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FSS-Based Electromagnetic Absorbers for Stealth Application

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Abstract - With advancements in Radio Frequency (RF) and wireless technologies, RF absorbing structures are needed, especially in areas such as electromagnetic interference (EMI) and strategic target detection technologies. With many wireless technologies used for communication, applications, such as stealth technologies, require frequency-dependent performance. This paper discusses the development of a wideband, polarization-insensitive, angularly stable circuit analog absorber based on the multiple-resonance concept. The design consisted of a dual layer of frequency-selective surfaces (FSS) with periodic unit cells loaded with lumped resistors.

***Index Terms* -** Microwave Absorber, Circuit analog absorber, Frequency Selective Surfaces (FSS),

INTRODUCTION

An electromagnetic absorber is a material or structure designed to attenuate or absorb electromagnetic (EM) waves by suppressing their reflection and transmission. The absorber material or body interacts with electromagnetic waves, leading to the conversion of electromagnetic energy into another form, most commonly in the form of heat or thermal energy. Electromagnetic absorbers have a wide range of applications, such as radar cross-section reduction (RCSR) for military stealth applications and reduction of electromagnetic interference.

One of the early technologies used for electromagnetic absorption in stealth applications was the "Salisbury Screen"[1][2][3], which comprises of a metallic ground plane with a lossless dielectric of quarter-wavelength thickness and a thin resistive layer on the front. The incident wave on the structure was partially reflected from the front surface of the structure. The remaining transmitted wave is reflected from the metallic plane behind. As the wave reflected from the metallic plane will have to travel twice the dielectric thickness or half wavelength, it will be out of phase with the wave reflected from the thin resistive layer and cause the two

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waves to cancel out. This effect prevents wave reflection or transmission by effectively absorbing the waves.

A transmission line equivalent model of the is shown in Figure 1. It consists of a parallel configuration of a resistive sheet and a metallic ground plane. Owing to the quarter-wave distance, the impedance of the metallic ground plane becomes infinite. The impedance of the resistive screen becomes equal to Z_{in} or 377 Ω and absorption can be achieved.

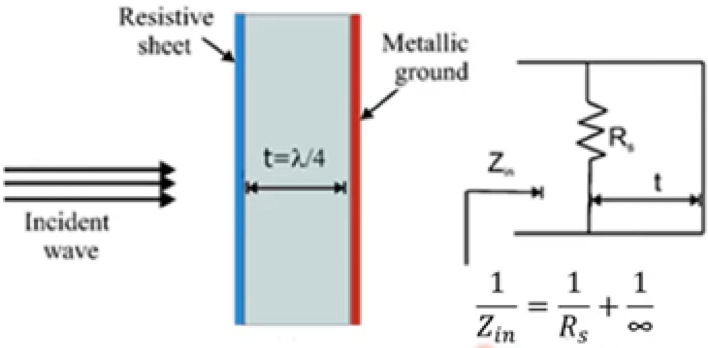

Figure 1: Salisbury Screen

Salisbury Screens are classified as resonant absorbers, which exhibit frequency-dependent characteristics. The "Jaumann absorber"[4]is a multilayered modified version of the Salisbury screen consisting of alternating Dielectric and Resistive layers. This structure in a similar way can produce multiple absorption maxima that can be adjusted to create an absorption bandwidth.

Geometric Transition absorbers[5] with broadband characteristics are utilized in applications, such as the construction of Anechoic Chambers. These are two-dimensional periodic arrays of pyramidal or conical structures of length on the order of one wavelength, made of lossy materials such as rubber or plastic foam loaded with carbon. The structure establishes a dielectric gradient transition to a lossy medium, thereby causing absorption. Owing to their large dimensions, geometric absorbers are not suitable for applications such as the target RCSR.

Traditional RF absorbers have inherent limitations, with one of the important factors being their thickness, which must be at least λ/4. Another aspect is that there is very limited control over the absorption properties, as natural materials that match the free space impedance are not easily available.

Given the limitations of traditional electromagnetic absorbers, such as thickness and limited control over absorption properties, the exploration of frequency-selective surfaces (FSS) based on metamaterials offers promising alternatives. The unique properties of these materials, which are derived from their geometric structures rather than their constituent materials, present a novel approach for achieving efficient broadband absorption.

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CIRCUIT ANALOG ABSORBER

Frequency-selective surface (FSS) absorbers [6][7] based on metamaterials have emerged as the choice to overcome some of these limitations. Metamaterial absorbers have gained attention owing to their low thickness, low weight, and design flexibility. Metamaterials were initially proposed by Walser in 2001 as artificial composite structures or materials with supernormal physical properties[8]. The properties of metamaterials are derived from the geometry of the periodic structures of the subwavelength unit cells rather than the material properties. These are typically layered structures composed of a metallic pattern array on a dielectric substrate backed by a highly conductive ground plane. The absorption mechanism arises from the destructive interference between the multiple-order reflections within the dielectric substrate. The properties of these absorbers depend on their frequencies. One of the challenges for FSS-based absorbers is their limited bandwidths. Multi-resonant absorbers can be designed using complex geometries. However, the complex nature of these patterns presents challenges for simultaneously controlling multiple resonant frequencies to achieve broadband response[9].

An efficient solution to overcome this bandwidth issue is to use a circuit analog (CA) absorber[10]. This consists of resistance-loaded high-impedance FSS cells backed by a metallic plane. It can be compared with a Jaumann absorber, where the resistive sheets are substituted by resistive sheets with a frequency-selective pattern that can achieve a broader bandwidth. The frequency selective performance of the sheets can be achieved by using classical FSS structures[11][12] The name "circuit analog absorber" comes from the fact that electromagnetic frequency response can be obtained through equivalent electrical circuit models comprising resistive, inductive, and capacitive elements.

By incorporating resistive elements into metamaterial-based FSS structures, CAAs can achieve impedance matching with free space impedance (~ 377 Ω) over a much wider frequency range. Resistive elements introduce frequency-independent losses, which contribute to broadband absorption. Multiple reactive lossy layers can be strategically designed to compensate for the intrinsic reactance of the grounded dielectric around the resonance frequency, further widening the absorption bandwidth

In this study, a CA absorber consisting of two layers of FSS structures loaded with lumped resistors was designed to achieve broadband response.

ABSORBER DESIGN AND ITS EQUIVALENT CIRCUIT

Based on the theoretical foundation of the FSS absorbers discussed earlier, this section discusses the design approach for the absorbers. An equivalent circuit model of the designed absorber was also derived to obtain a transmission line model of the absorber.

This study aimed to build a CA absorber in the C-band- and X-bands, which has applications in Stealth Technology for defence platforms. Various designs were analysed for this purpose,

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and a design consisting of two layers of an FSS structure with lumped resistors across unit cell elements was selected. The structure is shown in the diagram below:

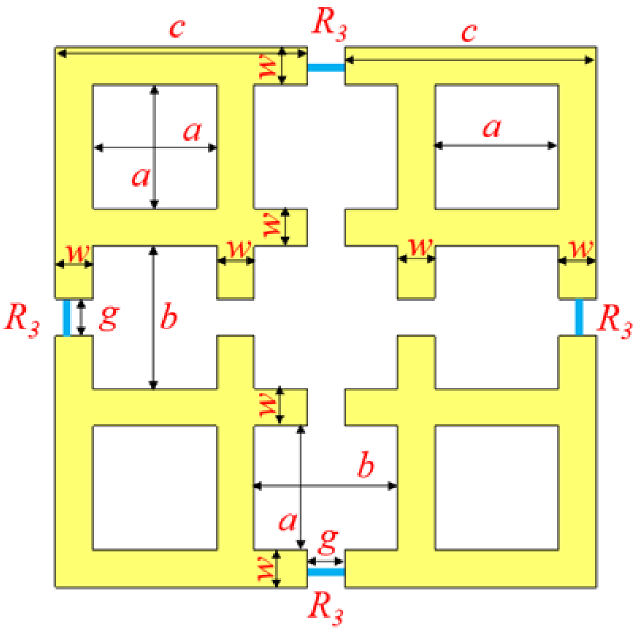

Figure 2: Top Layer of the proposed CAA

The top layer geometry consisted of a square mesh as given in the Figure 2 and the bottom geometry had two nested square loops as given in the Figure 2. As depicted in the figures, the surfaces are converted to high impedance by incising 0.5 mm gaps and connecting them with lumped resistors. A high-impedance surface introduces losses in the absorber, thereby absorbing electromagnetic radiation.

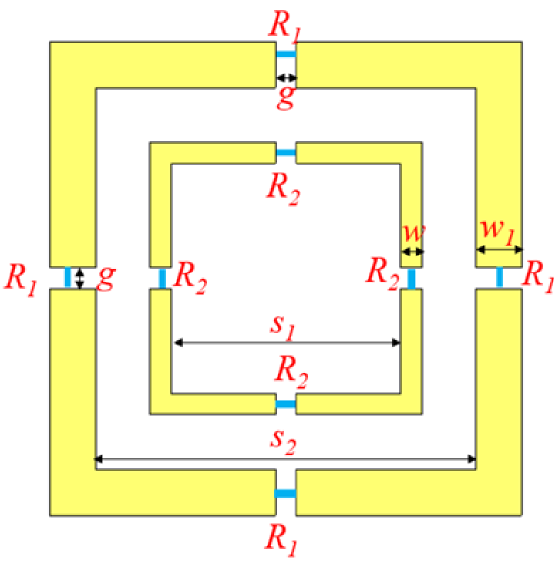

Figure 3: Second Layer of the proposed CAA

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A 2-dimensional array of unit cells forms the FSS structure. Each FSS structure was supported by a dielectric substrate with an air gap between them. The FSS structures were backed by a metallic plane separated by an air-gap. The metallic plane prevents wave transmission. The topological stack-up of the absorber is given in Figure 4

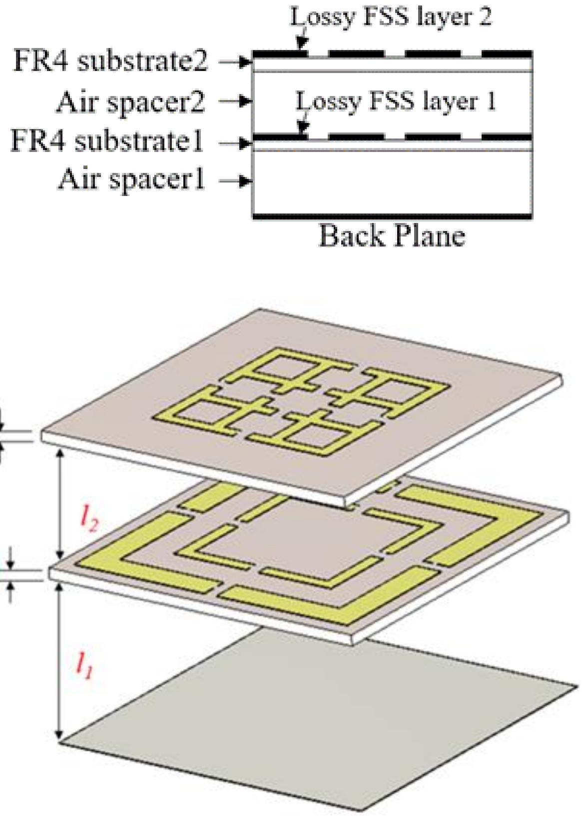

Figure 4: Stack up of the Proposed Unit Cell

The structure was analysed using the full-wave simulation tool CST Microwave Studio. The structure is modelled using the physical geometry of the structure, defined as variables for optimization. The conductive layers were defined using copper material and the substrate with FR4.

The design parameters used are as follows:

Thickness of the metallic planes: 0.035 mm

Conductivity of metallic (Cu) planes: 5.8 x10^7 S/m

Thickness of the FR4 substrate layers: 1= 0.4 mm

Relative permittivity of substrate (FR4): 4.3

Inner length of middle layer inner loop: s_1= 5.5 mm

Inner length of middle layer outer loop: s_2= 9.1 mm

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Air gap between ground and middle layer: l_1= 5.9 mm

Air gap between middle and top layers: l_2= 4.5 mm

Resistors used in middle layer outer loop: R1= 200 Ω

Resistors used in middle layer inner loop: R_2= 160 Ω

Resistors used in the top layer: R_3= 60 Ω

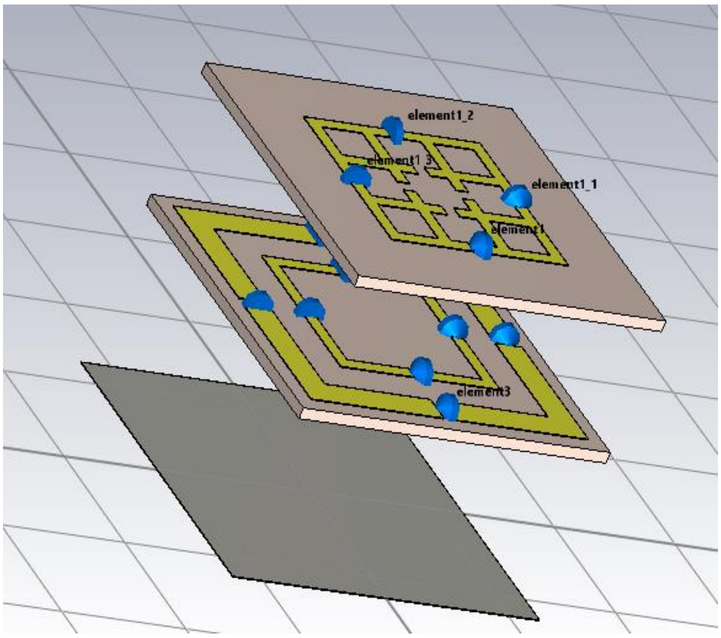

Figure 5 : Unit Cell modelled in CST

With the FSS element plane along the X-Y axis, the periodic structure is modelled by defining the unit cell boundary conditions for the X and Y boundaries. Floquet ports were defined on the Z-boundaries.

The model was subjected to a parametric variation analysis to achieve wideband performance and stability with respect to the angle of incidence, resulting in the parameters listed above.

An equivalent transmission-line model of the frequency-selective surface (FSS) was derived from the S-parameters, facilitating a more comprehensive understanding of the behaviour of the structure in the frequency domain. The structure modelled as a transmission line is shown in Figure 6.

The model consists of a metallic backplane that is represented as a short-circuit transmission line. It consists of R, L, and C in series, which represent the top layer parallel to the short-circuit transmission line. The middle layer is represented by parallel connections of R, L, and C, in series. These two RLC circuits represent the two loops in the middle layer. The transmission line segments of lengths l1 and l2 represent the air gaps.

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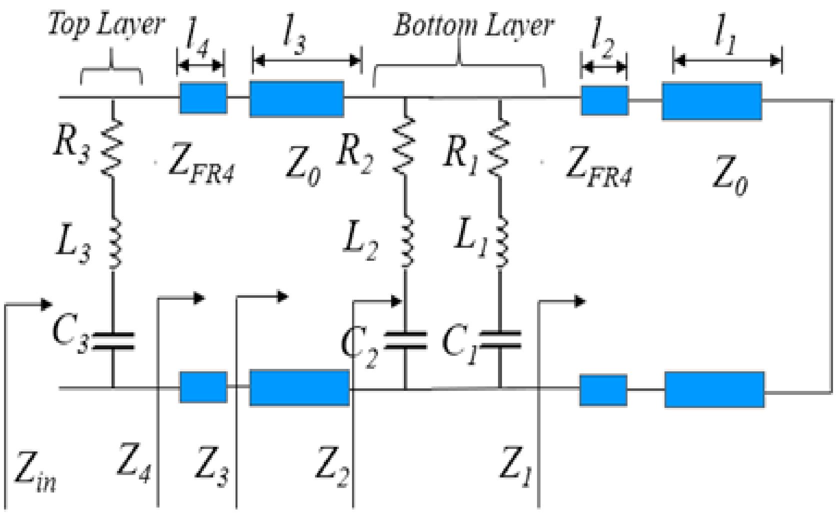

Figure 6: Equivalent transmission line circuit model

ANALYSIS OF THE RESULT

An average absorption of 10 dB was observed in the frequency range of 3 GHz to 14 GHz under normal incidence. Three resonances around 3.78 GHz, 7.44 GHz, and 12.5 GHz were obtained with an additional 10 dB absorption as shown in Figure 7.

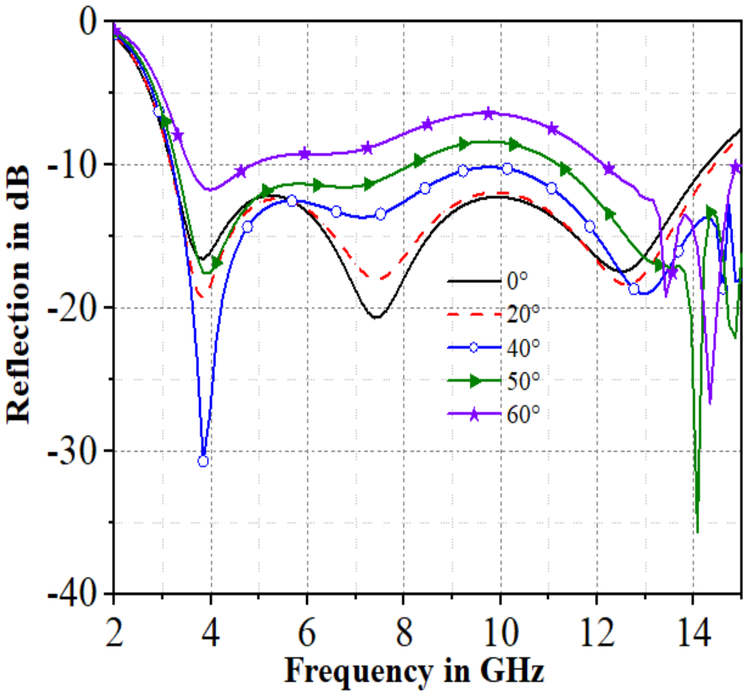

Figure 7: Reflection (TE)

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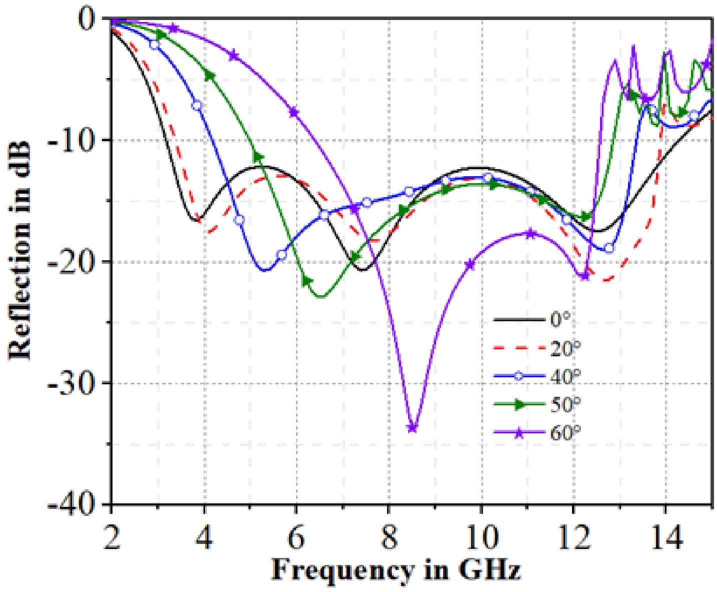

Figure 8: Reflection (TE)

For oblique incidences, a stable reflectivity of -10 dB is observed for incident angles up to 40° for transverse electric (TE) waves and 50° for transverse magnetic (TM) waves throughout the frequency band analysed. Figure 9 and 10 show the relative absorption for angular incidence with reference to normal incidence. It is observed that for the TE mode, the variation due to angular incidence is within 20% in the considered frequency range of 3 GHz to 14 GHz. For the TM mode, stable absorption was observed in the frequency range of 6GHz to 13GHz.

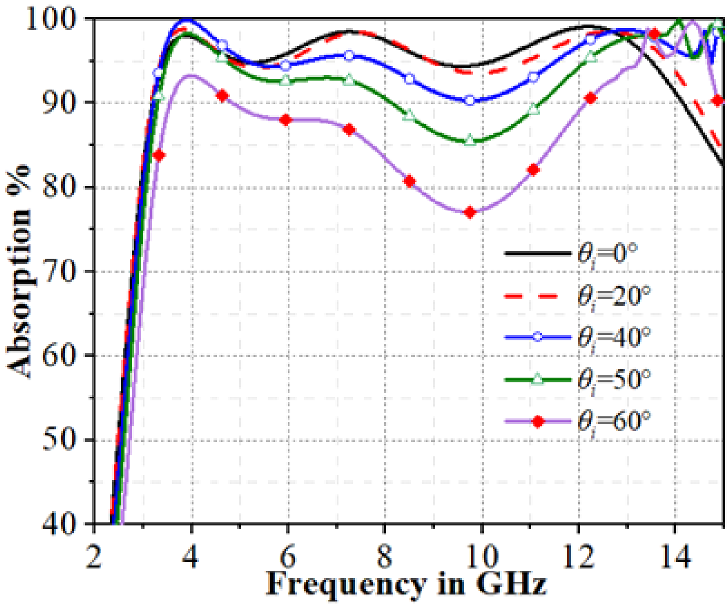

Figure 9: TE mode absorption normalised to 0° incidence

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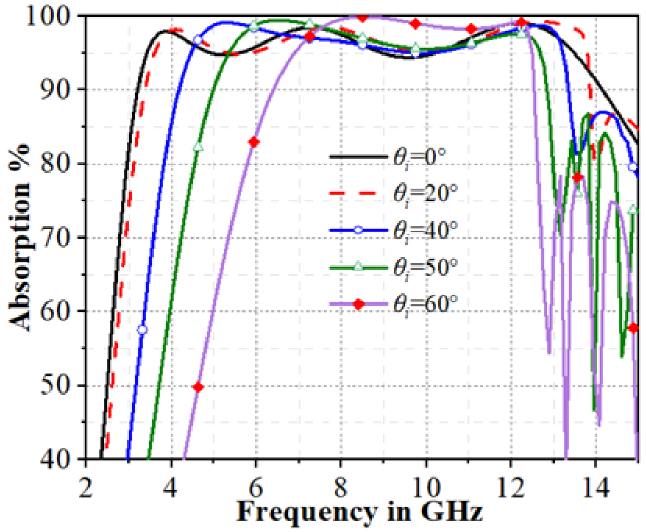

Figure 10: TM mode absorption normalised to 0° incidence

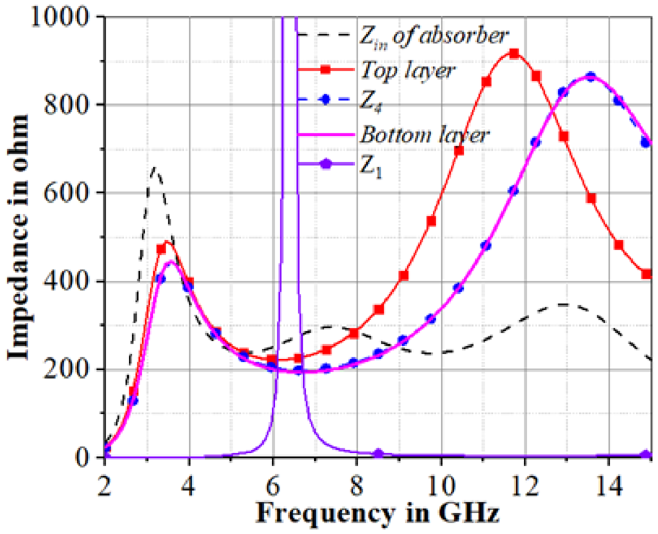

Figure 11: Imaginary part of Impedance

The input impedance of the structure was also analysed. A study was also carried out to determine the contributions from the individual layers of the designed CAA structure. Figure 11 shows the impedance of the total structure and individual layers. The overall structure showed an impedance near the free-space impedance of 377Ω resulting in absorption. It can be seen that the top and bottom layers contribute to this effect.

Figure 12 shows the phase of the wave reflected from the absorbers. It can be observed that the reflection from the total structure is near 180° at approximately 150°, leading to destructive interference.

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MEASUREMENT

The model obtained in the previous section was then realized as an array of 15 × 15-unit cells that formed the FSS in both the top and middle layers as shown in Figure 14. The array size was chosen considering practical measurement parameters, such as antenna dimensions, beamwidth, and physical mounting.

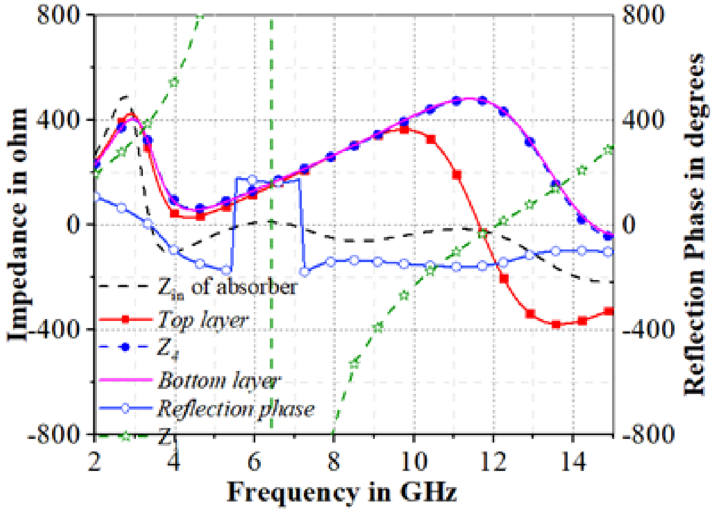

Figure 12: Reflection phase for different layers.

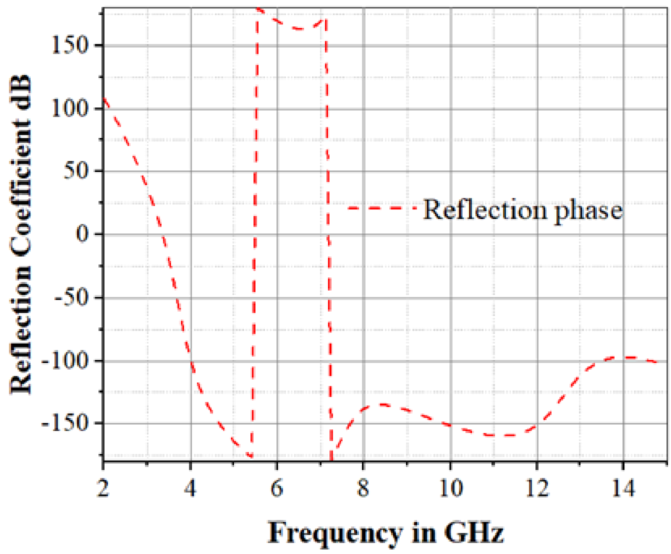

Figure 13: Reflection phase from the CAA

The FSS layers were constructed as PCBs on FR4 substrates. Low-dielectric plastic spacers establish air gaps between the FSSs and bottom continuous plane. SMD thin-film chip resistors were soldered at the resistive gaps. Thin-film chip resistors offer good frequency stability of up to 20GHz.

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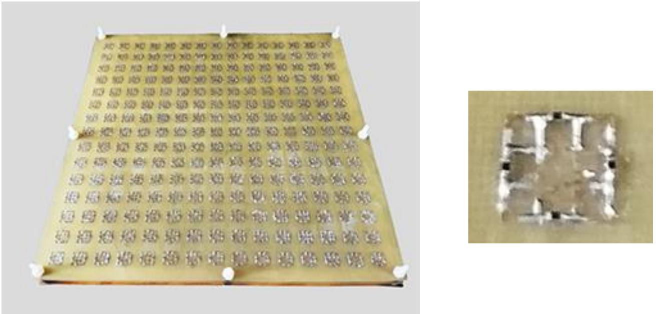
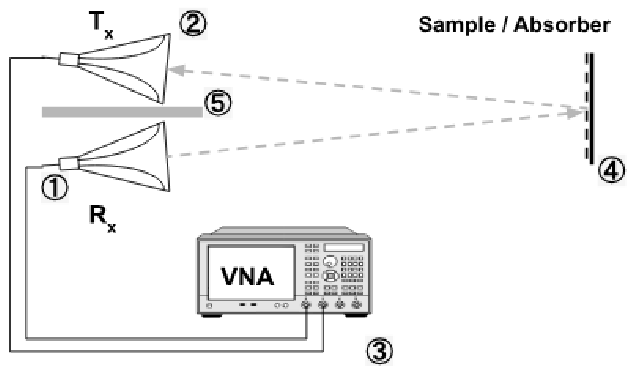


Figure 14:: FSS structure and unit cell

For absorption, free-space measurements of reflection with plane wave incidence were performed.



1. Transmitting Horn Antenna
2. Receiving Horn Antenna
3. Vector Network Analyser
4. Absorber to be measured
5. Form absorber

Figure 13: Measurement Set-up

The measurements were performed inside a ferrite-lined, shielded semi-anechoic chamber to ensure that no external or reflected waves from the side lobes were measured as shown in Figure 15 and Figure 16. Two ridged horn antennas were used for measurements. A calibrated network analyser was used for the measurements. The ridged horn antenna provides a broadband frequency range compared with the narrow band of the horn antenna. The antenna used as the transmitter was connected to Port 1 of the Network Analyzer, and the other antenna was used to receive the reflected wave; that is, the receiver was connected to Port 2. The antennas were kept near each other to achieve near-normal incidence. A foam absorber was placed between the two antennas. The foam absorber reduces the coupling between the two antennas by absorbing electromagnetic waves that would otherwise be

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radiated and received by the adjacent antennas. The network analyser was configured to measure S_{12} to obtain the relative reflection. The measurement sample was maintained at a distance of 1m from the antennas to ensure that it was in the far field from the lowest frequency of measurement for plane wave measurement.

Initially, the measurements were performed using copper as the reflecting element. The results of this measurement were recorded as V_0(dB) and used as a reference. The copper plate was then replaced with the fabricated. FSS structure and the measurements were repeated. The difference between the two readings indicates absorption by the structure.

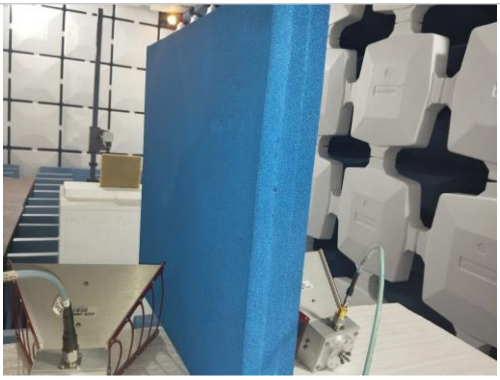

Figure 16: Measurement Set-up

The Figure 17 shows the comparison between the Simulated and Measured results. It is seen that the measured result shows good concurrence with the simulated results.

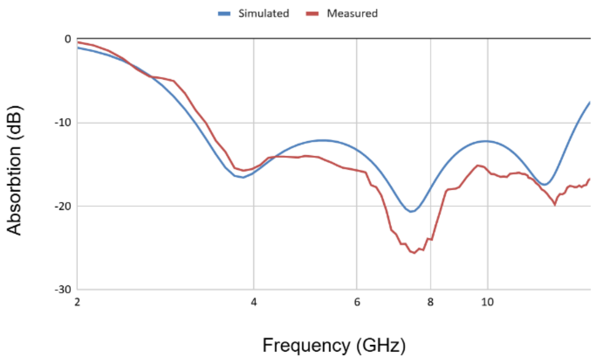

Figure 17: Comparison between the Simulated and Measured results

CONCLUSION

In conclusion, this paper details the creation, simulation, and experimental evaluation of an innovative FSS-based circuit analog absorber, highlighting its proposed application for use in stealth technology. The simulated and experimental results showed a good concurrence. The

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developed CAA measures just 10.5mm and delivers broadband performance across the frequency band of 3 GHz to 14 GHz, covering the C and X Bands utilised in radar systems, with good angular stability. This makes it a strong contender for stealth applications. Future studies might investigate the scalability of this design and its ability to adapt to various frequency ranges, thereby improving the electromagnetic wave absorption technologies.

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