Theoretical and Experimental Study of Split Semi Horse Shoe Structure

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Abstract

In this paper a new planar metamaterial structure that looks like semi-horse shoe in shape (SSHSS) is designed and simulated. Theoretical analysis of proposed structure done using equivalent circuit theory. Medium effective parameters are extracted using modified NRW approach which proved the metamaterial property of the new unit cell. Radiation pattern, directivity and gain of the new structure were illustrated which gives the possibility of using SSHSS as the antenna. Proposed structure shows multiband characteristics. This antenna shows high directivity (7.92 dBi, 7.86 dBi, 10.11 dBi) and moderate gain (2.55 dBi, 3.90 dBi, 5.07 dBi) at 5.83 GHz, 8.41 GHz, 10.68 GHz respectively. RT duroid is used for fabrication of prototype of the proposed structure. This new structure can be used as metamaterial inspired antenna as well as normal patch antenna. Experimental results shows good agreement with simulated and theoretical results.The proposed structure has been simulated using IE3D electromagnetic simulator.

1. Introduction

Artificial Metamaterials were first proposed by Prof. Veselago in 1968[1]. Present day communication technology demands miniaturized wireless systems. Antenna designing is very challenging domain for advanced communication devices. In early decade of metamaterial discovery researcher focuses on realization of these periodic structures. Now they are looking for use of these artificial materials in present day communication devices. Multiband operation, pattern & frequency reconfiguration is possible by loading of these new structures to conventional patch antennas. A large variety of Split ring Resonator (SRR) design were designed so far after first unit cell proposed by J. B. Pendry in 1999[2]. D. R. Smith et.al. in [3] have demonstrated first composite medium composed of SRR and thin wires. In [4] R.W. Ziolkowski *et al.* showed that the radiation power of small antennas increases by incorporation of metamaterials. Gain of patch antenna improved by using CSRR in ground plane in [5]. M.S. Sharawi et. al. in [6] proposed a new compact antenna for MIMO having good isolation between elements using CSRR in ground plane. J. G. Joshi et. al. proposed offset fed diamond shaped split ring (DSSR) structure to improved bandwidth [7]. In [8] Vipul sharma et. al. presents a new planar microstrip elliptical split-ring resonator (ESRR) showing negative refractive index at multiple bands .In [9] a new planar triangular split ring resonator (TSR) showing left hand property at Ku band is proposed. In [10] G. Singh et. al. proposed a new planar split semi horse shoe structure (SSHSS) used as antenna for X band. To change the resonance frequency from X band to ISM band, split vertical length & stub length has been changed in present work. Every shape of SRR has its own advantages and disadvantages. This new structure does not incorporate metallic rod for getting negative permittivity.

This paper is organized in five sections. Design specifications and theoretical analysis of the new structure are presented in section II. Simulation and use of simulation results to verify the metamaterial property is presented in section III. Experimental findings are presented in section IV. Section V showed the conclusion of paper.

2. Geometry of Proposed Resonator

In this section theoretical analysis using equivalent circuit theory and physical specifications of split semi-horse shoe structure (SSHSS) is presented. The physical specifications of proposed structure are given in Table 1. RT Duroid 5880 substrate having relative permittivity 2.20, loss tangent=0.0009 and thickness h = 1.575 mm is used to simulate and fabricate the prototype. Simulation of the structure is done by IE3D electromagnetic simulator software.

Table1: Physical dimension of the proposed structure

Parameters	r_1	r_2	r_3	r_4	W	S	w	L	D
Present Design Values	6	8	9	11	2	1	4.4	24.16	2
Ref.[10]	6	8	9	11	2	1	3.6	20.59	2
Ref.[11]	6	8	9	11	2	1	4	23.47	2

*All values are in mm

Figure 1 shows the geometry of proposed split semi-horse shoe structure with both rings has vertical split cut in Y-axis.

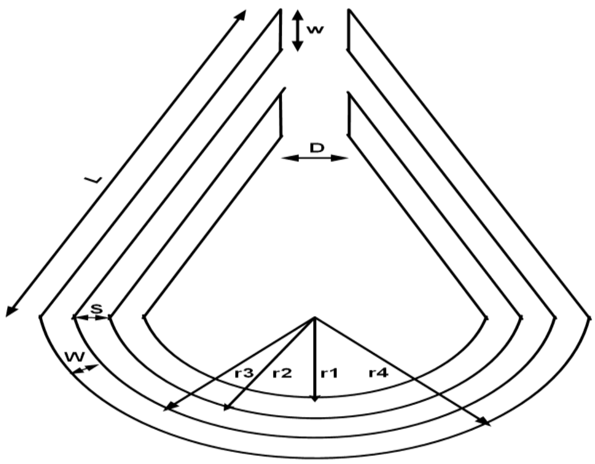

Figure 1: Geometry of Split Semi-Horse Shoe Structure

2.1. Theoretical Analysis of SSHSS

Theoretical analysis of the proposed structure is done by principles of equivalent circuit theory. The antenna resonates due to the reactance (i.e., inductance and capacitance) present in the structure. These inductances and capacitances lead the structure to behave as a LC tank circuit. For the calculation of inductance and capacitance the of unit cell, structure is divided in four sections as shown in [12] Fig.2. Equivalent circuit model of the SSHSS is shown in Fig.3.

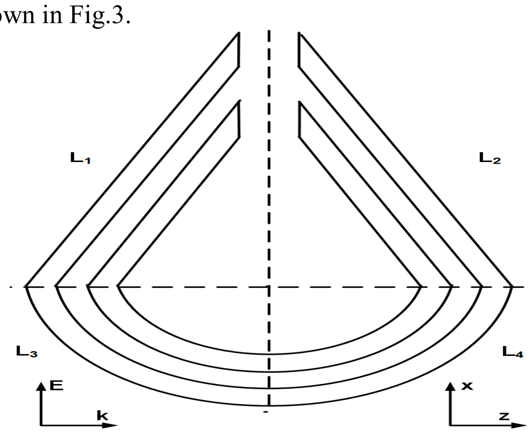

Figure 2: SSHSS divisions for calculation of inductors

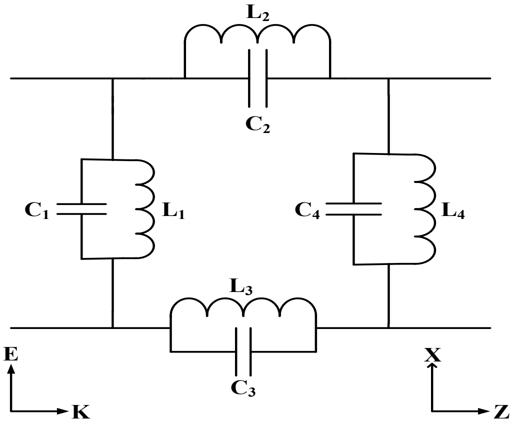

Figure 3: Equivalent circuit model of the SSHSS

L_1 and L_2 estimated by following expressions [13]

$$L_{1,2} = \frac{K\mu N^2 L}{2\pi}\left[\ln\left(\frac{2}{\rho}\right) + 0.5 + 0.178\rho + 0.0416\rho^2\right] + \frac{\mu N^2 L}{2\pi}[0.5\frac{(N-1)S^2}{(\rho L)^2} + 0.178\frac{(N-1)S}{NL} - \frac{1}{N}\ln(\frac{(W+t)}{W}) \quad (1)$$

where ρ is the filling ratio given as $\rho = \frac{NW+(N-1)S}{L}$ N is the number of rings.μ is the permeability of free space. K is integrality coefficient introduce to reduce the error in calculation of L caused by split in the strip, K is expressed as $K = \frac{(2L-2S)-D}{(2L-2S)}$ .The self inductance of the two ring (L_{ring}) having width W and radius r is calculated using following equations [13];

$$L_{ring} = \frac{\mu N^2 d}{2}\left[\ln\left(\frac{d}{W}\right) + 0.9 + 0.2\frac{W^2}{d^2}\right] + \frac{\mu N^2 d}{2}[0.5\frac{(N-1)S^2}{(\rho d)^2} + 0.4\frac{(N-1)S(W+S)}{d^2} - \frac{1}{N}\ln\left(\frac{(W+t)}{W}\right)) \quad (2)$$

where ρ is the filling ratio given as $\rho d = NW + (N-1)S$ and $d = \frac{d_1+d_2}{2}$,$d_1 = r_1 + r_2$,$d_2 = r_3 + r_4$.

The mutual capacitance (C_{rings}) per unit radian between the two rings is given by equation given below [14],

$$C_{rings} = \frac{2}{\pi}\varepsilon_0\epsilon_r\, r\ln \quad (3)$$

where r is radius of the ring, W is ring width and S is gap between two rings.

The mutual capacitance (C_{strips}) between the two strips is given by equation given below [14]:

$$C_{strips} = \frac{\varepsilon_r\varepsilon_0 AtL}{S} \quad (4)$$

Where A is the modification factor, t is the thickness of metallic strip, L is the length of the overlapping area, S is the gap between strip, ε_r is the relative permittivity of the substrate (2.20) and ε_0 is the permittivity of free space (8.854×10^{-12} F/m).

The gap capacitance is estimated at the two splits. It is vital to estimate the capacitances of the outer and inner splits, but it is difficult because of the intense electromagnetic brink effects, so they are estimated by modifying the parallel plane capacitance formula with a modified factor ,that is [14];

$$C_{gap} = \frac{\varepsilon_r\varepsilon_0 Atw}{g} \quad (5)$$

Where A is the modification factor, t is the thickness of metallic strip, w is the vertical width of the strip, ε_r is the relative permittivity of the substrate (2.20) and ε_0 is the permittivity of free space (8.854×10^{-12} F/m).

The value of distributed capacitances C_1, C_2, C_3 and C4 can be determined by using C_{rings} , C_{strips} , C_{gap} calculated above using the following approaches [14]:

$$C_1 = C_2 = C_{strips} + C_{gap} \quad (6)$$

$$C_3 = C_4 = \frac{1}{2} C_{rings} \qquad (7)$$

After simplifying the equivalent circuit for present design, the equivalent inductance and capacitance for first resonance frequency is found as L_{eq}=36.90 nH and C_{eq}=0.0251 pF. By using the value of Leq, C_{eq} numerically calculated resonant frequency is f_r= 5.72 GHz. While the simulated resonant frequency is 5.83 GHz which shows the 1.88% of error and experimental frequency is 5.845 Ghz all these three are in good agreement.

3. Simulation Results and Discussion

The proposed SSHSS structure is coaxially excited at x=-7.5 mm, y=-6.8mm and x=2.3mm, y=10.3mm. Figure 4 shows the simulated reflection coefficient (S_{11}) and phase reversal (S_{12}) characteristics of the proposed metamaterial structure (SSHSS) upto 20 GHz. Figure 5, shows the reflection coefficient (S_{11}) at 5.83 GHz frequency in expanded view is -24.24 dB, it is also clear that structure exhibits phase reversal in the resonant frequency band which implying that the wave vector changes its phase by an angle of 180^0 at the interface. This antenna shows metamaterial behavior at 5.83 GHz, 8.41 GHz, 12.67 GHz , 14.87 GHz resonance frequency while show normal behavior at 10.64 GHz. Table 2 shows the summary of the simulated results. This antenna shows multiple resonance frequency due to the multiple reactance (i.e., inductance and capacitance) present in the structure.

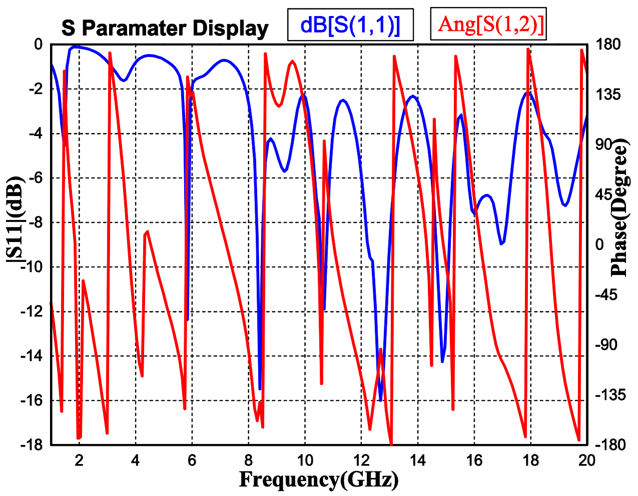

Figure 4: S_{11} (dB) and S_{12} (phase angle) of the SSHSS antenna

Table 2 Summary of the simulated results

Resonance Frequency(GHz)	Return Loss S_{11} (dB)
5.83	-11.50 (-24.24 dB expanded view)
8.41	-15.41
10.68	-12.04331
12.67	-15.80
14.87	-14

Figure 6 depicts the simulated polar radiation pattern of the SSHSS structure in both planes.

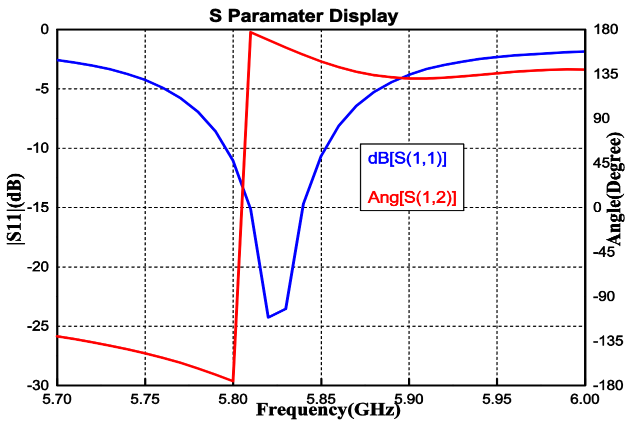

Figure 5: Expanded view of the S_{11} (dB) and S_{12} (phase angle)

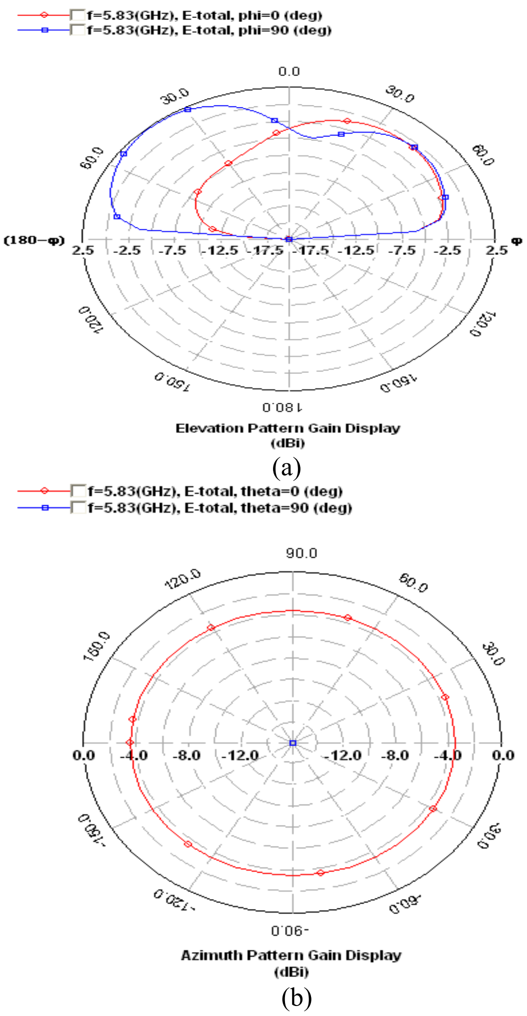

Figure 6: Radiation pattern (a) elevation (b) azimuth

Figure 7 shows the gain and directivity versus frequency plot. It is clear that proposed design shows high directivity at all resonance frequency while gain is moderate at first 3 resonance frequency. Figure 8 shows the VSWR plot (Voltage Standing Wave Ratio) of the proposed structure. For all frequency bands VSWR value is less than 2 which is within the acceptable limits for practical applications.

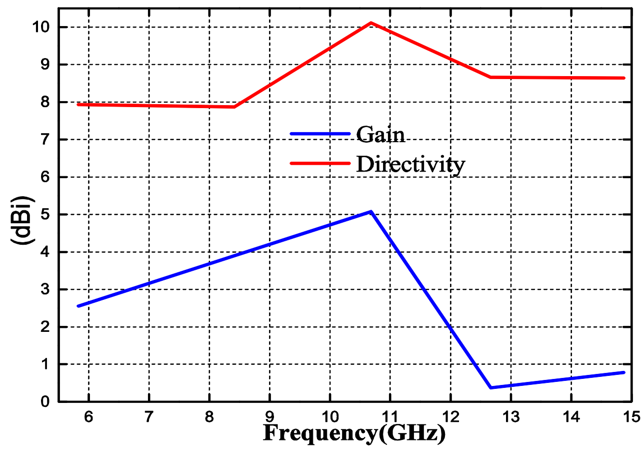

Figure 7: Gain and Directivity vs Frequency plot

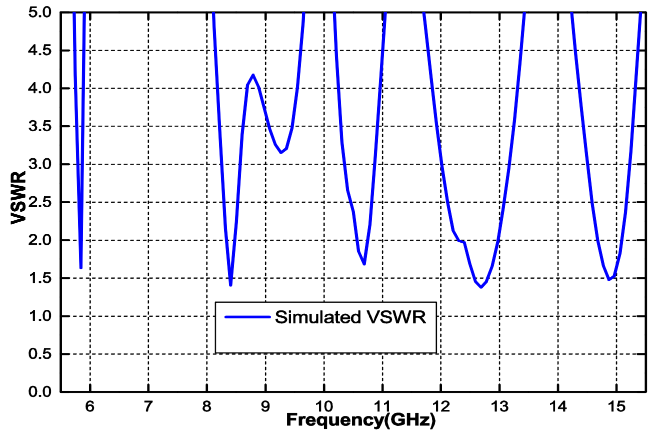

Figure 8: VSWR vs Frequency Plot

3.1. Effective Medium Parameter Extraction of SSHSS

Effective medium parameters of new unit cell (SSHSS) are numerically calculated by modified NRW approach formulas given in [10, 11]. This is done by exporting the S-Parameters from IE3D software to MATLAB and using the following equations [15,16],

$$\mu_r = \frac{2}{jk_0 d}\frac{1-V_2}{1+V_2} \quad (1)$$

$$\varepsilon_r = \frac{2}{jk_0 d}\frac{1-V_1}{1+V_1} \quad (2)$$

Where k_o is the wave number, d is the height of the substrate. V_1 and V_2 are the composite terms which are defined in Eqs. (3) and (4) [15,16],

$$V_1 = S_{21} + S_{11} \quad (3)$$

$$V_2 = S_{21} - S_{11} \quad (4)$$

Figure 9 and Figure 10 shows the extracted permeability, permittivity and index of refraction from S-parameters for this new metamaterial structure at first two resonance frequency. From figure 9 it is clear that value of permeability, permittivity and index of refraction is negative at 5.83 GHz frequency band.

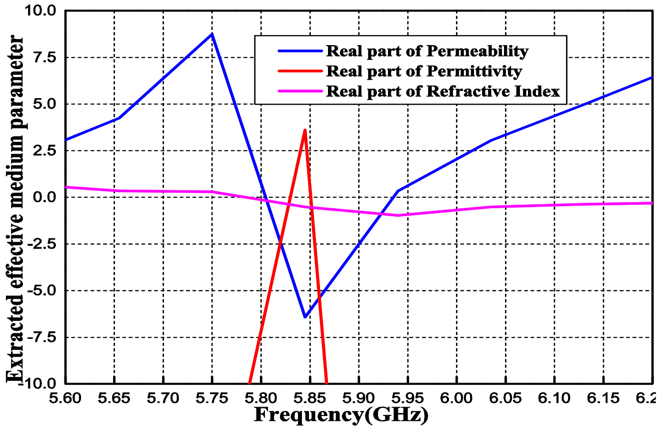

Figure 9: Extracted effective medium parameter (6 GHz)

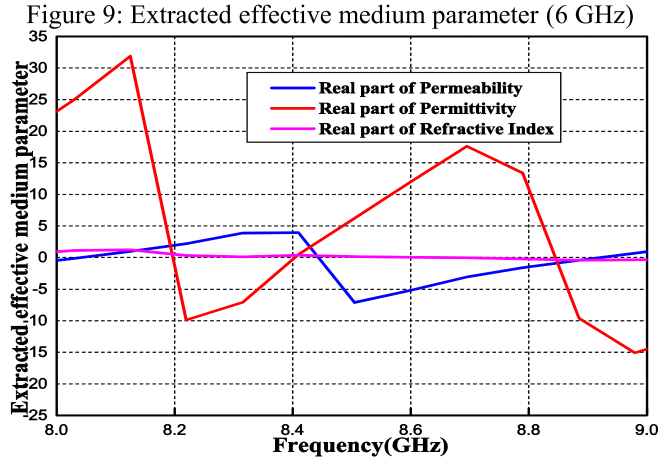

Figure 10: Extracted effective medium parameter (8 GHz)

Figure 10 depicts that value of permeability is negative, permittivity and index of refraction is near zero at 8.41 GHz.

4. Experimental Discussion

Figure 11 shows the top and bottom view of fabricated prototype of proposed split semi-horse shoe structure antenna (SSHSS).

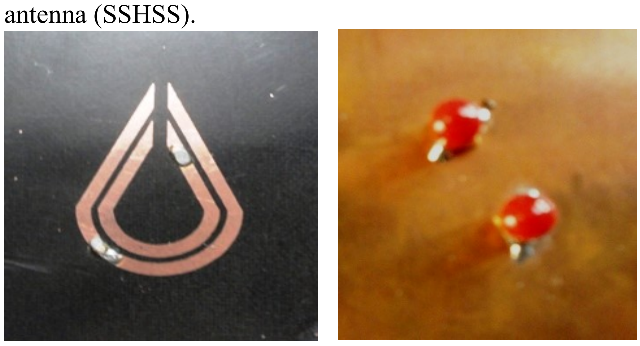

Figure 11: Fabricated prototype of proposed design

Experimental study of the fabricated prototype is done by Rohde & Schwarz vector network analyzer (VNA) up to 20 GHz. There is a good agreement between simulated and measured results for first and fourth resonance frequency while there is small upper shift in second resonance frequency. Third band reflection coefficient gets disturbed. These changes may occur due to our limitation in fabrication. Figure 12 shows the screen shot of VNA screen. There are 3 extra band at 3.89 and 16.22, 18.8 GHz which were absent in simulated results. Figure 13 shows the comparison of simulated and experimental results upto 20 GHz. Figure 14 and 15 shows zoomed view of comparison between simulated and measured results for first two resonance frequencies. Summary of measured results presented in Table 3.

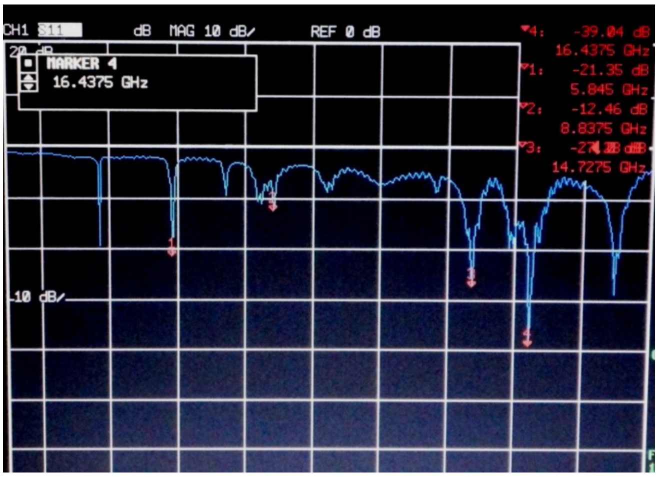

Figure 12: Measured return loss of the antenna on VNA

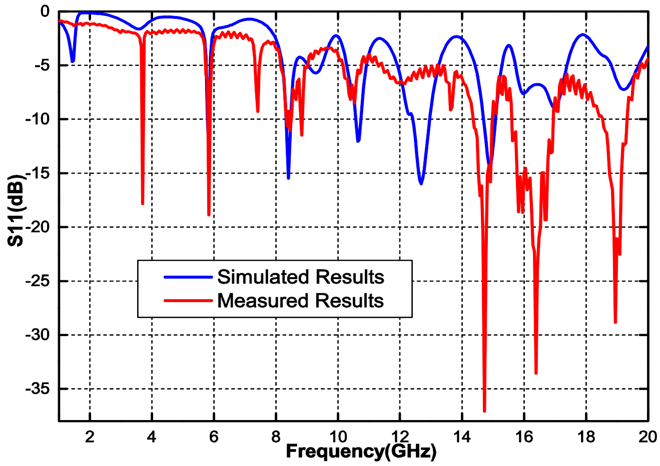

Figure 13: simulated and measured return loss

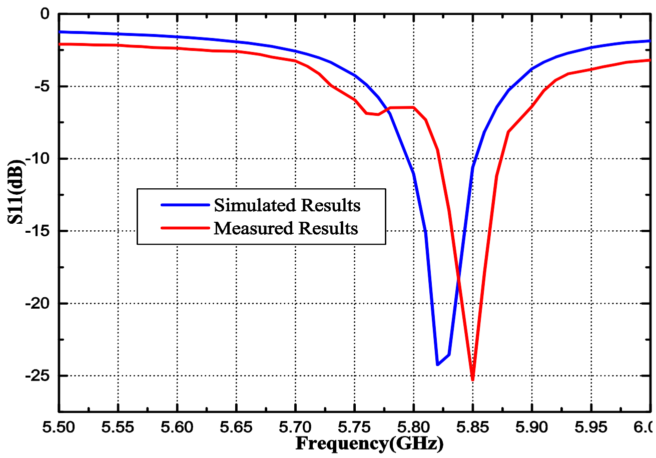

Figure 14: simulated and measured return loss at 6 GHz

Table 3 Summary of the measured results

Resonance Frequency(GHz)	Return Loss S_{11} (dB)
5.845	-21.35
8.8375	-12.46
10.5475	-8.75
13.635	-9.14
14.7275	-27.41

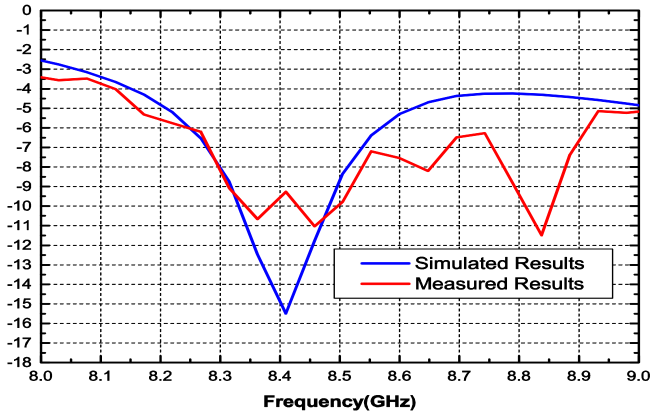

Figure 15: simulated and measured return loss at 8 GHz

5. Conclusions

This manuscript presents a new split semi-horse shoe structure (SSHSS) used as antenna. Theoretical analysis of the new structure done using equivalent circuit theory.This structure is planar as it does not have metallic rod on back side for getting negative permittivity. This antenna shows multiple resonance frequency due to the reactance (i.e., inductance and capacitance) present in the structure. Fabrication of new structure is simple. By changing split vertical length & length of stub, inductance and capacitance value changed so that resonance frequency changed X band to ISM band in present work. Metamaterial characteristics are proved using effective medium theory at 5.83 GHz and 8.41 GHz. It works as metamaterial inspired (ISM & X band) as well as normal patch antenna. Radiation pattern, directivity and gain of the new structure were illustrated which gives the possibility of using SSHSS as the antenna. Experimental findings of antenna show close agreement with simulated & theoretical results.

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