B. TECH. PROJECT REPORT

On

An Ultrathin Miniaturized FSS-Based Rasorber Design based on 2.5-Dimensional Geometry

BY

Vaibhav kumar (160002058)

DISCIPLINE OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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An Ultrathin Miniaturized FSS-Based Rasorber Design based on 2.5-Dimensional Geometry

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:
Vaibhav kumar (160002058)

Guided by:
Dr. Saptarshi Ghosh

INDIAN INSTITUTE OF TECHNOLOGY INDORE
December 2019

CANDIDATE'S DECLARATION

We hereby declare that the project entitled **"An Ultrathin Miniaturized FSS-Based Rasorber Design based on 2.5-Dimensional Geometry"** 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, 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(s)

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 designing **An Ultrathin Miniaturized FSS-Based Rasorber based on 2.5-Dimensional Geometry** is prepared under the guidance of Dr. Saptarshi Ghosh.

Through this report I have tried to design a rasorber structure that can transmit low frequency electromagnetic (EM) wave and can absorb EM wave at high frequency. The designed structure is ultra-thin as well as miniaturized, thus becoming much convenient during the commercial production of the structure. I have tried to the best of my ability and knowledge to explain the content in a lucid manner. I have also added 3-D models and figures to make it more illustrative.

Vaibhav kumar (160002058)

B.Tech. IV Year

Discipline of Electrical Engineering

IIT Indore

Acknowledgements

I would wish to thank Dr. Saptarshi Ghosh for his kind support and valuable guidance. It is through 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.

Vaibhav kumar (160002058)
B.Tech. IV Year
Discipline of Electrical Engineering
IIT Indore

Abstract

This paper presents a frequency selective surface (FSS) based rasorber design using 2.5-dimensional (2.5-D) concept. The proposed design comprises of convoluted meander line and interdigital capacitor (IDC) patterns printed on opposite sides of a dielectric substrate, connected through metallic vias. This increases the current path, thus realizing a miniaturized-element bandpass response at 1.06 GHz (having 1.51 dB insertion loss), corresponding to the unit cell dimensions of $0.0339\lambda_0 \times 0.0339\lambda_0$, where λ_0 is the operating wavelength. Further, the structure exhibits a narrow-band absorption at 7.27 GHz, due to the adaptive ground plane behavior of the IDC geometry. The topology is angularly stable (upto 75^0 incident angle) for both TE and TM polarizations. Equivalent circuit analysis and parametric variations have also been studied to investigate the miniaturization characteristic of the proposed 2.5-D FSS.

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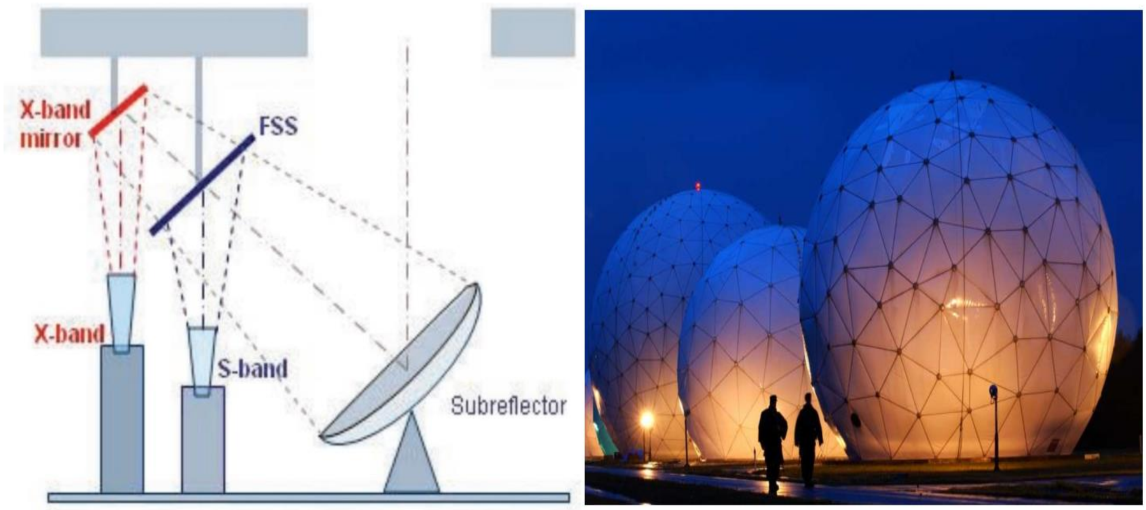
Chapter 1

Introduction

1.1 Overview

A frequency selective surface (FSS) is a repetitive surface designed to reflect, transmit and absorb electromagnetic waves at a certain frequency. They are usually constructed by printing metallic patterns on single/both sides of a dielectric substrate. Under plane wave excitation, the incident wave induces electric currents flowing through the metallic elements, which then resonate at a particular frequency and re-radiate the energy. These re-radiated fields add constructively or destructively with the incident wave giving rise total reflection or transmission or absorption depending on the type of the elements. Currently, applications of FSSs are found in radomes, spatial filters, electromagnetic shielding, dichroic sub reflectors, polarizers, analog absorbers etc.



(a) (b)

Figure 1.1: (a) Sub reflectors at work and, (b) Radomes [*image: wikipedia*].

The complexity in the design of existing FSSs, constraint in size and sensitivity to the angle of incidence limit their functionality, thus showing the demand for improving their characteristics. In this report, few of these limitations have been improved, and also focus has been made in miniaturization of FSS as well as 2.5-dimensional structure.

1.2 Traditional FSS Elemental Geometries

Traditional FSS geometries can be classified into two groups: patch and slot [1].

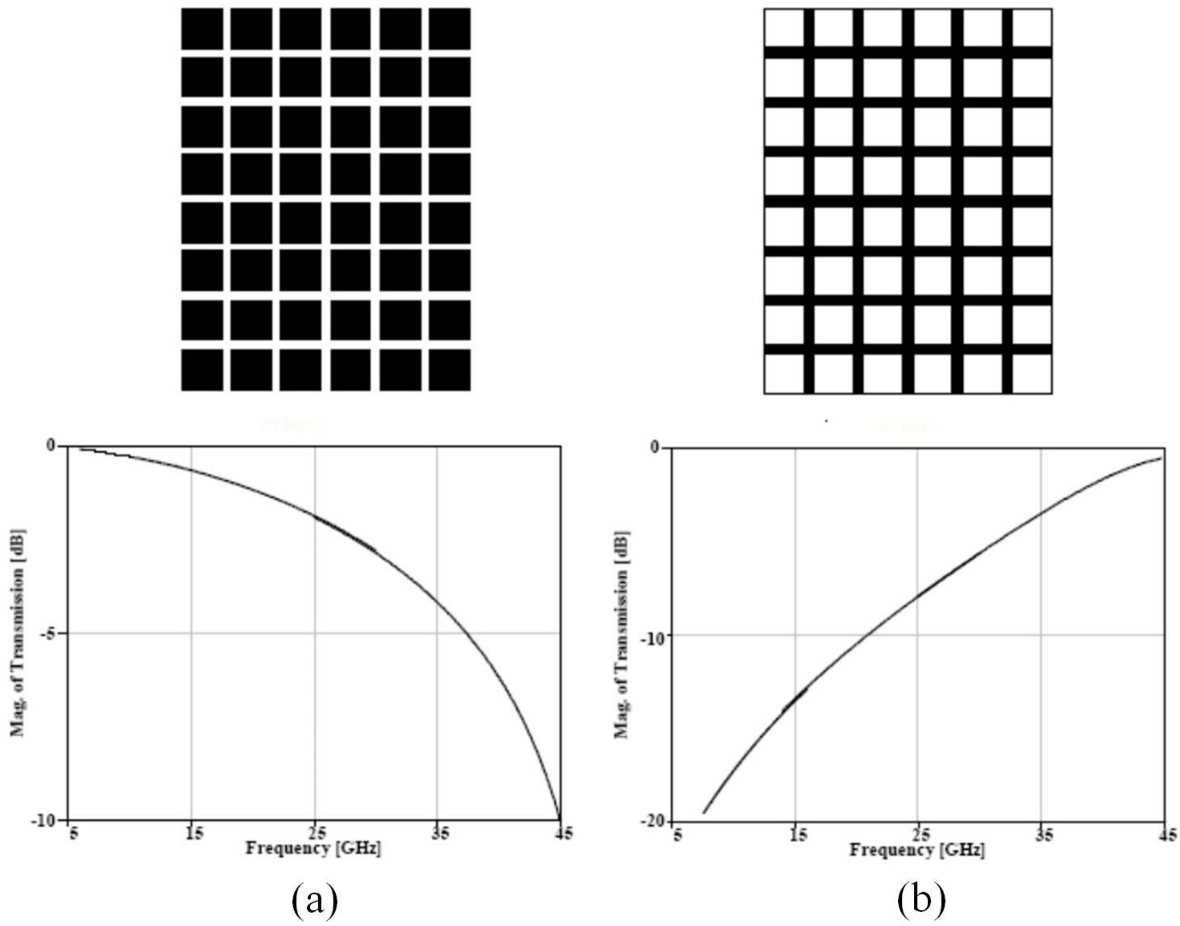


Fig. 1.2. Periodic structures comprising of complimentary elements, (a) patches and (b) slots (wire-grid), and their transmission coefficient. The patch-array produces a capacitive response, whereas the array of slots is inductive(as shown in its equivalent circuit) [Courtesy: T. K. Wu, Frequency- selective surface and grid array. Wiley, New York, 1995].

Patch type design can be considered as capacitive surface, whose frequency response is provided in Figure 1.2 (a) and the complementary wire grid structure (in Figure 1.2(b)) has an inductive response, hence acting as a highpass filter. These inductive and capacitive surfaces can be put together to produce a desired filter response.

Over the years, many FSS designs have been proposed for single and multiband filtering applications. Depending on the application requirements, different FSS designs can be chosen to fulfill the demands. These requirements usually include level of dependence on the incidence angle of the incoming wave, level of cross-polarization, bandwidth, and level of band separation.

1.3. Rasrober

Conventional bandpass filters allow transmission of a particular frequency with minimum loss, while the other signals get reflected in random directions. This reflected signal may get detected or interpreted by the newly developed polystatic anti-stealth radars, thus creating challenges to stealth techniques or filters. Therefore, an absorptive FSS (AFSS) is highly desired to counter or address this problem.

Absorptive FSS (AFSS) is a kind of multilayer periodical structure, which not only transmit the EM wave at some frequencies, but it can also absorb the out-of-band incoming wave. This AFSS structure, also known as rasorber, is generally composed of two layers: one absorptive and another transmissive. Recently, several AFSS designs and their applications as stealthy radome to reduce bistatic radar cross-section of antenna have been reported. However, most of these designs have large thickness, complicated geometry, and high fabrication cost. Since the absorptive layer is made from resistive contribution, the thickness is quite large for most of the existing structures, thus restraining them from practical applications. Further, the periodicity is also large.

CHAPTER 2

2.1. Need for Miniaturization

Traditionally, FSSs based constructed structures has strict dependence of its frequency response on the incident angle and polarization of the incident electromagnetic (EM) wave owing to the large size of the resonant elements. Moreover, in the practical applications with limited space, it is difficult to contain sufficient numbers of a resonant-type element to act as an infinite FSS. Thus, a new type of frequency selective surface with miniaturized elements has been applied, which is mainly known as miniaturized-element frequency selective surfaces (MEFSSs). This type of FSS is composed of a periodic array of sub wavelength elements. Its frequency response shows less dependence on the incident angle and polarization of EM wave.

Miniaturized FSS Design and Analysis

2.2. Constituent Miniaturized Elements

It is well known that an interdigital capacitor (IDC) provides different impedance responses under different orientations of an incident electromagnetic (EM) wave [3]. When the electric field is directed along the capacitive fingers (*y*-polarization), the topology gives rise to high capacitance and small inductance in series connection. This leads to a low-pass response that can be represented by a series LC connection, as illustrated in Fig. 2.2 (a). Under *x*-polarization, the same geometry provides a transparent behavior (low capacitance and high inductance in parallel combination). A high-pass filter characteristic is thus attained, which can be modeled by a parallel LC network, as shown in Fig.2.2 (b).

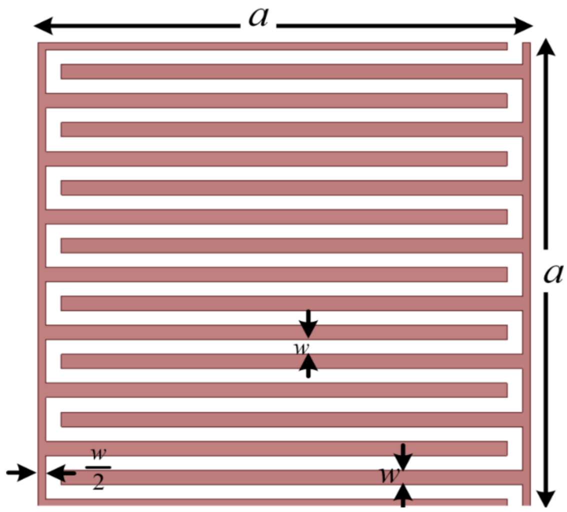


Figure 2.1: An interdigital capacitor (IDC) with 15 number of fingers having dimensions of a=9.6 mm and w=0.3 mm made of copper of thickness (t_c =0.035 mm), placed on top of the dielectric surface FR 4 (ε_r =4.4, $tan\delta$ =0.02) having dimension of 9.6mm×9.6mm and thickness of t_d =0.4 mm.

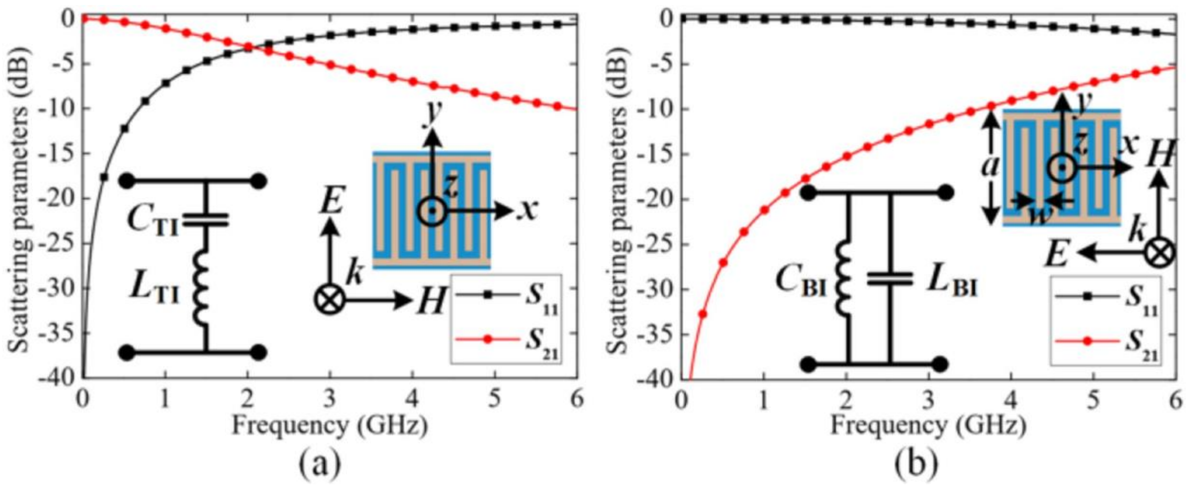


Fig. 2.2. Frequency response the structure comprising an IDC (*w* = 0.3 mm and a= 9.6 mm) printed on a dielectric substrate under (a) *y*-polarized and (b) *x*-polarized incident EM wave. Inset shows the equivalent circuit models of the IDC geometry under different polarizations. [Ref. 3]

In a similar way, meander patterns exhibit high-pass and low- pass characteristics, when the electric field is polarized along the *y*- and *x*-directions, respectively. Under a *y*-polarized EM wave, high inductance and small capacitances result, thereby leading to a bandpass response (equivalent to high-pass at low frequency) at 4.74 GHz, as depicted in Fig. 2.4(a). In contrast, a low-pass filter response is observed in Fig. 2.4(b) for an *x*- polarized electric field. These bandpass and low-pass behaviors of the meander line correspond to parallel and series *LC* circuits under the *y*- and *x*-polarization, respectively [3].

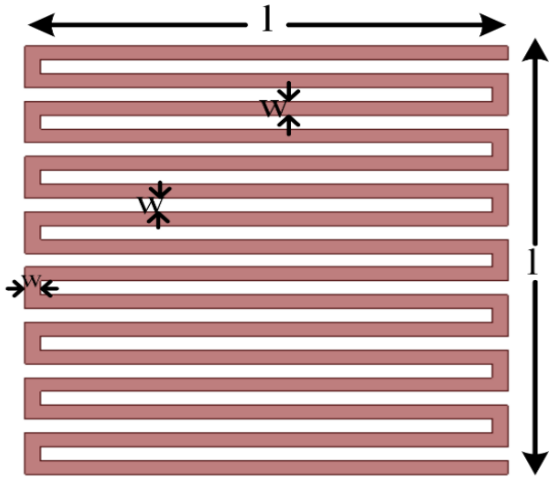


Figure 2.3: A Meander line pattern with 16 number of fingers having dimensions of a=9.6 mm, w=0.3 mm and l=9.3 mm, made of copper of thickness (t_c =0.035 mm), printed on top of the dielectric surface FR 4(ε_r =4.4, $tan\delta$ =0.02) having dimension of 9.6 mm×9.6 mm and thickness of t_d =0.4 mm.

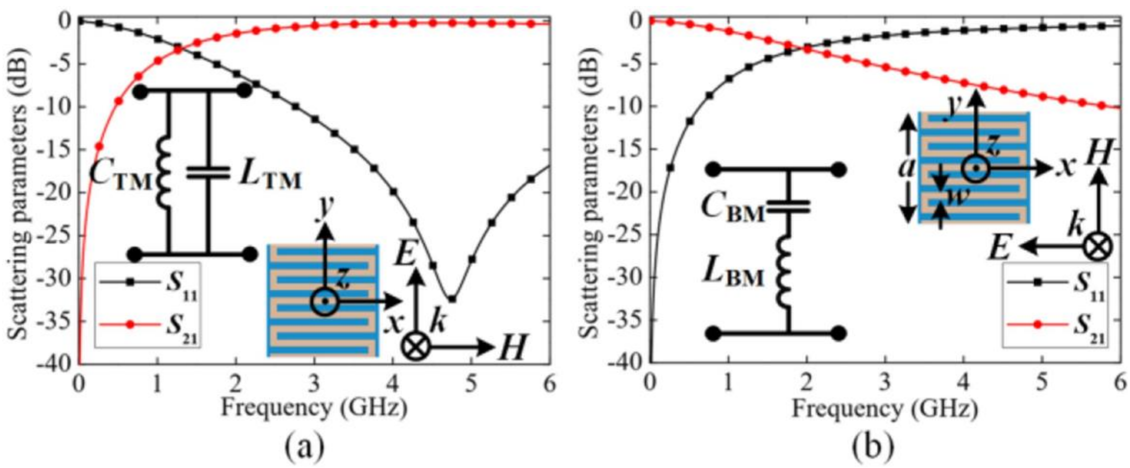


Fig. 2.4. Frequency response the structure comprising a meander line (w = 0.3 mm and a = 9.6 mm) printed on a dielectric substrate under (a) *y*-polarized and (b) *x*-polarized incident EM wave. Inset shows the equivalent circuit models of the meander line under different polarizations [3].

Therefore, when the two particular patterns in Fig 3.1 and 3.2 are combined in a single geometry (by placing them on the top(meander) and bottom(IDC) sides of the dielectric substrate FR4), the topology gives rise to an overall high value of capacitance and a low value of inductance from both meander and IDC under a y-polarized EM wave. Thus the combined structure also exhibits a capacitive behavior and acts as a low-pass filter response, as depicted in Fig. 3.6.

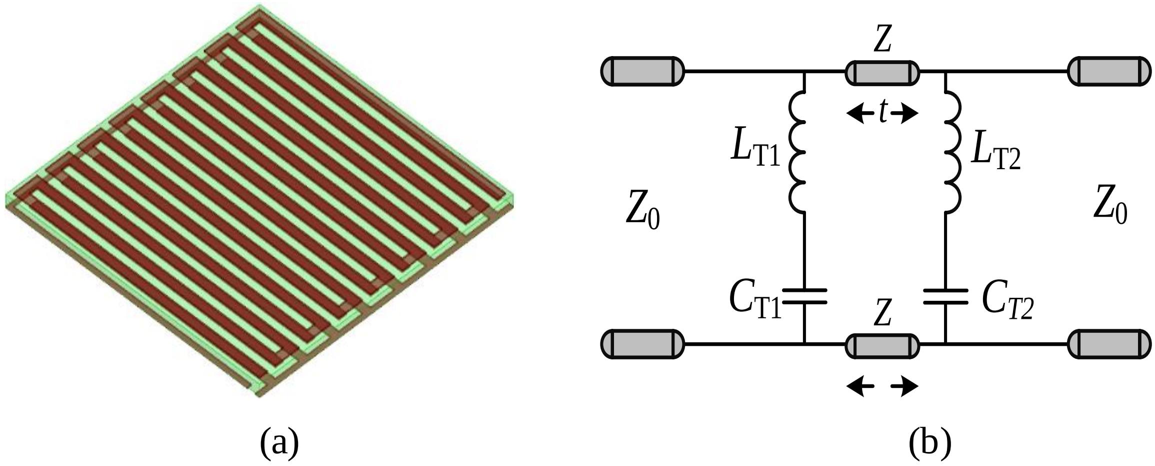


Fig. 2.5. (a) Unit cell geometry of the miniaturized FSS structure, and (b) Its equivalent circuit model, under y-polarized EM waves.

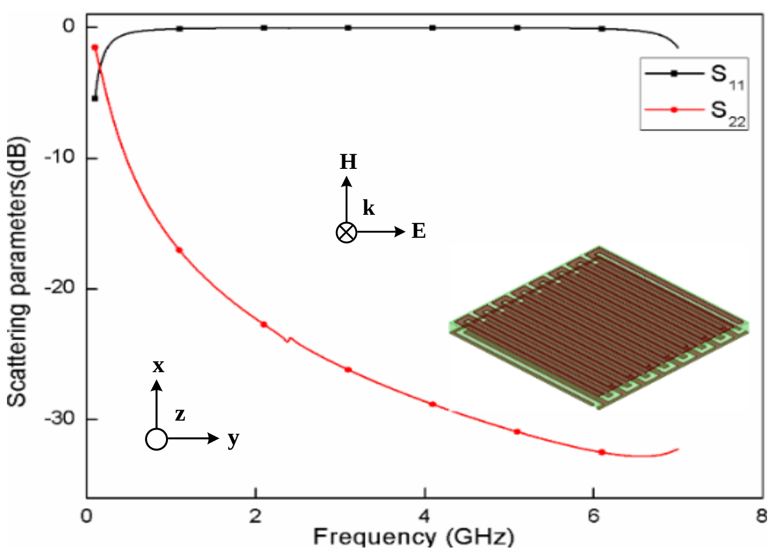


Fig. 2.6. Simulated scattering parameters of the miniaturized FSS geometry under *y*-polarized incident wave.

CHAPTER 3

DESIGNS

3.1. 2.5-Dimensional geometry

When top and bottom layer patterns are connected through metallic vias, then the geometry is known as 2.5-dimensional (2.5-D) geometry. This connection between the top and bottom patterns, increase the current path, and subsequently reduce the resonance frequency. This helps in realizing miniaturized FSS structure.

3.2. Proposed 2.5-D FSS Structure

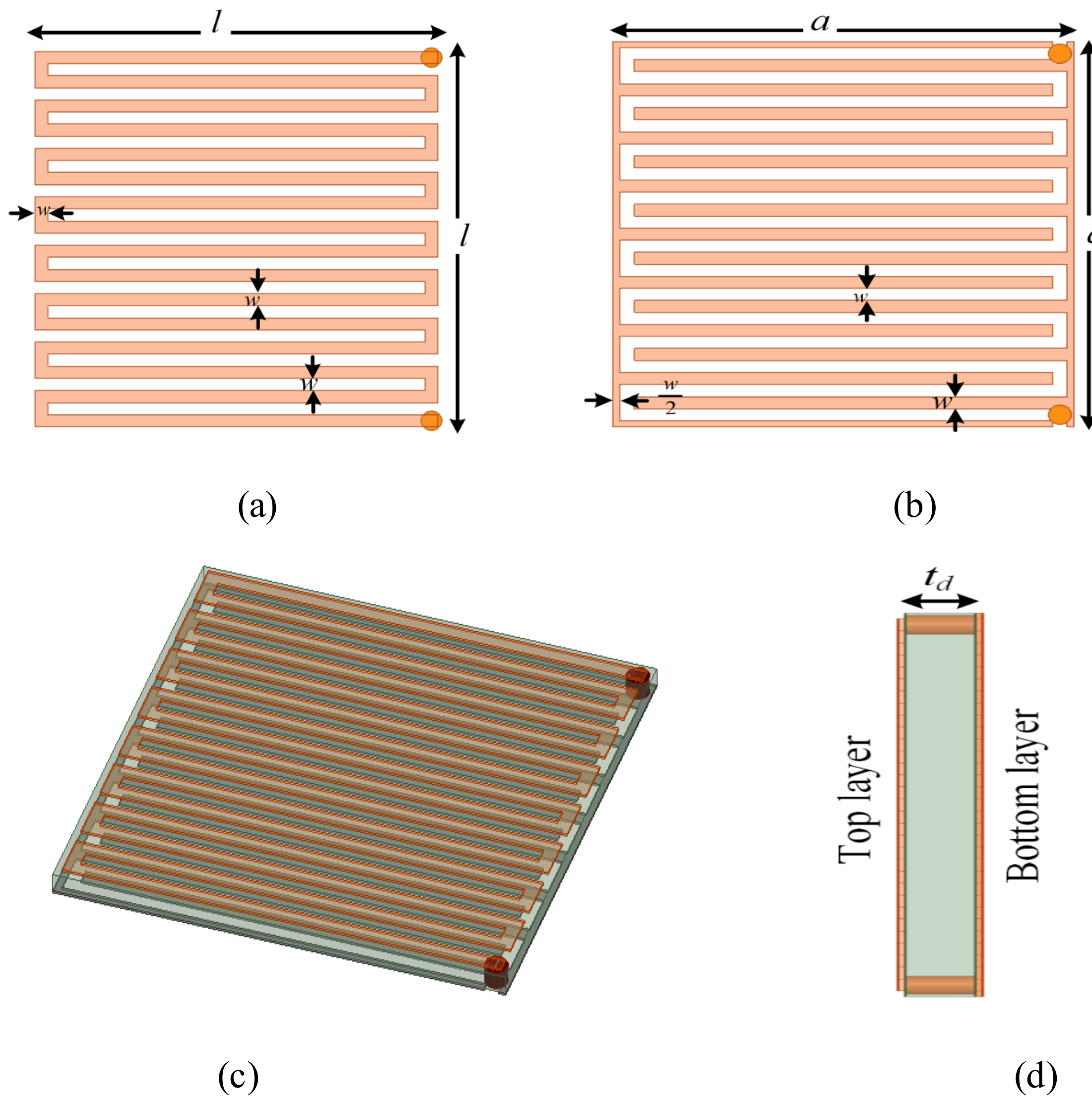


Fig 3.1. Unit cell geometry of the miniaturized FSS structure. (a) Top view of

top layer, (b) Top view of bottom layer, (c) Overall structure, and (d) Side view of the unit cell. The geometric dimensions of the proposed structure are as follows: a=9.6 mm, w = 0.3 mm, l = 9.3 mm, c_h.=0.3mm and c_r=0.24mm .

The above structure, while further explored by connecting metallic vias between the top and bottom pattern, the response is improved greatly in terms of miniaturization. The unit cell geometry of the modified FSS structure consists of a convoluted meandering metallic pattern printed on the top side of the dielectric substrate and IDC on the bottom side. The top metal layer is confined within the unit cell, whereas the bottom layer is connected with the neighboring unit cells along the edges of the IDC. The top and bottom layers are also connected together through metallic vias (with height c_h=0.3mm and radius c_r=0.24mm) at two corners of the geometry, as shown in Fig. 3. The metallic pattern of both meander lines and IDC are made of copper ($\sigma = 5.6 \times 10^7$ S/m) each having thickness (t_c) of 0.035, and FR-4 is used as the dielectric substrate having relative permittivity (ε_r) of 4.4, dielectric loss tangent (tan δ) of 0.02, and thickness (t_d) of 0.3 mm combining to form an ultra-thin miniaturized FSS structure.

3.3. ANALYSIS

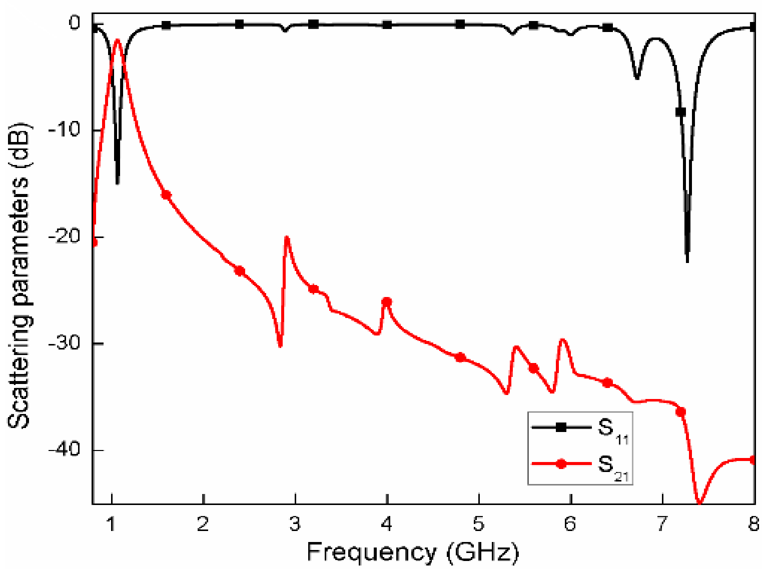
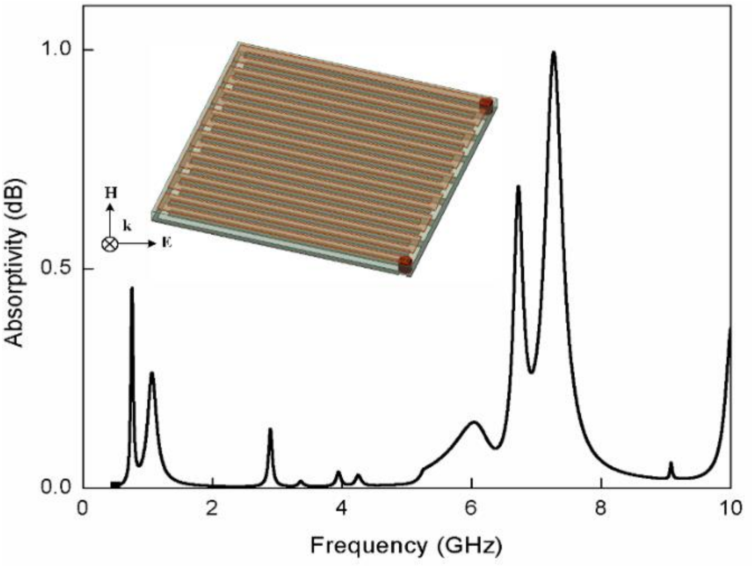


Fig. 3.2. Simulated scattering parameters of the FSS under normal incidence.

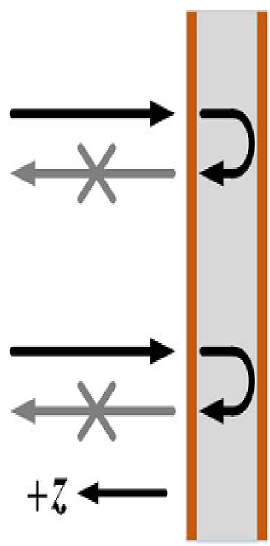
When an EM wave is incident on the proposed FSS, the geometry exhibits large inductance owing to meander lines. In addition, the top and bottom layer patterns are connected by metallic vias, thus causing further increase in the effective inductance. This results in a low frequency band stop response at 1.06 GHz with insertion loss 1.41 dB, as observed in Fig. 3.2. Owing to such low-frequency resonance, the FSS exhibits a miniaturization characteristic having unit cell size of $0.0339\lambda_o \times 0.0339\lambda_o$, λ_o being the free space wavelength. The frequency response also shows that there is absorption of the incident EM waves at 7.27 GHz.

As we know, absorptivity response is given by,

$$A = 1 - |S_{11}|^2 - |S_{21}|^2$$



(a)



(b)

Fig.3.3. (a) Absorptivity response of the proposed structure, (b) Trajectory of the incoming and reflected incident EM waves by the bottom layer(IDC) .

And from fig.4.5 (b) we can see that the bottom layer IDC pattern acts as almost a reflector i.e. $|S_{21}|=0$ (magnitude of transmission coefficient is almost zero), and due to the top meander line layer the $|S_{11}|$ (magnitude of reflection coefficient) is very low at the resonance frequency of 7.27 GHz, thus the magnitude of absorptive response **A** reaching maximum. This can be verified form the absorptive response curve of the structure shown in fig.3.3 (a) where we can say that there is approximately 98% of absorption of the incident EM waves at resonance frequency of 7.27 GHz.

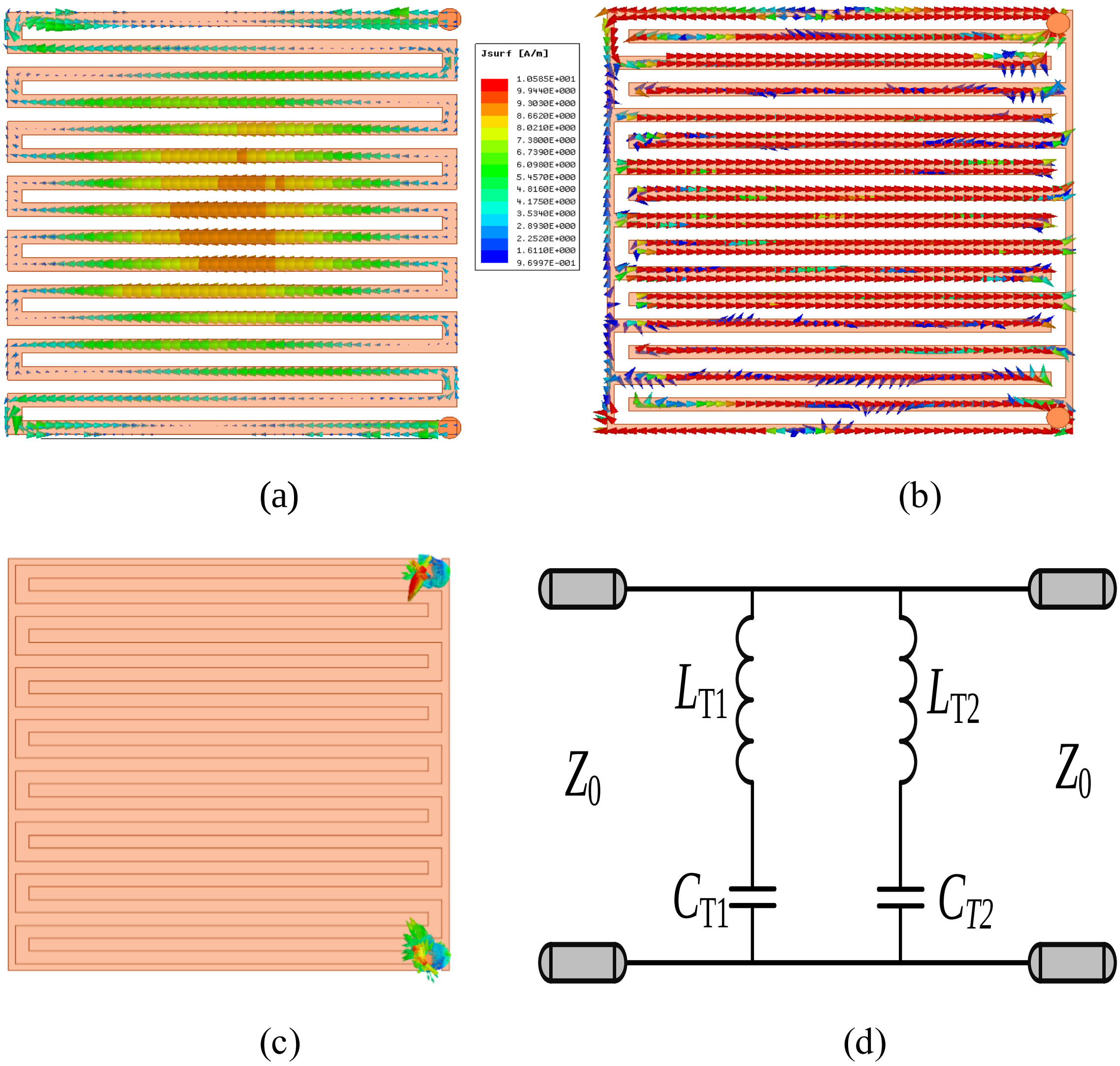


Fig. 3.4. Surface current distributions in (a) top, (b) bottom layers, and (c) in the metallic vias, (d) the equivalent simplified circuit model of the proposed FSS structure at 1.06 GHz.

To further explain the resonance mechanism, surface current distributions of the proposed FSS have been illustrated in Fig.3.4. It is observed that the current is propagating along the convoluted patterns in both the layers, and utilizing the metallic vias to complete the current path. This overall increases the effective inductance, thus resulting in low resonance frequency at 1.06 GHz. This can further be explained using the simplified equivalent circuit model of structure by comparing fig..5 (b) i.e. without via and fig.3.4 (d) i.e. when the top and bottom layer are connected through the metallic vias where L_{t1}, C_{t1} and L_{t2}, C_{t2} are inductance and capacitances of top and bottom layer respectively. From this we can observe that the transmission line Z_0 acts as short circuit model due to the current flowing from top to bottom forming a closed loop circuit, thereby increasing the overall inductances of the whole circuit thus lowering in the resonance frequency of the circuit.

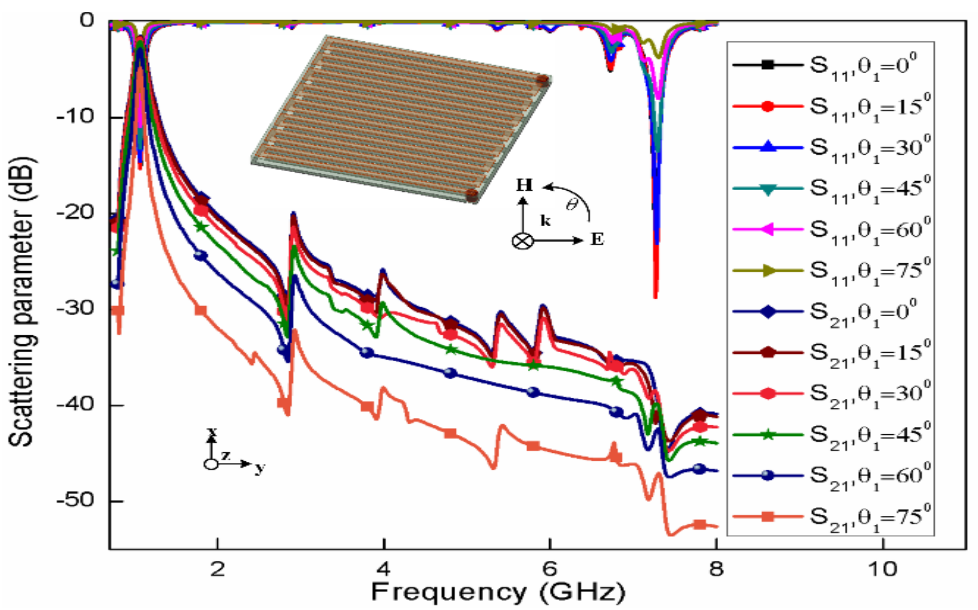


Fig.3.5. Angular response of the proposed structure.

It can be observed from the angular or theta response of the structure that it exhibits good angular stability for TE polarizations, upto 75^0 angle of incidence.

3.4. Importance of Meander line and IDC pattern

When the meander line pattern is replaced with metallic wire line the simulated scattering parameters response is shown in Fig. 3.6, from which we can observe that the structure simply produces a bandpass response at a very low frequency of 0.96 GHz (with insertion loss of 1.41 dB), which is somewhat difficult to measure with the present day measuring apparatus provided to us. This structure is only applicable for transmitting of a certain range (narrow) EM waves, else everything for reflection with nothing to absorb, thus limiting is uses greatly.

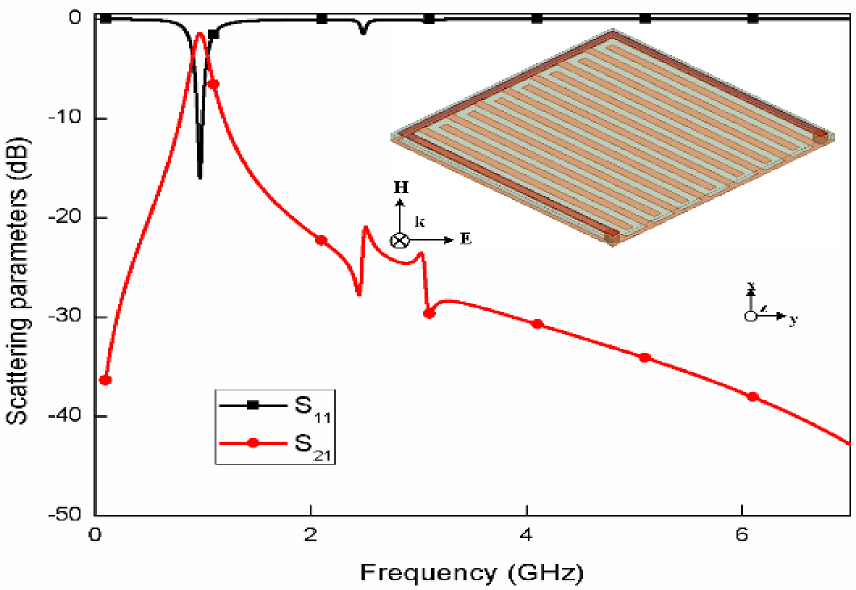


Fig.3.6. Scattering parameters response of the designed FSS, replacement of meander pattern with simple metallic line.

Similarly, when meander as well as IDC patterns are substituted with the same wire line pattern as shown in the Fig. 3.7, from the simulated response of the scattering parameters in Fig 3.7, the given structure produces a wide-band bandstop response/filter at the high resonance frequency of 7.65 GHz, which shows how is deviation of the result with our goal of making a rasorber structure with minimum resonance frequency. The equivalent circuit model of the present structure can be said to be the combination of series inductance L (high value) and capacitance C (low value).

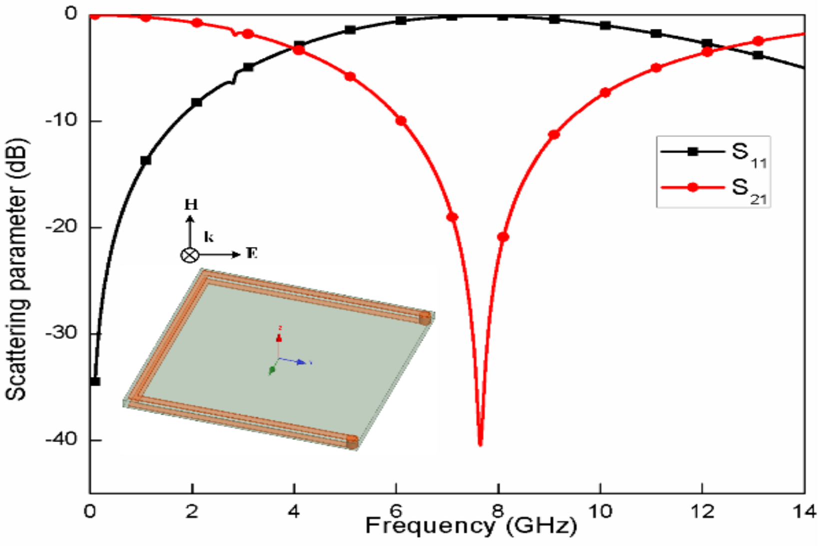
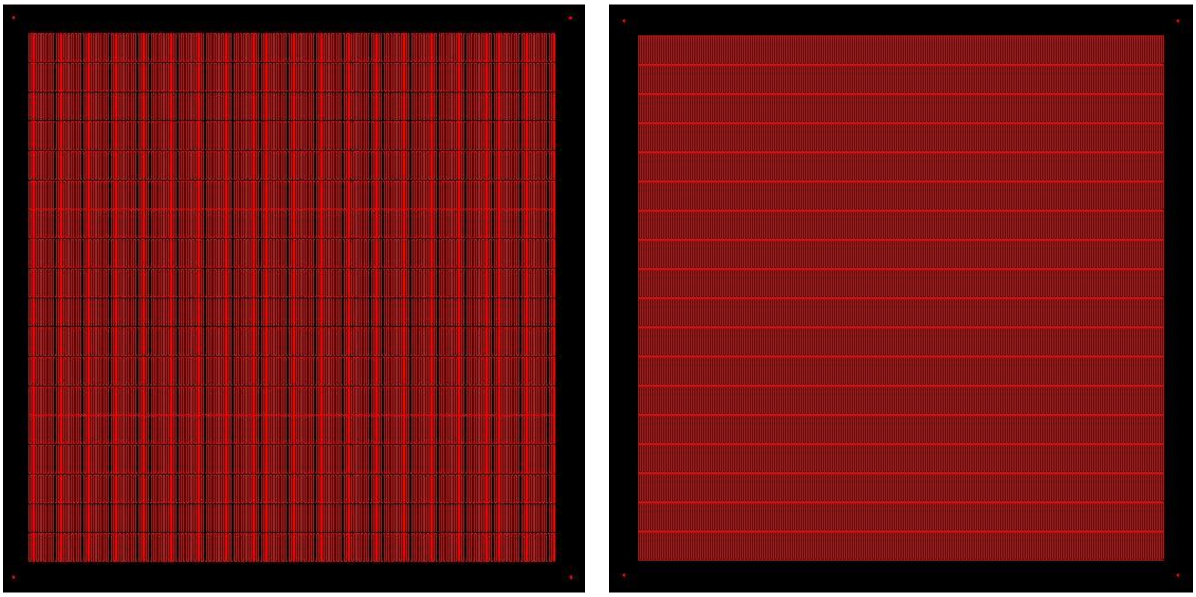
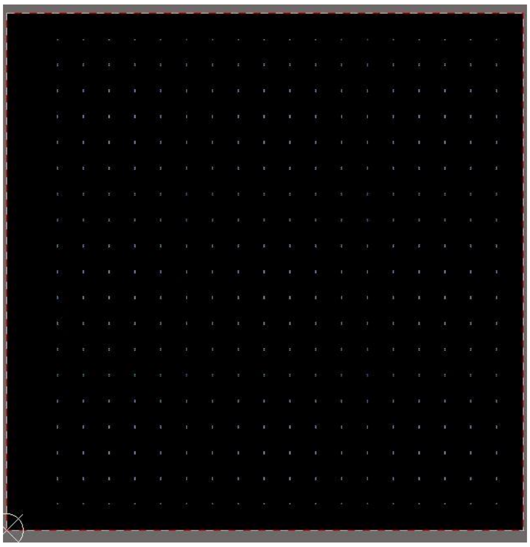


Fig.3.7. Scattering parameters response of the designed FSS, replacement of meander pattern as well as IDC with simple metallic line.

3.5. Fabrication Files



(a) (b)



(c)

Fig.3.8. Gerber files of fabricated proposed structure with (a) top layer, (b) bottom layer, and (c) Via mapping.

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

FUTURE SCOPE

The proposed structure in Fig.3.4 can further be used to create to create a polarization-insensitive structure which is four fold symmetric in nature and having its own advantage compared earlier proposed rasorber design. One such example of the four-fold symmetric structure is shown in fig.4.1 (a, b, c) below using only meander on the top and IDC patterns in the bottom. From the frequency response shown in fig.4.2 we can observe the structure produces two bandpass resonance frequencies at f_1=2.3 GHz with insertion loss at -1.27 and f_2=6.42 GHz with insertion loss -1.18 dB as well as a bandstop frequency at 4.27 GHz. These designs are still far from the required objective and can further be improved on, which shall also be my future objective to complete this design.

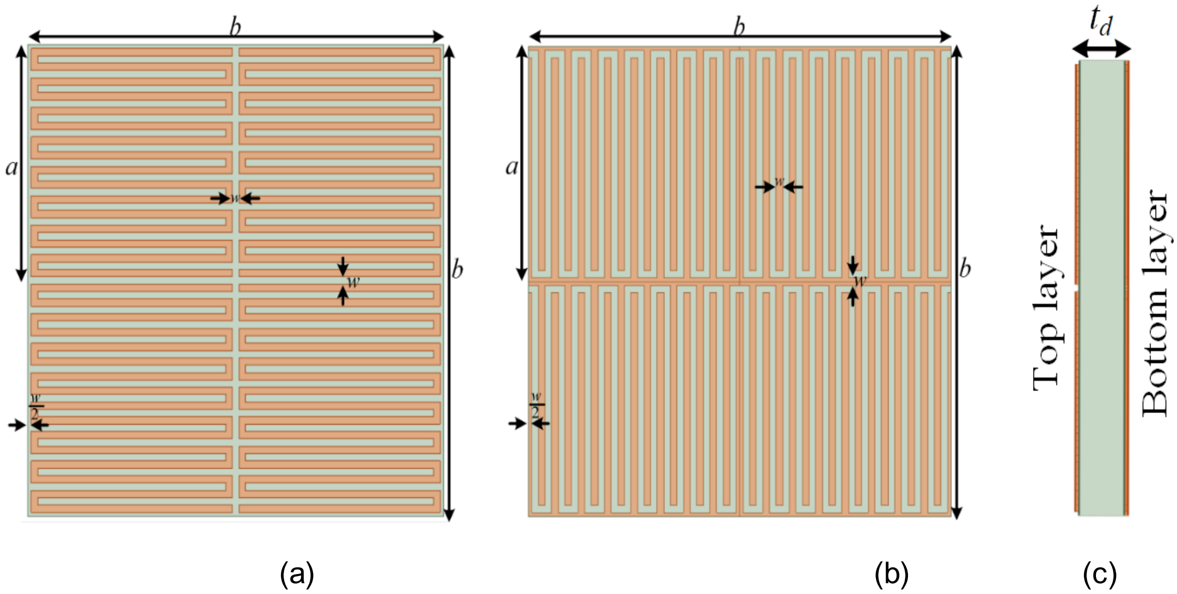


Fig.4.1. Unit cell geometry of the FSS structure. (a) Top view of top layer, (b) Top view of bottom layer, and (c) Side view of the unit cell. The geometric dimensions of the proposed structure are as follows: a=9.6 mm, w = 0.3 mm, l = 9.3 mm and b=19.2 mm.

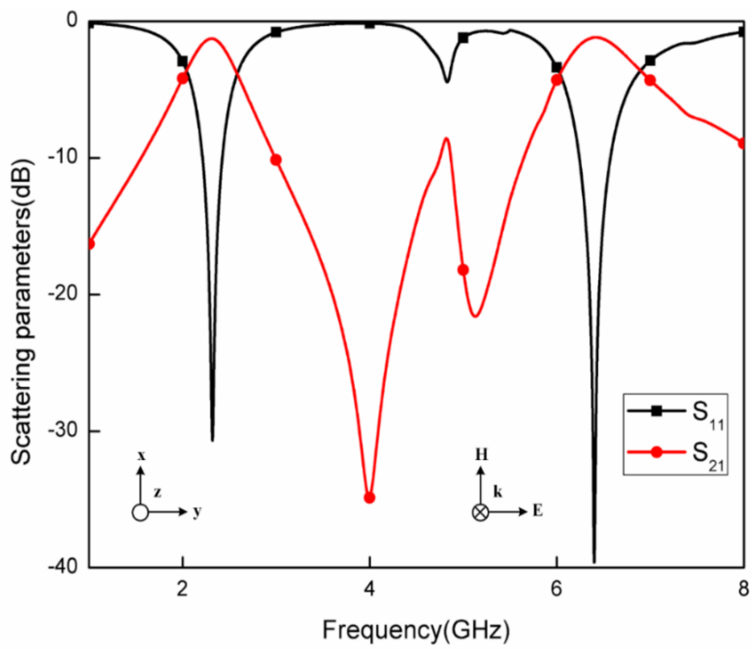


Fig.4.2. Scattering parameters response of the designed FSS.

CONCLUSION

- The proposed structure shows **bandpass response** at 1.06 GHz with insertion loss of 1.41 dB, having miniaturized unit cell dimension of **$0.0339\lambda_0 \times 0.0339\lambda_0$.**
- There is absorption of incident EM waves at 7.27 GHz.
- Highly angular stable (**upto 75^o angle of incidence under TE polarizations**).
- Filtering mechanism has been explained using **surface current distribution plot**.
- The miniaturization remains constant **irrespective of width and gap of the metal patches** of the structure.
- Can be used for **stealth technology,** radar cross section, radome, EMI/EMC applications and wireless communication.

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