B. TECH. PROJECT REPORT

On

A Comparative Analysis between Circuit Analog and Capacitive Circuit based Broadband Absorbers

BY

Gaurav Singh (160003051)

DISCIPLINE OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY INDORE

2019

A Comparative Analysis between Circuit Analog and Capacitive Circuit based Broadband Absorbers

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of
BACHELOR OF TECHNOLOGY
in
ELECTRICAL ENGINEERING

Submitted by:
Gaurav Singh (160003051)

Guided by:
Dr. Saptarshi Ghosh

INDIAN INSTITUTE OF TECHNOLOGY INDORE

December 2019

CANDIDATE’S DECLARATION

I hereby declare that the project entitled **“A Comparative Analysis between Circuit Analog and Capacitive Circuit based Broadband Absorbers”** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in Electrical Engineering completed under the supervision of **Dr. Saptarshi Ghosh, Assistant Professor, Department of Electrical Engineering, IIT Indore** is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Signature and name of the student with date

CERTIFICATE by BTP Guide

It is certified that the above statement made by the student is correct to the best of my knowledge.

Signature of BTP Guide with date and designation

Preface

This report on **A Comparative Analysis between Circuit Analog and Capacitive Circuit based Broadband Absorbers** is prepared under the guidance of **Dr. Saptarshi Ghosh.**

The aim of this project is to understand the underlying differences between the circuit analog and capacitive circuit absorber, so that better absorbers having wide bandwidth and minimum electrical thickness can be designed. Few designs have been introduced to better understand these concepts. The proposed designs are practically realizable using the existing technologies.

Gaurav Singh
B.Tech. IV Year
Discipline of Electrical Engineering
IIT Indore

Acknowledgement

I wish to thank Dr. Saptarshi Ghosh for his kind support and valuable guidance.

It is his help and support, due to which I was able to complete the design and technical report.

Without his support this report would not have been possible.

Gaurav Singh
B.Tech. IV Year
Discipline of Electrical Engineering
IIT Indore

Abstract

This paper presents two broadband absorber structures based on circuit analog (CA) and capacitive circuit (CC) concepts. Each of the proposed designs is made of multiple resistive layers separated by an air spacer and terminated by a ground plane. The CA structure employs square resistive loops printed on dielectric substrates, whereas square resistive patches are being used in the CC geometry. The proposed CA absorber exhibits 142.08% absorption bandwidth (for absorptivity > 90%) at the expense of a large thickness ($0.296\lambda_o$, λ_o being the wavelength corresponding to the centre absorption frequency). On the other hand, the CC absorber provides 76.41% absorption bandwidth corresponding to a thinner substrate ($0.135\lambda_o$). Both the designs are polarization-independent and angularly stable, despite having small profile, low resistance, and simple design. A comparison has also been made between the CA and CC concepts, thereby highlighting their performances over one another.

Table of Contents

List of Figures

Chapter 1

Introduction

Electromagnetic absorbers are the passive devices where the incident electromagnetic energy gets absorbed due to different types of losses (conducting, dielectric or both). After the advent of radar, there has been tremendous research undergoing to design structures that are capable of absorbing radio waves. The rapid development of various wireless electronic devices requires an extensive knowledge of electromagnetic interference and materials that provide cheap and effective shielding from the unwanted radiation. Electromagnetic absorbers find several applications in different domains. One of the important applications in the microwave area is microwave bolometer, where the incident wave is absorbed and the temperature rise occurs, providing a measure of incident power of electromagnetic radiation. They are also useful in solar cell applications where the incident solar radiation is converted into electrical power. Another application of electromagnetic absorber in the terahertz region is the thermal detector. Absorbers also find applications in radio frequency identifier (RFID) system, where the digital bits are represented by signals with different frequencies. Absorption is necessary to detect the particular bit corresponding to the desired frequency of detection. In defense purpose, microwave absorbers find their utmost importance in stealth technology applications. The lightweight absorbing materials are used in this method to “hide” the target. When the target is coated with microwave absorber, the radar cross-section (RCS) decreases, which is a measure of reflected power from the target in radar detection system. The design of these absorbers vary from one application to the other. For instance, light weight and rigid designs exhibiting good absorption over wide frequency range are desirable in aeronautics applications.

The Salisbury screen, one of the very first absorbers, has been designed using a resistive sheet placed at a distance of quarter-wavelength above the conducting plate [1]. Although the screen has simple design topology, its bandwidth is finite due to quarter-wavelength criteria. To overcome this limitation, Jaumann absorber has been introduced employing multiple resistive sheets [2]. But this increases the overall thickness, thus being not suitable for practical applications. In 2000, K. N. Rozanov determines the ultimate thickness to bandwidth ratio, known as the Rozanov limit that is practically achievable by the absorbers [3]. Subsequently, various types of wideband absorbers have been presented in the last few years, aiming to reach the Rozanov limit. The circuit analog (CA) absorber, one of the proposed concepts, can be realized by appropriately depositing the resistive and conductive patterns on a dielectric substrate [4]-[6]. However, this CA has large electrical thickness due to the constraint of quarter-wavelength condition that needs to be maintained at the centre frequency of the absorption bandwidth. To overcome this drawback, the capacitive circuit (CC) absorber has recently been developed [7]-[9], where the existing bandstop resonating mechanism of CA absorber is replaced by the low pass element in CC geometry.

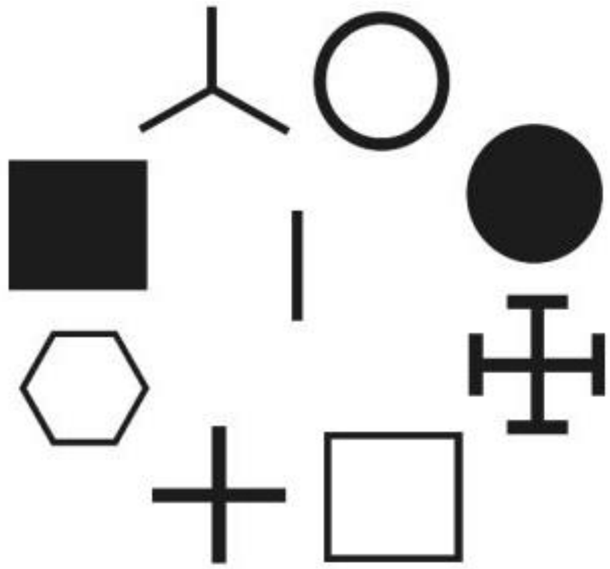
The wideband absorber, made either using CA or CC concept, is typically realized by the use of resistive elements in periodic arrangement, and the geometry is terminated by a ground plane. The resistive components absorb the incident electromagnetic (EM) wave over a large frequency, thus providing wideband absorbers. This finite resistance can be attained by several ways, viz. use of lumped resistors [10], [11], implementation of patterned resistive sheet [12], [13], and painting of resistive inks [14], [15]. Mounting of lumped resistors in a large periodic structure is subjected to manufacturing constraints, and patterning of resistive sheet is expensive. In contrast, resistive ink can easily be painted on a substrate using low-cost screen printing method [16], [17] and thus has been adopted in the proposed designs.

In this paper, two different approaches, viz. CA and CC concepts have been exploited to design two different broadband absorbers. The CA absorber exhibits large absorption bandwidth, at the expense of higher electrical thickness, whereas the CC absorber has smaller thickness giving considerable bandwidth. Both the proposed designs are polarization-independent as well as angularly stable up 30^{o} angle of incidence.

Chapter 2

FSS Structure

Frequency selective surfaces (FSSs) in general, are periodic metal-dielectric arrays often arranged in a two dimensional planar surface. The frequency response of an FSS is mainly dependent on the design of the metallic pattern present in one period (unit cell) provided that the array size is ideally infinite. Traditionally, FSSs are designed using various elements such as patch, dipole, slot, ring, loop, etc., as shown in figure below



Although there is a wide variety of available shapes, FSSs work on a similar principle of operation that can be explained by the resonance phenomenon. When a plane EM wave is incident on a FSS structure, the elements of the periodic array resonate at a specific frequency depending on the designed geometry, properties of the material in use and the orientation of the incident EM wave. The layout of the metallic elements controls the effective capacitance and inductance of the design, whereas the orientation of the incident wave (polarization and incident angle) limits its exposure on the structure.

During the numerical simulation of a FSS structure, a single unit cell design is considered with suitable periodic boundary conditions to mimic the ideal infinite two dimensional planar arrangement.

With the onset of FSS-based design tactics, absorber structures having reduced size and improved performance have been possible to design. As mentioned previously, FSS based absorbers consist of designed metallic patterns printed on a dielectric substrate with a bottom ground plane (made of copper) in most cases. This ensures zero transmission. Therefore, the absorptivity of the structure can be expressed as:

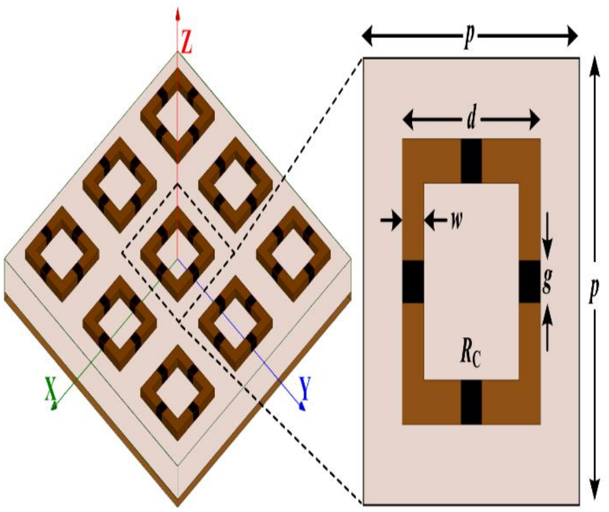
$$A(\omega) = 1-|S_{11}(\omega)|^2-|S_{21}(\omega)|^2$$

where $S_{11}(\omega)$ and $S_{21}(\omega)$ are the reflectivity and the transmitivity of the absorber, at given frequency (ω). To maximize $A(\omega)$, $S_{21}(\omega)$ is made zero by placing the ground copper plane. $S_{11}(\omega)$ can be minimized if the input impedance of the absorber is properly matched with that of free space. Since the input impedance can be precisely controlled by varying different parameters of the FSS design, perfect impedance matching leading to high absorption at a desired frequency can be made possible. This results in a FSS based absorber, which has the advantages of simplified structural geometry, reduced thickness and improved angular stability

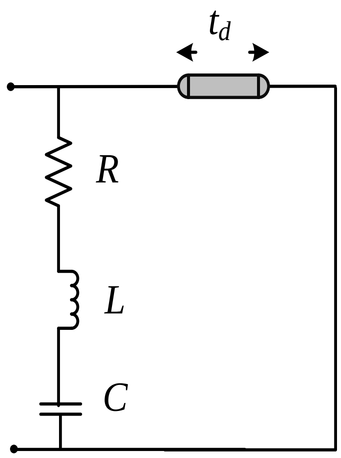
Chapter 3

Circuit Analog Absorber

Circuit Analog absorber is an upgradation to the Salisbury Screen and Jaumann Absorber, which contains a resistive element as well as reactive element as well. A layer having lossy properties is placed at a quarter-wavelength distance above the conducting plate for CA absorbers. The layer having lossy properties can be realised by either resistive sheet or resistor-loaded frequency-selective designs. Circuit Analog absorber can be represented by an equivalent circuit. The corresponding circuit for a CA absorber usually consists of series RLC. This equivalent circuit is only an approximation that explains the mechanisms of the CA absorber.



A circuit analog absorber



Equivalent circuit model

Different Types of Circuit Analog Absorbers

Circuit Analog Absorbers

Lumped Resistors

Advantages: Low cost

Disadvantages:

- Time-consuming to solder large number of lumped resistors
- It needs precise accuracy, if opted for manual soldering

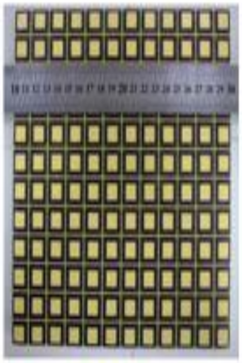
Resistive Ink Coated Dielectric Sheets

Advantages: High accuracy

Disadvantages:

- Expensive due to complicated fabrication
- Highly sensitive and delicate; difficult to use in outdoor applications

Resistive Paints



Advantages:

- Low cost
- Moderate accuracy
- Easy Fabrication
- Roll-to-roll fabrication

Proposed Design For Circuit Analog Absorber

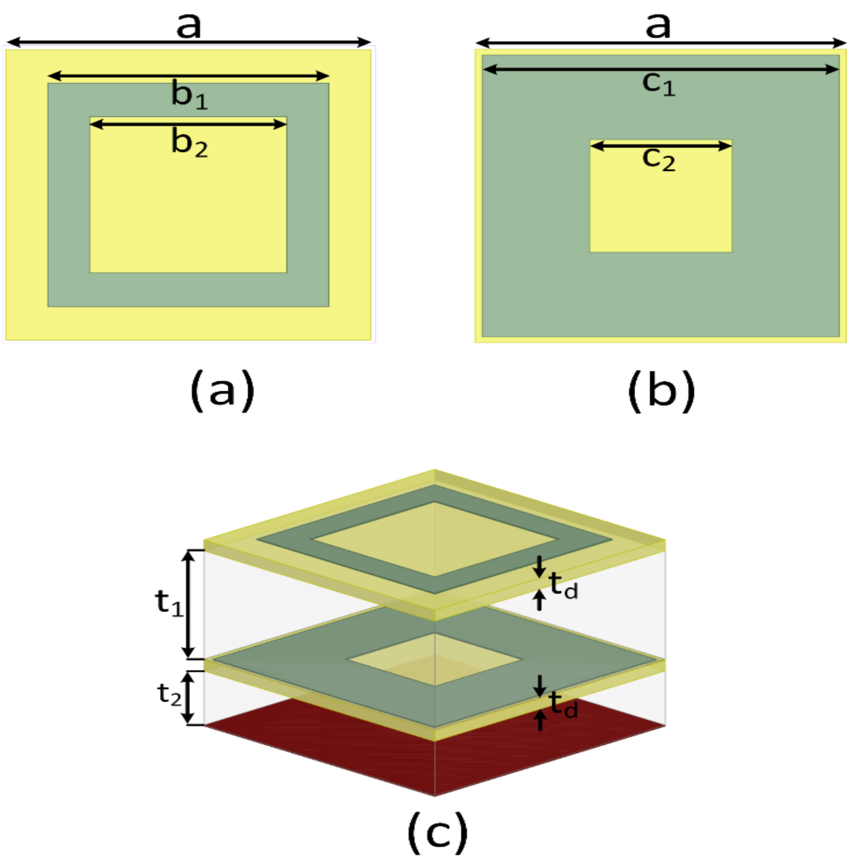


Fig.1 Proposed CA absorber. (a) Top view of top resistive layer, (b) top view of bottom resistive layer, and (c) oblique view.

Fig. 1 illustrates the geometry of the suggested CA absorber under investigation. The structure is double-layered, each layer having square resistive loop printed on a substrate. The resistance and inductance are obtained from the square loops, whereas the capacitance is generated from the gaps between the unit cells. Dielectric used is FR4, which has relative permittivity (ε_r) of 4.4, loss tangent (*tan* δ) of 0.02, and thickness of t_d. The top and bottom layer is separated from each other by an air spacer (having thickness of t_1), while a conducting ground plane is separated from the bottom substrate by another air spacer (having thickness of t_2). Y Shield HSF-74 electro-conductive shielding paint is used for making the resistive loop patterns. The conductivity of the paint is 664 S/m, and the thickness of the paint is considered as 40 μm. The bottom ground plate is made of copper having conductivity $\sigma = 5.8 \times 10^7$ S/m and thickness of 37 μm. The unit cell dimensions are as follows: a = 13 mm, b_1 = 10 mm, b_2 = 7 mm, c_1 = 12.5 mm, c_2 = 5 mm, t_1 = 5 mm, t_2 = 2.5 mm, and t_d = 0.5 mm.

Response Obtained

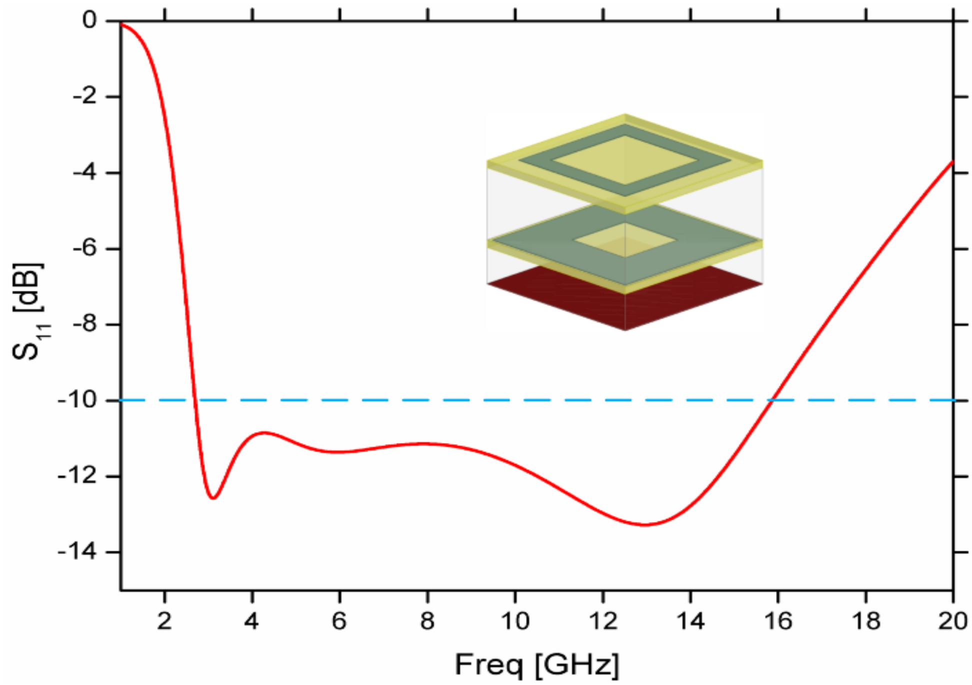


Fig. 2. Simulated reflection coefficient (S_{11}) of the proposed CA absorber.

Fig 2 shows the simulated reflection-coefficient response of the suggested CA structure, which gives reflectivity below -10 dB from 2.69 to 15.89 GHz. Since there is no transmission because of the copper plate at the back, this reflectivity response corresponds to above 90% absorptivity for the same frequency range. Thus the structure provides a fractional bandwidth of 142.08% with respect to the centre frequency 9.29 GHz, at the expense of 0.296 λ_0 electrical thickness.

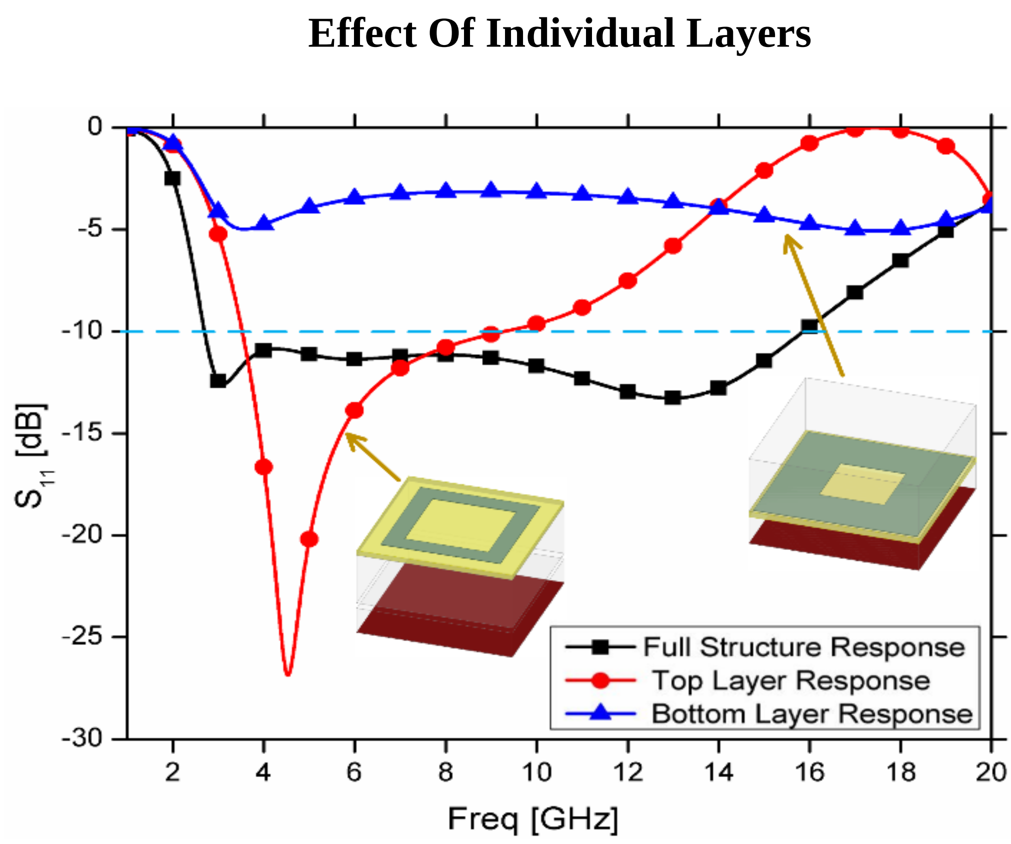


Fig. 3. Simulated reflection coefficient of the proposed CA absorber for different layers.

To show the impact of the individual layers, the top and bottom resistive layers have been separately analyzed in Fig. 3. When the bottom resistive layer (along with the ground plane) is studied while removing the top resistive layer and its associated FR4 substrate, the structure exhibits high reflectivity (around -4 dB) over the frequency range of 2.97 to 19.98 GHz. On the other hand, when the bottom resistive layer (and its associated FR4 substrate) has been removed to study the top resistive layer, it shows a -10 dB reflection coefficient bandwidth in the frequency range 3.52 to 9.30 GHz. Thus, the individual layers don't contribute to a single portion of the overall response as in case of a single-layered structure, but the two layers act in synergy with each other to create the overall wideband absorption. This can be attributed to the fact that the two layers are at different distance from the ground plane and they have different patterns in terms of dimension.

Response For Different σ Of Resistive Paint

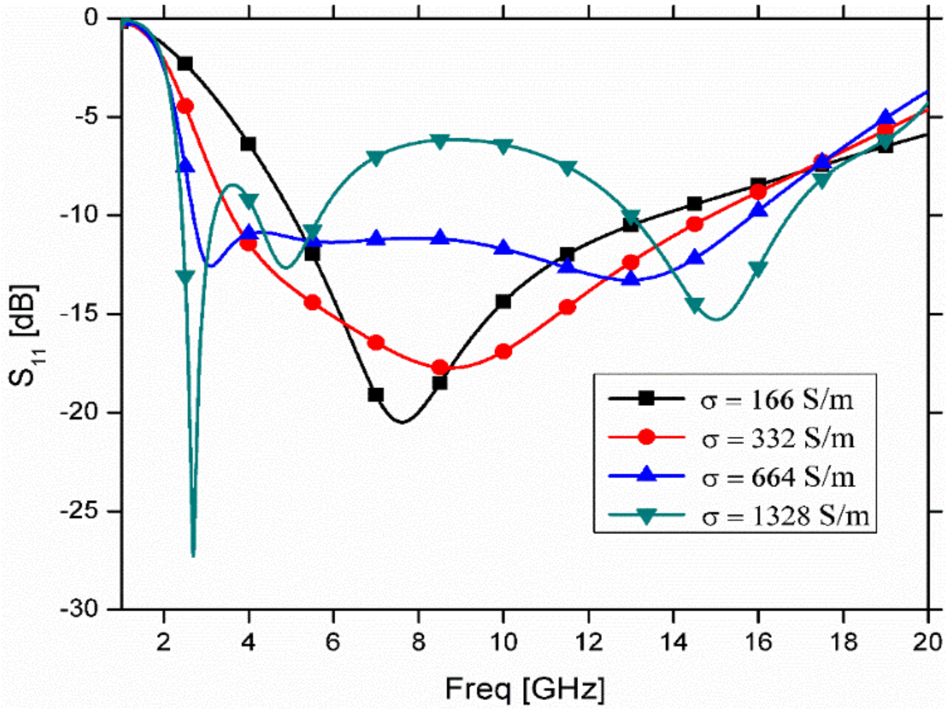


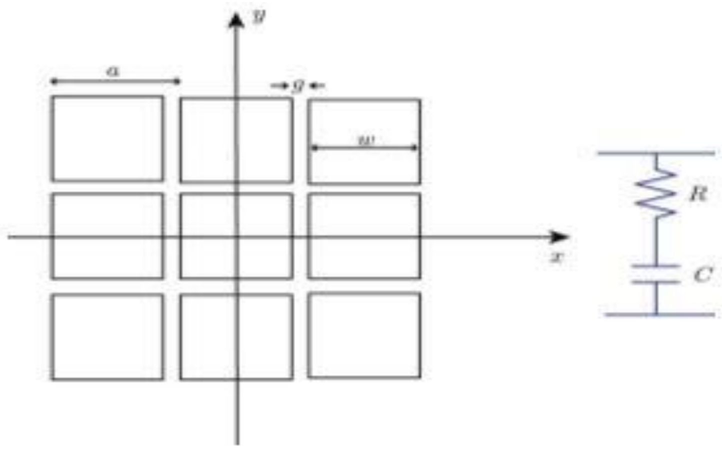
Fig. 4. Simulated reflection coefficient of the proposed CA absorber for different values of conductivity (σ) of the resistive ink.

To observe the contribution of the resistive sheets, the conductivity of the square loops, present in both the layers have been varied, as shown in Fig. 4. As the conductivity is reduced, the resistance provided by the two pattern increases. While increasing the resistance, the absorptivity subsequently increases, but the bandwidth gradually reduces. Thus, there exists a trade-off for any particular geometry, to achieve a desired absorptivity with larger bandwidth and minimum electrical thickness.

Chapter 4

Capacitive Circuit Absorber

The previous section shows that in a CA absorber, a trade-off has to be made between the absorption bandwidth and the electrical thickness. A CA absorber generally consists of a series/parallel *RLC* circuit, where the resonance is generated from the structure. This causes an additional problem of creating anti-resonance and higher order harmonics. This not only deteriorates the quality of absorption in the higher frequency, but also puts the limitation in the absorption bandwidth, for a finite thickness. On the contrary, a CC absorber, made from a combination of RC circuits (with a very small valued inductance), is free from the above limitations, and thus can offer better flexibility instead of trade-off problem.



Patch used in capacitive circuit method and its equivalent model

Proposed Design For Capacitive Circuit Absorber

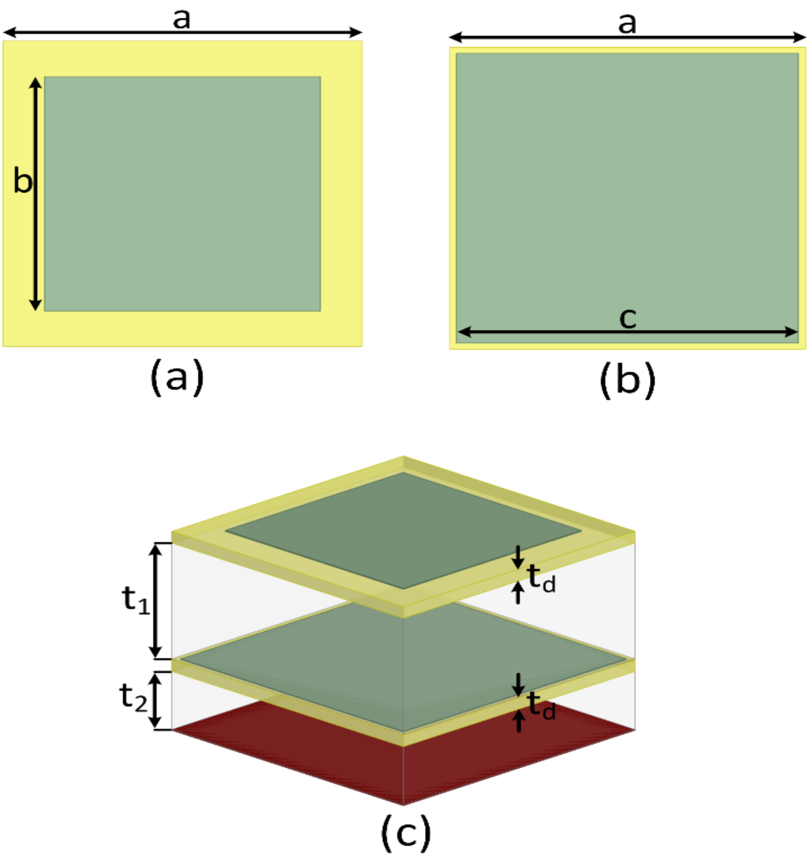


Fig. 5. Proposed CC absorber. (a) Top view of top resistive layer, (b) top view of bottom resistive layer, and (c) oblique view.

To further explore the above concept, the previously proposed CA structure has been slightly modified to design a CC absorber, as shown in Fig 5. The resistive square loops in both the top and bottom layers are replaced by square resistive patches. This arrangement significantly reduces the inductance of the CC absorber in comparison to the earlier CA absorber. The resistive patches exhibit large resistance (R) and the gap between successive unit cells provide the requisite capacitance (C), thus resulting in a RC circuit. The unit cell dimensions of the proposed CC structure are as follows: a = 13 mm, b = 10 mm, c = 12.5 mm, t_1 = 5mm, t_2 = 2.5 mm, and t_d = 0.5 mm.

Response Obtained

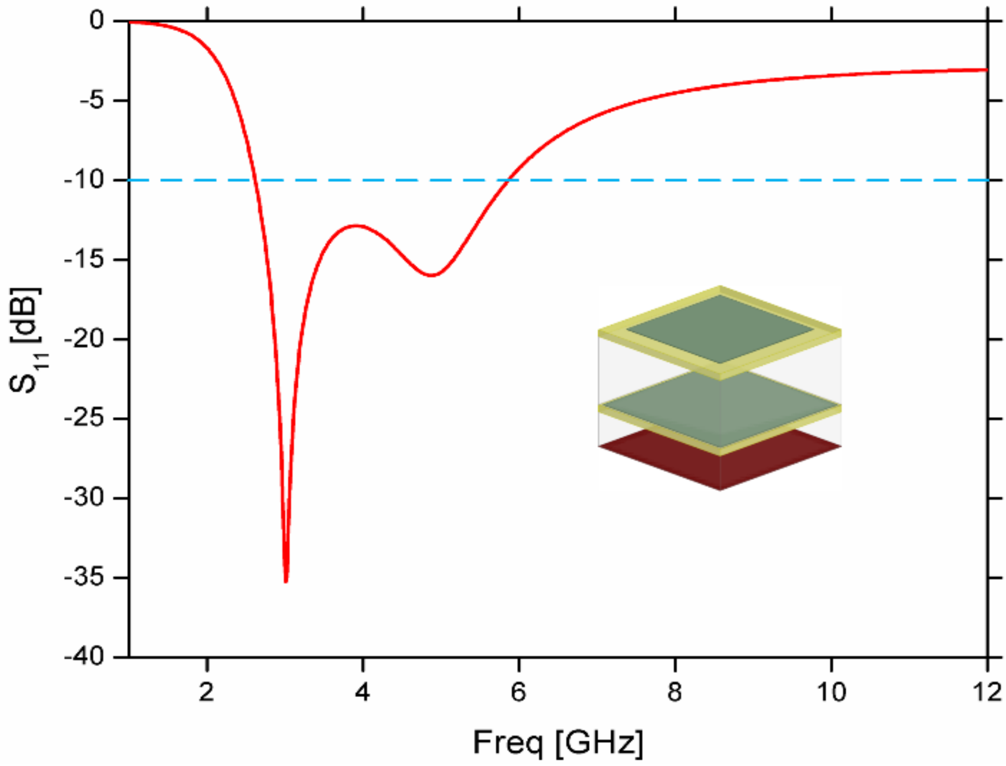


Fig. 6. Simulated reflection coefficient (S_{11}) of the proposed CC absorber.

As observed from Fig 6, the proposed CC structure exhibits reflection coefficient below -10 dB from 2.62 to 5.86 GHz. This gives a fractional bandwidth of 76.41% with respect to the central frequency 4.24 GHz. This smaller bandwidth, as compared to the previous CA structure, is resulted due to the use of same resistance (Y Shield HSF-74) for similar thickness profile. However, the overall electrical thickness of the structure has been drastically improved from $0.296\lambda_0$ to $0.135\lambda_0$. Thus, the proposed CC absorber can be used in some specific applications, where lower electrical thickness is required instead of wideband absorption.

Response For Oblique Incident Angles

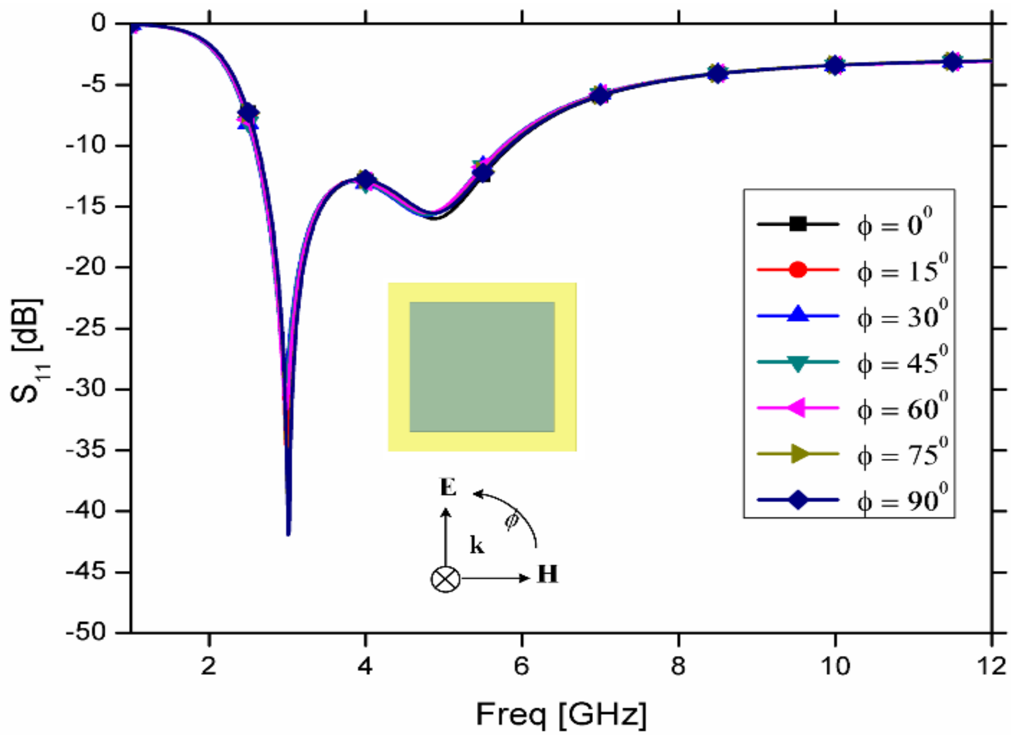


Fig. 7. Simulated reflection coefficient (S_{11}) of the proposed CC absorber for different values of polarization angle under normal incidence.

The design is analysed for varying polarization angles in Fig. 7 and the identical reflection responses confirm that the proposed CC absorber design is polarization-independent, owing to its four-fold symmetry.

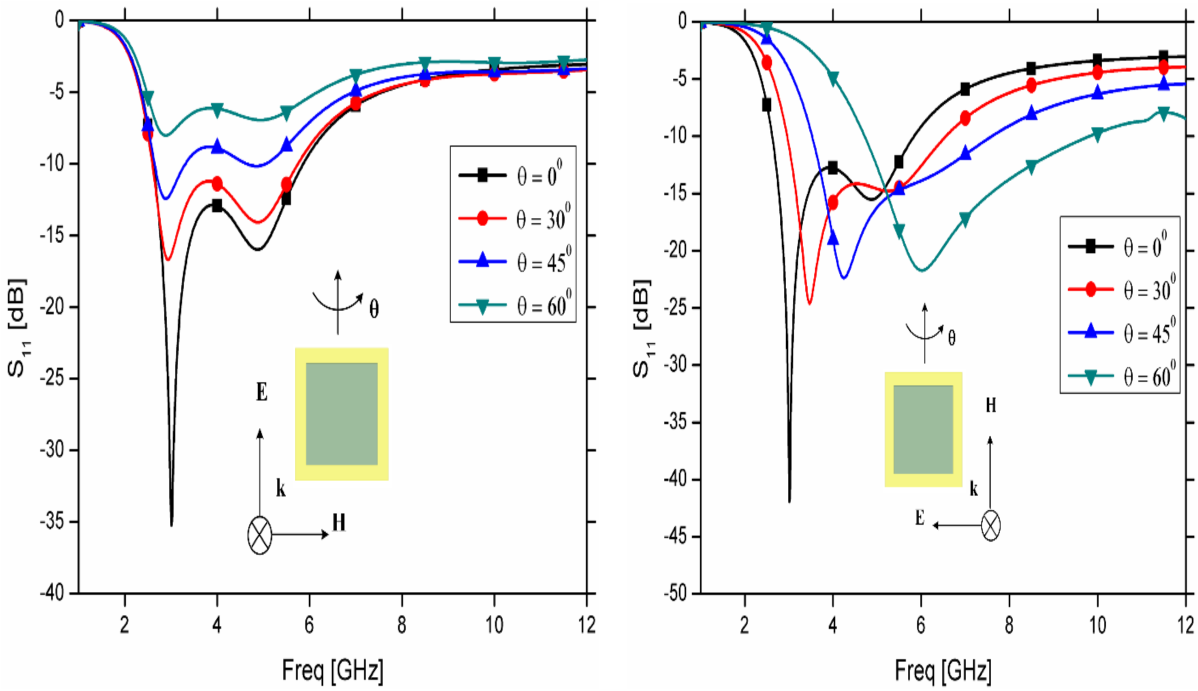


Fig. 8. Simulated reflection coefficient (S_{11}) of the proposed CC absorber for different values of incident angles under (a) TE mode, and (b) TM mode.

The suggested design has also been investigated for various incident angles under both transverse electric (TE) and transverse magnetic (TM) mode, as depicted in Fig. 10. While studied under TE mode, the structure is found to be angularly stable till 40° angle of incidence. With increasing angle, the absorptivity gradually deteriorates. In contrast, the absorption bandwidth slowly drifts to higher frequency region with increasing angle for TM polarized wave.

Response For Different σ Of Resistive Paint

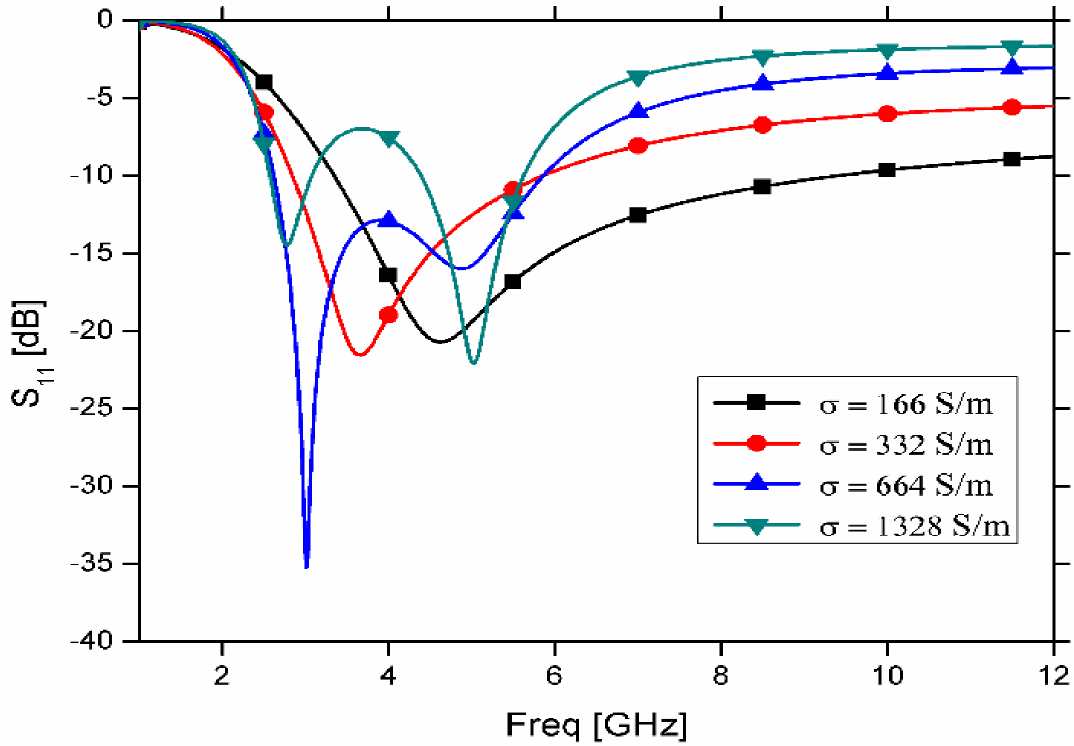


Fig. 9. Simulated reflection coefficient of the proposed CC absorber for varying values of conductivity (σ) of the resistive ink.

Similar to the previous CA structure, the absorptivity as well as the absorption bandwidth of the proposed CC absorber can be tuned by varying different parameters of the geometry. One of the important parameters is the resistance of the ink used in the geometry. The sheet resistance (R_S) of the paint can be controlled by the equation given as: $R_S = 1/(\sigma t)$, where σ is the conductivity of the ink, and t is the paint thickness. Thus, either by decreasing the conductivity or by reducing the thickness of the ink, the resistivity as well as the absorption response can be significantly enhanced. Fig.9 illustrates the reflection coefficient response of the suggested CC absorber for varying conductivity of the resistive paint, and the graph supports the above conclusion. The same response can also be obtained while reducing the thickness of the pattern.

Modified Design (1) Of Capacitive Circuit Absorber Using Reduced Paint Thickness

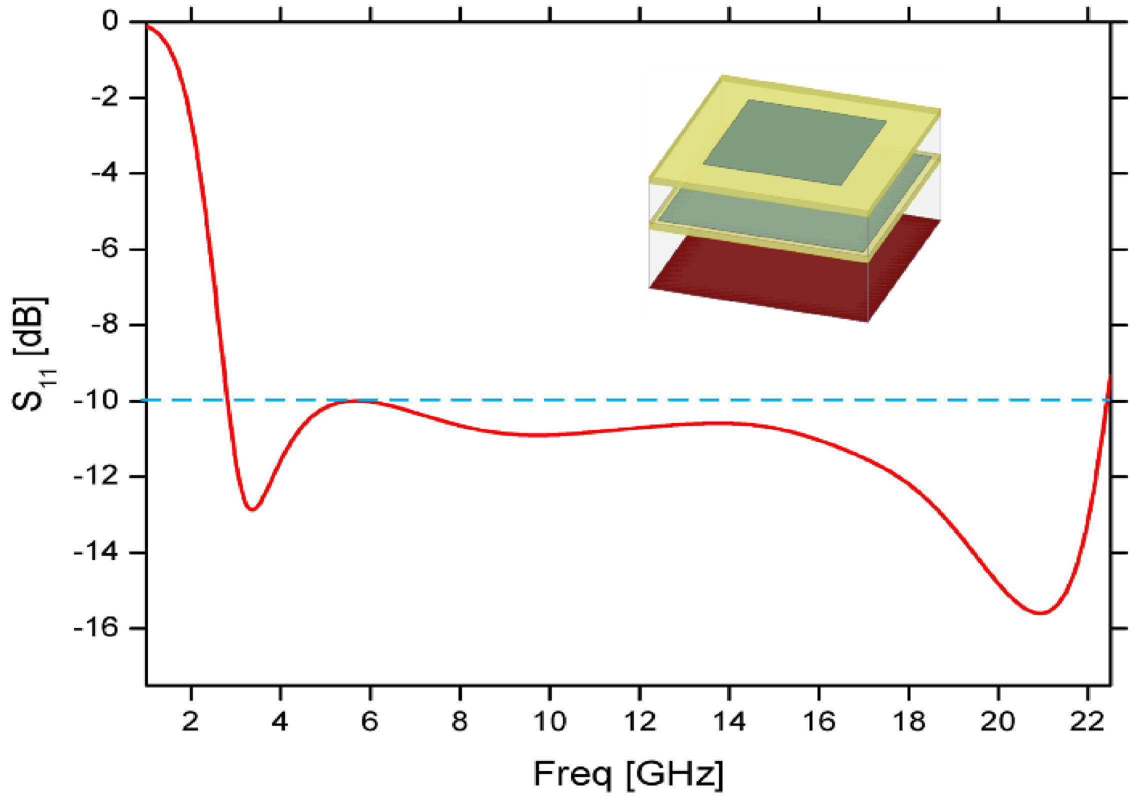


Fig. 10. Simulated reflection coefficient (S_{11}) of the modified CC absorber (1).

Another CC absorber has been designed with similar configuration, where the resistive ink thickness has been modified along with slight change in the geometric dimensions of the structure. This results in an improved wideband response, having reflectivity below -10 dB from 2.88 to 22.31 GHz that corresponds to absorption bandwidth of 154.26%, as observed in Fig. 8. Here, the paint conductivity is kept constant, but the thickness is reduced from 40 µm to 16 µm. The other parameters of the modified design are as follows: a = 13 mm, b = 8 mm, c = 12.2 mm, t_1 = 3 mm, t_2 = 4.5 mm, and t_d = 0.5 mm.

Modified Design (2) Of Capacitive Circuit Absorber Using Meander Concept

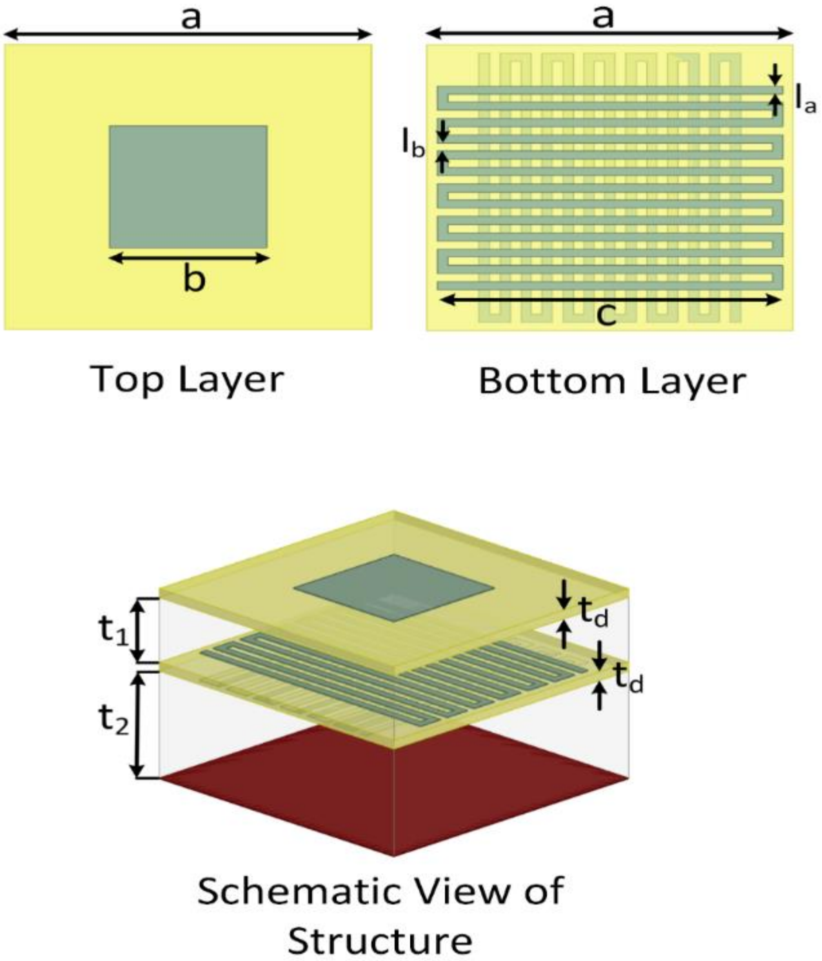


Fig. 11. Proposed modified CC absorber (2) : (a) Top view of top resistive layer, (b) top view of bottom resistive layer, and (c) oblique view.

The modified design 1 gives wide bandwidth, but it uses paint thickness of 16 µm which is difficult to fabricate. To overcome this drawback a new design is poposed which uses the meander concept. The meander provides large capacitance and very low inductance. The new design eliminates the need of using reduced paint thickness hence it is practically feasible. The dimensions of the new proposed design are as mentioned: a = 14 mm, b = 6 mm, c = 13.2 mm, l_a= 0.4mm, l_b= 0.4mm, t_1 = 2.9 mm, t_2 = 4.8 mm, t_d = 0.4 mm and paint thickness= 40 µm

Response Obtained For Modified Design (2)

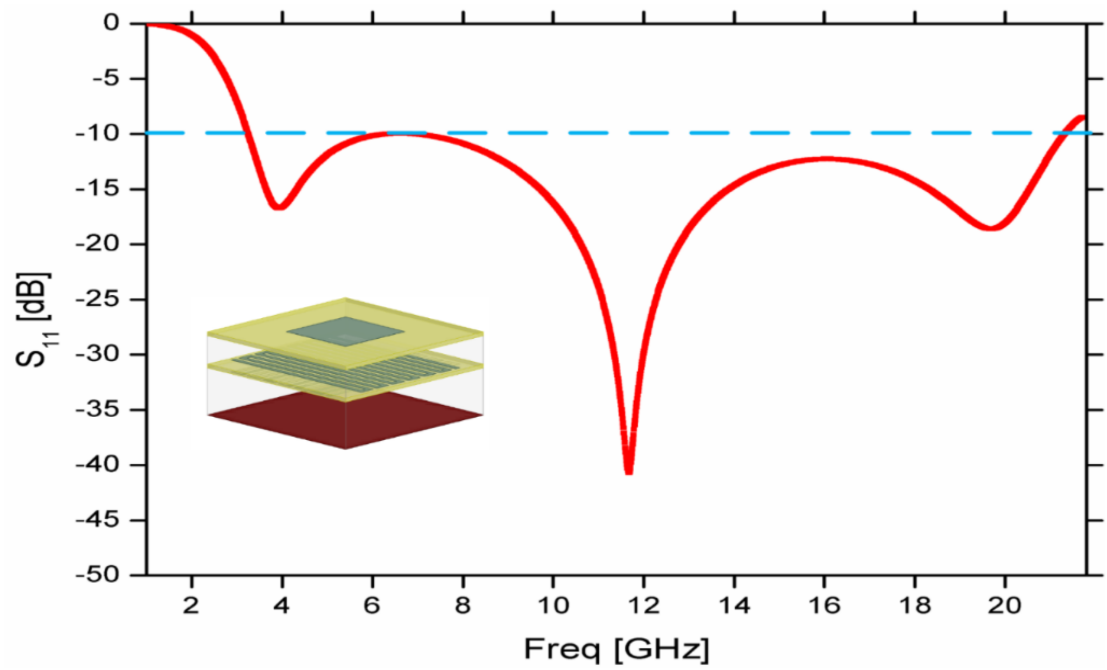
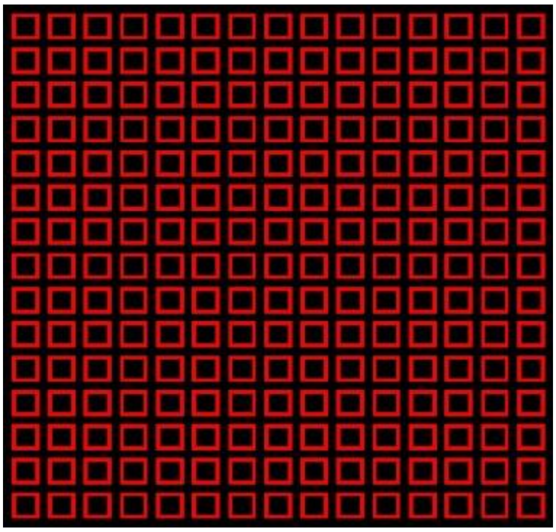


Fig. 12. Simulated reflection coefficient (S_{11}) of the modified CC absorber (2).

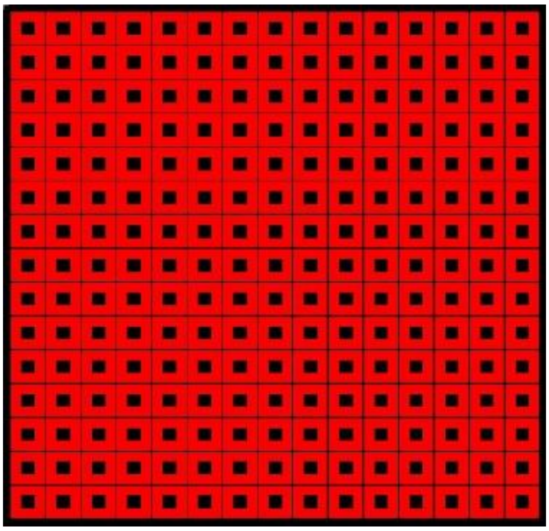
The response shows reflectivity below -10 dB from 3.24 to 21.32 GHz that corresponds to absorption bandwidth of 147.23% at central frequency 12.28 GHz, as observed in Fig. 12.

Chapter 5

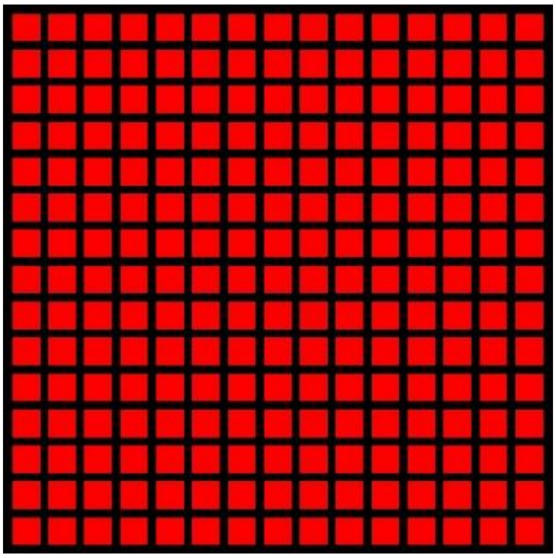
Gerber Files



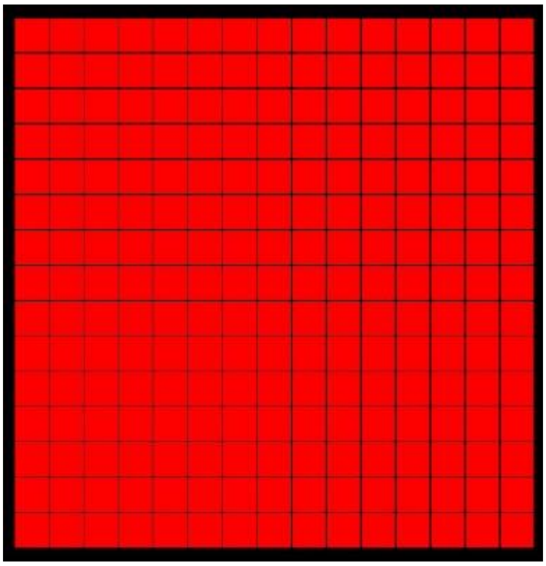
Top Layer CA



Bottom Layer CA



Top Layer CC



Bottom Layer CC

The Gerber Files have been made using HFSS and ADS software and the designs have been sent for fabrication.

Conclusion and Future Scope

This paper investigates two different concepts (CA and CC) to realize wideband absorber structures. The proposed designs employ vertically stacked resistive layers to absorb the incident EM wave over wide frequency span. Both the structures can provide broadband absorption at the expense of finite substrate thickness; CA technique focuses on large bandwidth, whereas CC method aims to improve the electrical thickness. While compared with earlier reported wideband absorbers, both the proposed structures have improved absorption responses either in terms of fractional bandwidth or electrical thickness, as observed in table below. The geometries can be fabricated using screen printing technique and the measured responses can be verified with the simulated results.

TABLE . COMPARISON WITH OTHER BROADBAND ABSORBERS

Absorber structure	**Method employed**	**Thickness (at f_l)**	**Fractional bandwidth**
[8]	CC with lumped resistor	$0.076\ \lambda_l$	82.5%
[9]	CA+CC with lumped resistor	$0.067\ \lambda_l$	63.3%
[10]	CA with lumped resistor	$0.123\ \lambda_l$	75.2%
[11]	CA with lumped resistor	$0.158\ \lambda_l$	63.4%
[13]	CA with resistive sheet	$0.101\ \lambda_l$	83.1%
[15]	CC with resistive sheet	$0.095\ \lambda_l$	75.7%
Proposed Works	**CA with resistive sheet**	$\mathbf{0.086\ \lambda_l}$	**142.1%**
	CC with resistive sheet	$\mathbf{0.083\ \lambda_l}$	**76.4%**
	CC with resistive sheet (modified 1)	$\mathbf{0.092\ \lambda_l}$	**154.3%**
	CC with resistive sheet (modified 2)	$\mathbf{0.101\ \lambda_l}$	**147.2%**

In the future works improvements can be made to shift the absorption bandwidth in the lower frequency range, so as to achieve minimum electrical thickness.

References

[1] W. W. Salisbury, "Absorbent body for electromagnetic waves," *U.S. Patent* 2,599,944, 1954.

[2] E. F. Knott, J. F. Shaeffer, and M. T. Tuley, *Radar Cross Section*, 2nd ed. Raleigh, NC, USA: SciTech, 2004.

[3] K. N. Rozanov, "Ultimate thickness to bandwidth ratio of radar absorbers," *IEEE Trans. Antennas Propag.*, vol. 48, no. 8, pp. 1230-1234, 2000.

[4] Y. Shang, Z. Shen, and S. Xiao, "On the design of single-layer circuit analog absorber using double-square-loop array," *IEEE Trans. Antennas Propag.*, vol. 61, no. 12, pp. 6022-6029, 2013.

[5] M. Li, S. Q. Xiao, Y.-Y. Bai, and B.-Z. Wang, "An ultrathin and broadband radar absorber using resistive FSS," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 748-751, 2012.

[6] S. Ghosh, S. Bhattacharyya, and K. V. Srivastava, "Design, characterisation, and fabrication of a broadband polarization-insensitive multilayer circuit analogue absorber," *IET Microw. Antennas Propag.*, vol. 10, no. 8, pp. 850–855, 2016.

[7] A. Kazem Zadeh and A. Karlsson, "Capacitive circuit method for fast and efficient design of wideband radar absorbers," *IEEE Trans. Antennas Propag.*, vol. 57, no. 8, pp. 2307-2314, 2009.

[8] Y. Han and W. Che, "Low-profile broadband absorbers based on capacitive surfaces," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 74-78, 2017.

[9] M. Saikia and K. V. Srivastava, "Design of thin broadband microwave absorber using combination of capacitive and circuit analog absorbers," *IEEE Indian Conf. Antennas Propog. (InCAP)*, Hyderabad, India, pp. 1-4, 2018.

[10] M. Yoo and S. Lim, "Polarization-independent and ultrawideband metamaterial absorber using a hexagonal artificial impedance surface and a resistor-capacitor layer," *IEEE Trans. Antennas Propag.*, vol. 62, no. 5, pp. 2652-2658, 2014.

[11] S. Ghosh, S. Bhattacharyya and K. V. Srivastava, “Design and analysis of a broadband single layer circuit analog absorber,” *46th European Microwave Conference (EuMC)*, London, pp. 584-587, 2016.

[12] Y. Okano, S. Ogino, and K. Ishikawa, “Development of optically transparent ultrathin microwave absorber for ultrahigh-frequency RF identification system,” *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 8, pp. 2456–2464, 2012.

[13] H. Sheokand *et al.*, “Transparent broadband metamaterial absorber based on resistive films,” *J. Appl. Phys.*, vol. 122, art. no. 105105, 2017.

[14] H.-B. Zhang *et al.*, “Resistance selection of high impedance surface absorbers for perfect and broadband absorption,” *IEEE Trans. Antennas Propag.*, vol. 61, no. 2, pp. 976–979, Feb. 2013.

[15] J. Lee and B. Lee, “Design of thin microwave absorbers using capacitive screen,” *International Workshop Antenna Tech. (iWAT)*, Seoul, pp. 199-201, 2015.

[16] F. Costa, A. Monorchio, and G. Manara, “Analysis and design of ultrathin electromagnetic absorbers comprising resistively loaded high impedance surfaces,” *IEEE Trans. Antennas Propag.*, vol. 58, no. 5, pp. 1551–1558, 2010.

[17] Y. Tayde, M. Saikia, K. V. Srivastava, and S. A. Ramakrishna, “Polarization-insensitive broadband multilayered absorber using screen printed patterns of resistive ink,” *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 12, pp. 2489-2493, 2018.

[18] N. Hakla, S. Ghosh, and K. V. Srivastava, “Design of low profile broadband capacitive circuit absorber, *IET Electron. Lett.*, vol 52, no. 22, 2016.