variation was carried out for incidence angles of 0° , 15° and 30° .

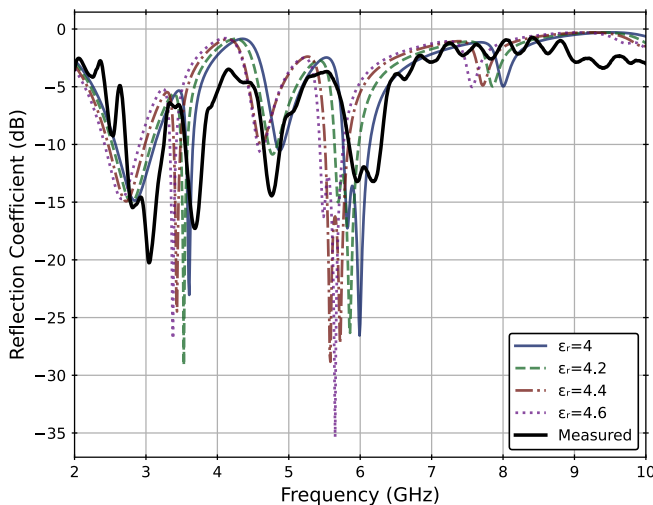


Fig. 15. Simulated and measured reflection coefficients S_{11} .

The simulated results presented in Fig. 15 were generated using the modeling approach outlined in Section III, which assumes an infinitely periodic array and neglects both horn antennas and finite-size effects. In comparison, the measured results were obtained from a finite 7×7 prototype that was characterized using horn antennas. The overall dimensions of the fabricated array were selected based on the horn antenna configuration used in the measurements, so that the illuminated region remained largely contained within the sample area. This comparison is justified because the unit-cell simulations capture the intrinsic response of an infinite periodic structure, while the horn antennas provide quasi-plane wave illumination over the sample.

Fig. 15 presents the comparison between the simulated and measured reflection coefficients. A clear similarity can be observed between the curves, with only a slight shift in the target bands. Since the dielectric constant of commercial FR-4 substrates may vary with the manufacturing process, additional simulations were performed using dielectric constant (ϵ_r) values of 4.0, 4.2, 4.4 and 4.6, with 4.4 corresponding to the nominal value used in CST Microwave Studio. The results indicate that variations in the substrate permittivity primarily shift the resonance frequencies, helping to explain the differences observed between the simulated and measured responses.

This deviation can be compensated through some minor adjustments in the loop dimensions, ensuring better agreement between simulation and measurement. The results obtained show primary reflection minima close to the target frequency at 3.69 GHz (with a minimum of -17.3 dB) and 5.96 GHz (minimum of -13.2 dB). Additional minima identified during measurement are detailed in Tab. III. The corresponding reflection bands with $S_{11} \leq -10$ dB are 2.72–3.26 GHz, 3.55–3.81 GHz, 4.65–4.89 GHz and 5.85–6.30 GHz, as summarized in Tab. IV.

The appearance of unexpected bands in the measurements could be attributed to deviations in alignment within the assembled structure due to unavoidable fabrication tolerances. During the layer stacking process, slight variations in spacing, alignment, and feature dimensions, either within the overall assembly or among the individual loops, can accumulate. This accumulation can lead to unanticipated shifts in the measured response.

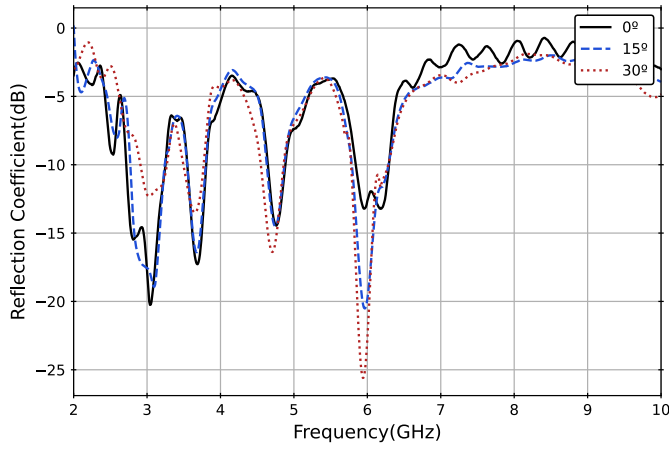


Fig. 16. Measured reflection coefficients S_{11} under different incidence angles.

TABLE III
MEASURED FREQUENCIES WITH MINIMUM REFLECTION.

Frequency (GHz)	Magnitude (dB)
3.04	-20.3
3.69	-17.3
4.76	-14.5
5.96	-13.2
6.19	-13.2

Fig. 16 illustrates the effect of the incidence angle on the reflection response. As the angle increases, the high-frequency resonance is improved, while a slight reduction is observed at lower frequencies. Despite some fluctuations, the general trend of the curve remains consistent with the theory. At 30° , a noticeable phenomenon can be seen: the primary frequency bands of interest at 3.5 GHz and 5.8 GHz are kept as clearly defined, while still allowing additional unexpected bands to emerge. This result indicates a stable performance under angular variation, and it suggests opportunities for further optimization of the structure.

Fig. 17 shows the comparison between the simulated and measured transmission coefficients. A larger discrepancy can be observed between the two results, particularly below 8 GHz, where there

TABLE IV
MEASURED REFLECTION BANDS (I.E., $S_{11} \leq -10$ dB).

Frequency Range (GHz)	Bandwidth (MHz)
2.72 – 3.26	540
3.55 – 3.81	260
4.65 – 4.89	240
5.85 – 6.30	450

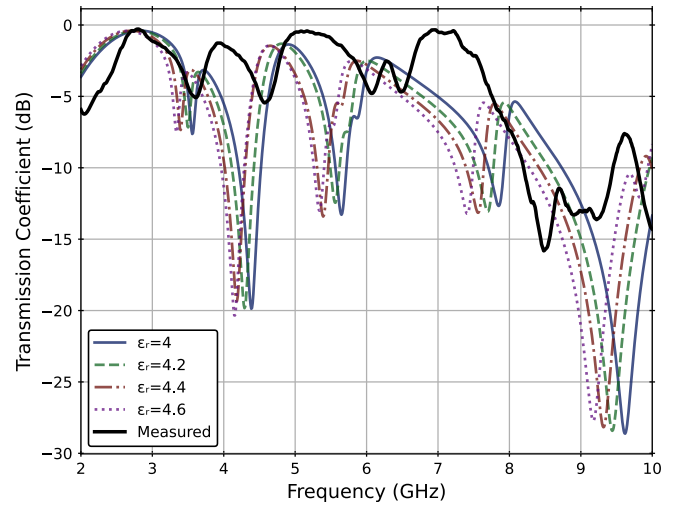


Fig. 17. Simulated and measured transmission coefficients S_{21} .

TABLE V
MEASURED TRANSMISSION BANDS (I.E., $S_{21} \leq -10$ dB).

Frequency Range (GHz)	Bandwidth (MHz)
8.20–9.46	1260
9.80–10.24	440

are no pronounced minima in the measured data below 8 GHz. However, the overall trend remains consistent, indicating that the structure could be reconfigured to operate effectively in this range. For higher frequencies, i.e., greater than 8 GHz, a broad transmission band is observed from 8.20 to 9.46 GHz, as summarized in Tab. V, in agreement with the simulation, with the minima described in Tab. VI.

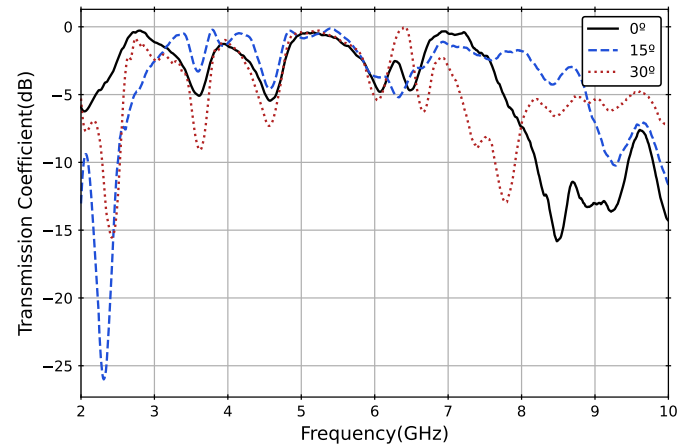


Fig. 18. Measured transmission coefficients S_{21} under different incidence angles.

When the angle of incidence is varied, as illus-

TABLE VI
MEASURED TRANSMISSION FREQUENCY MINIMA.

Frequency (GHz)	Magnitude (dB)
8.48	-15.8
9.22	-13.6
10.02	-14.3

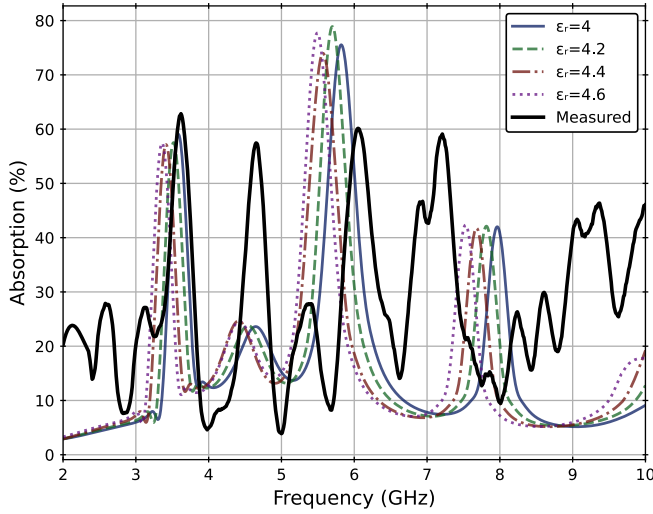


Fig. 19. Simulated and measured absorptions.

trated in Fig. 18 an improvement in the transmission of low frequencies becomes evident. For incidence angles of 15° and 30° , a significant minimum is observed around 2.5 GHz, along with noticeable shifts in the higher-frequency bands above 8 GHz, as summarized in Tab. VI.

TABLE VII
MEASURED ABSORPTION BANDS (I.E., ABSORPTION $\geq 50\%$)

Frequency Range (GHz)
3.52–3.73
4.58–4.73
5.95–6.18
7.11–7.31
10.06–10.26

The absorption calculated from the measured S-parameters is shown in Fig. 19, together with the simulated response for comparison. For the absorption response, a similar frequency shift was also observed. Below 5 GHz, the measured data show better agreement with the simulated curve for $\epsilon_r = 4.0$. However, above 5 GHz, the same frequency displacement observed in the other analyzed responses remains present. This frequency shift has been observed for the 3.5 GHz absorption band, along with

an unexpected peak near 4.65 GHz, as listed in Tab. VIII. The absorption peak observed may be associated with an additional resonant mode generated by the electromagnetic coupling between adjacent metallic loops. Due to the interaction between the resonant elements, secondary resonances can arise, resulting in the appearance of unexpected absorption peaks. The higher band is also shifted toward approximately 6.0 GHz, while additional significant peaks appear around 7.21 GHz and 10.17 GHz. As summarized in Tab. VII, the measured absorption bands of 3.52 GHz to 3.73 GHz and 5.95–6.18 GHz are close to the simulated predictions, while additional bands are also observed, as listed in Tab. VII.

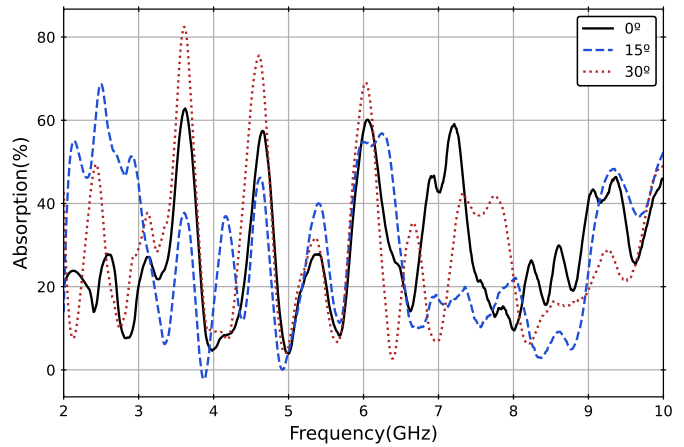


Fig. 20. Measured absorptions under different incidence angles.

As illustrated in Fig. 20, the angular variation further enhanced the absorption performance for 30° incidence, where one peak exceeded 80% absorption and two additional peaks remained above 60%. This result highlights the angular robustness of the structure.

TABLE VIII
COMPARISON OF ABSORPTION PEAKS FOR SIMULATED AND MEASURED DATA.

Band	Simulated (GHz, %)	Measured (GHz, %)
1	3.47, 76.9%	3.62, 62.8%
2	5.63, 77.6%	4.65, 57.4%
3	—	6.05, 60.1%
4	—	7.21, 59.1%
5	—	10.17, 56.5%

VII. CONCLUSION

This paper presents the design, performance evaluation and fabrication of a metasurface absorber

with transmission capability that utilizes square loops instead of a solid ground plane. The proposed structure consists of two different loop designs: one loop acts as the ground plane, while the other is placed on the front of the substrate, accompanied by an additional dielectric layer on the front. The absorber operates under normal incidence at two frequencies, 3.5 GHz and 5.8 GHz, exhibiting simulated absorption peaks of 76.9% at 3.5 GHz and 77.6% at 5.63 GHz. Measured results, however, revealed additional absorption peaks and frequency shifts relative to the simulated predictions. Absorption peaks of 62.8%, 57.4%, 60.1%, 59.1% and 56.5% were recorded at frequencies of 3.62 GHz, 4.65 GHz, 6.05 GHz, 7.21 GHz and 10.17 GHz, respectively. These results align closely with the simulated response, and further enhancements are needed based on the measured data to improve performance. Such adjustments would help to minimize the frequency shifts observed in the experimental data and to elevate the absorption peaks to values closer to 80%. The proposed structure can be employed as a chipless tag by detecting its characteristic electromagnetic signature. In addition to the absorption response, the transmission characteristics also offer possibilities for coding and identification. Specifically, different resonant configurations can generate distinct spectral signatures. These features together create potential applications in conveyor belt monitoring systems and identification platforms that could rely on transmission-response detection. The results demonstrate that employing loops in the ground plane is a viable approach, which can be further optimized, representing a step forward in the development of this technique.

ACKNOWLEDGMENT

This work was supported in part by FAPERJ (Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro) through project E-26/210.311/2024 and E-26/210.847/2024. The authors would like to thank the LAPROP Laboratory of the Fluminense Federal University; the Integrated Electronic Warfare Laboratory (LIGE), which provided support during the measurements carried out in this work, and the Brazilian agencies CNPq and CAPES.

REFERENCES

- [1] J. Gao, Y. Zhang, Y. Sun, and Q. Wu, "Coupling effects in dielectric metamaterials," *Results Phys.*,

- vol. 17, p. 103038, 2020. doi: 10.1016/j.rinp.2020.103038. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2211379720304484>
- [2] S. Mahmud, A. R. Chowdhury, S. Hannan, M. Tariqul Islam, A. S. Alshammari, and M. S. Soliman, "Polarization-selective metamaterial absorber using tailored y-shaped srr for uwb device and doppler navigation aids applications," *Heliyon*, vol. 10, no. 23, p. e40102, 2024. doi: 10.1016/j.heliyon.2024.e40102. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2405844024161336>
- [3] S. Barzegar-Parizi and A. Khavasi, "Designing dual-band absorbers by graphene/metallic metasurfaces," *IEEE J. Quantum Electron.*, vol. 55, no. 2, p. 1–8, Apr. 2019. doi: 10.1109/jqe.2019.2901992. [Online]. Available: <http://dx.doi.org/10.1109/JQE.2019.2901992>
- [4] Q. Wang, F. Zhang, Y. Xiong, Y. Wang, X.-Z. Tang, C. Jiang, I. Abrahams, and X. Huang, "Dual-band binary metamaterial absorber based on low-permittivity all-dielectric resonance surface," *J. Electron. Mater.*, vol. 48, no. 2, pp. 787–793, 2019. doi: 10.1007/s11664-018-6796-2. [Online]. Available: <https://doi.org/10.1007/s11664-018-6796-2>
- [5] B. Zhang, J. Hendrickson, and J. Guo, "Multispectral near-perfect metamaterial absorbers using spatially multiplexed plasmon resonance metal square structures," *J. Opt. Soc. Am. B*, vol. 30, no. 3, pp. 656–662, Mar 2013. doi: 10.1364/JOSAB.30.000656. [Online]. Available: <https://opg.optica.org/josab/abstract.cfm?URI=josab-30-3-656>
- [6] S. Gharat, P. Kulkarni, S. Prabhu, and C. Garde, "Dualband and tripleband metamaterial absorber in wr1 band and lower terahertz frequencies," 2022. doi: 10.48550/arXiv.2203.13442. [Online]. Available: <https://arxiv.org/abs/2203.13442>
- [7] I. Issah, C. R. Fernández, M. Habib, S. Chervinskii, and H. Caglayan, "Dual-band metal-insulator-metamaterial absorber," 2022. doi: 10.48550/arXiv.2209.00867. [Online]. Available: <https://arxiv.org/abs/2209.00867>
- [8] F. Ding, Y. Cui, X. Ge, Y. Jin, and S. He, "Ultra-broadband microwave metamaterial absorber," *Applied Physics Letters*, vol. 100, no. 10, Mar. 2012. doi: 10.1063/1.3692178. [Online]. Available: <http://dx.doi.org/10.1063/1.3692178>
- [9] B. X. Khuyen, B. S. Tung, Y. J. Yoo, Y. J. Kim, K. W. Kim, L.-Y. Chen, V. D. Lam, and Y. Lee, "Miniaturization for ultrathin metamaterial perfect absorber in the vhf band," *Sci. Rep.*, vol. 7, no. 1, p. 45151, 2017. doi: 10.1038/srep45151. [Online]. Available: <https://doi.org/10.1038/srep45151>
- [10] Z. Liu, L. Guo, and Q. Zhang, "Design of dual-band terahertz perfect metamaterial absorber based on circuit theory," *Molecules*, vol. 25, no. 18, 2020. doi: 10.3390/molecules25184104. [Online]. Available: <https://www.mdpi.com/1420-3049/25/18/4104>
- [11] C. M. Watts, X. Liu, and W. J. Padilla, "Metamaterial electromagnetic wave absorbers," *Advanced Materials*, vol. 24, no. 23, pp. OP98–OP120, 2012. doi: 10.1002/adma.201200674. [Online]. Available: <https://advanced.onlinelibrary.wiley.com/doi/abs/10.1002/adma.201200674>
- [12] R. Aghahari, S. Singh, D. Samantaray, B. Kumar, S. Bhattacharyya, M. Mahto, and P. K. Jain, "Triple-band metasurface absorber for rf energy harvesting applications," *Microw. Opt. Technol. Lett.*, vol. 65, no. 8, pp. 2252–2261, 2023. doi: 10.1002/mop.33728. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/mop.33728>
- [13] J. Wang, T. Lang, Z. Hong, M. Xiao, and J. Yu, "Design and fabrication of a triple-band terahertz metamaterial absorber," *Nanomaterials*, vol. 11, no. 5, 2021. doi: 10.3390/nano11051110. [Online]. Available: <https://www.mdpi.com/2079-4991/11/5/1110>

- [14] F. Younis, O. Khan, J. Ahmad, M. Qasim, H. Luo, and S. Wang, "A highly efficient triple band metasurface enabled absorber for 5g/6g millimeter wave applications," *Sci. Rep.*, vol. 15, p. 29455, 08 2025. doi: 10.1038/s41598-025-12790-1.
- [15] A. Sellier, T. V. Teperik, and A. de Lustrac, "Resonant circuit model for efficient metamaterial absorber," *Opt. Express*, vol. 21, no. S6, pp. A997–A1006, Nov 2013. doi: 10.1364/OE.21.00A997. [Online]. Available: <https://opg.optica.org/oe/abstract.cfm?URI=oe-21-106-A997>
- [16] N. M. Chowdhury, M. Hakim, T. Alam, A. Maash, M. Singh, M. Soliman, M. Islam, and M. Islam, "Interconnected four split rectangular ring resonator flexible metamaterial for microwave sensing application," *Sci. Rep.*, vol. 15, 07 2025. doi: 10.1038/s41598-025-00040-3.
- [17] Y. I. Abdulkarim, L. Deng, M. Karaaslan, Ş. Dalgac, R. H. Mahmud, F. Ozkan Alkurt, F. F. Muhammadsharif, H. N. Awl, S. Huang, and H. Luo, "The detection of chemical materials with a metamaterial-based sensor incorporating oval wing resonators," *Electronics*, vol. 9, no. 5, 2020. doi: 10.3390/electronics9050825. [Online]. Available: <https://www.mdpi.com/2079-9292/9/5/825>
- [18] S. Sato, K. Sakabe, H. Onoe, and T. Kan, "Biodegradable rf metamaterial perfect absorber for wireless soil ph monitoring," *Advanced Materials Technologies*, vol. 10, 12 2024. doi: 10.1002/admt.202401134.
- [19] X. Han, Z. Zhang, and X. Qu, "A novel miniaturized tri-band metamaterial thz absorber with angular and polarization stability," *Optik*, vol. 228, p. 166086, 2021. doi: 10.1016/j.ijleo.2020.166086. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0030402620318957>
- [20] A. Mishra and C. Li, "5.8-ghz ism band intermodulation radar for high-sensitivity motion-sensing applications," in *2018 IEEE Radio and Wireless Symposium (RWS)*, 2018, pp. 4–6. doi: 10.1109/RWS.2018.8304930.
- [21] A. Schumacher, R. Merz, and A. Burg, "3.5 ghz coverage assessment with a 5g testbed," in *2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring)*, 2019, pp. 1–6. doi: 10.1109/VTCSpring.2019.8746551.
- [22] K. Shafique, B. A. Khawaja, F. Sabir, S. Qazi, and M. Mustaqim, "Internet of things (iot) for next-generation smart systems: A review of current challenges, future trends and prospects for emerging 5g-iot scenarios," *IEEE Access*, vol. 8, pp. 23 022–23 040, 2020. doi: 10.1109/ACCESS.2020.2970118.
- [23] N. Ullah, M. Islam, A. Hoque, P. Kirawanich, H. Alsaif, M. Soliman, and M. Islam, "Design and experimental validation of a compact dual-band metamaterial perfect absorber for electromagnetic energy harvesting applications," *Opt. Mater.*, vol. 157, p. 116054, 09 2024. doi: 10.1016/j.optmat.2024.116054.
- [24] W. Zhang, X. Wang, and K. Yang, "A dual-band broadband absorber using frequency selective surface for satellite antenna," *Sci. Rep.*, vol. 14, no. 1, p. 28311, 2024. doi: 10.1038/s41598-024-79804-2. [Online]. Available: <https://doi.org/10.1038/s41598-024-79804-2>
- [25] N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, "Perfect metamaterial absorber," *Phys. Rev. Lett.*, vol. 100, p. 207402, May 2008. doi: 10.1103/PhysRevLett.100.207402. [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevLett.100.207402>
- [26] M. Borgese, S. Genovesi, G. Manara, and F. Costa, "Radarcross section of chipless rfid tags and ber performance," *IEEE Trans. Antennas Propag.*, vol. 69, no. 5, pp. 2877–2886, May 2021. doi: 10.1109/tap.2020.3037800. [Online]. Available: <http://dx.doi.org/10.1109/TAP.2020.3037800>
- [27] Q. Li, X. Li, Y. Chen, F. Ding, C. Chen, H. Liu, and S. Xiao, "High-performance dual-band frequency-selective rasorber based on cascaded metasurface," *Front. Mater.*, vol. Volume 9 - 2022, 2022. doi: 10.3389/fmats.2022.949076. [Online]. Available: <https://www.frontiersin.org/journals/materials/articles/10.3389/fmats.2022.949076>
- [28] H. Zheng, L. Chen, and Y. Lee, "High-performance and flexible metamaterial wave absorbers with specific bandwidths for the microwave device," *Crystals*, vol. 13, no. 6, 2023. doi: 10.3390/cryst13060868. [Online]. Available: <https://www.mdpi.com/2073-4352/13/6/868>



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