CSC-SR Structure Loaded Electrically Small Planar Antenna

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Abstract **─** This paper aims at a new planar left hand metamaterial structure for loading planar microstrip antenna (MPA). A metallic planar dual turn spiral resonator (DTSR), useful for artificial magnetic media design, is merged with a capacitive loaded strip (CLS) on the same plane to design capacitive strip coupled spiral resonator (CSC-SR) unit cell structure. Apart from having small size, the new structure offers advantages of demonstrating wide left handed frequency band, and simplicity of fabrication being on same plane, hence indicating supremacy of its inclusion in engineering of left hand metamaterials. The size of proposed antenna is 0.177λ × 0.243λ. The electro-magnetic coupling of the proposed structure causes the MPA to resonate at lower frequency of 13.25 GHz due to loading effects. The proposed novel antenna is able to give better performance in terms of return loss, gain and fractional bandwidth and is suitable for satellite communication. The measured results are presented to validate simulated model of the proposed antenna.

Index Terms **─** High Frequency Structure Simulator, left hand metamaterials, spiral resonator.

I. INTRODUCTION

Today's need for multifunctional systems demands small handheld portable wireless equipment. In order to fulfill this demand, researcher community is always challenged to design new small sized and more multifunctional antennas. An ineffaceable mark in this direction has been created by outset of metamaterials by antenna researchers for improving the performance of conventional planar antennas such as patch antenna [1]. Metamaterials (MTMs) are structured composite materials with inimitable characteristics caused by interaction of electromagnetic waves with the finer scale repetition of natural materials [2]. These may be used to amend the effective electromagnetic parameters of planar antenna dielectrics and to design antennas with improved coupling to the feed, augmented impedance, matching bandwidths, scaled down size and narrower beam widths as compared to those which instead choose the conventional dielectric materials.

The notion of these materials come into sight with the revolutionary intangible idea of Veselago [3] but materialized with the work of Pendry to synthesize the materials artificially [4-6] with split ring resonators (SRRs) and thin wires. These are also termed as double negative materials or left hand materials (LHM). It is known that some metals like gold, silver show a negative permittivity at optical frequencies [5]. But no material with negative permeability exists in nature. Hence, several different approaches to design SRR have been developed and practiced for various microwave applications to investigate the physics behind them and effects of their geometry on the fundamental material parameters of LHM. The SRRs can be coupled in many different ways by coalescing them with microstrip, coplanar and stripline feed to add the planarity attribute. Depending on the type of coupling used and resonator, different characteristics of the circuit can be customized. Various shapes of SRRs including rectangular [7-8], symmetrical [9], triangular [10], hexagonal [11], spiral [12-14], circular [15-16], omega [17] and S-shaped [18] etc., and their configurations including edge-coupled and broadside-coupled [19] and complementary forms [20-21] etc. have been investigated in literature and are still in progress.

This paper focuses on electrically small rectangular microstrip patch antenna (MPA) loaded with new left hand metamaterial unit cell structure. This structure is formed by merging dual turn spiral resonator (DTSR) and capacitance loaded strip (CLS) on the same side of plane on which the antenna is fabricated. The main advantages of spiral resonator (SR) are its small electrical size at resonance, lack of magneto-electric coupling thus avoiding bi-anisotropic effects in the bulk medium made up of this inclusion and easy fabrication.

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The paper is planned in four Sections. After introduction of the topic of interest in Section I, Section II describes the materials used and gives the method of design, modeling, simulation of CSC-SR structure and proposed antenna. Section III presents the results and analysis of simulated results of proposed structure and loaded antenna followed by measured results of fabricated proposed antenna. Section IV concludes the presented work.

II. MATERIALS AND METHODS

A. Modeling of proposed CSC-SR unit cell structure and CSC-SR loaded antenna

Mostly, SRR based LHMs exhibit a very narrow negative refraction band which can be widened by inclusion of thin wire structure due to inherently wide negative permittivity region [22]. The proposed CSC-SR LHM unit cell structure therefore consists of two turns spiral resonator and a capacitive loaded strip (CLS). The CLS is united with SR and combined structure is used to load the MPA in the same plane. The antenna of size 0.177λ × 0.243λ with the parameters as mentioned in Table 1, is printed on Rogers RT/Duroid 5880 substrate of permittivity (ε_r) = 2.2, loss tangent = 0.0009 and thickness (h) = 2.361 mm. The patch antenna is displaced at a distance (d) of 0.5 mm from CSC-SR unit cell. Figures 1 (a) and 1 (b) show the cross sectional view and top view of proposed microstrip patch antenna respectively.

To simulate the CSC-SR loaded antenna, the coax base connector is used to feed the patch at an optimized position (-1.13, -2.5) mm with respect to origin for excellent impedance matching. The CSC-SR structure gets excited through the patch as it is placed near the patch.

The characteristic size of the basic unit cell should be much less than the operating wavelength to approximate it to the effective electric and magnetic properties of a medium according to effective medium theory. The dimensions of unit cell are calculated accordingly, with the fundamental equations used in [12]. Then, optimizing the parameters of CSC-SR structure and loaded antenna with 'Optimetrics' feature of High Frequency Structure Simulator (HFSS), final dimensions are determined.

As the unit cell structures can be approximated with appropriate lumped circuit elements with the quasi-static approach, the proposed structure may be equated to an LC circuit [13]. The SR ring is equivalent to an inductance coil and the split in the spiral produces a parallel plate capacitor. An electric current gets induced in the spiral when placed in a time varying magnetic field so that charge gets accumulated across the gap. The resonant response of the SR loop current to an external magnetic field produces a resonant magnetic moment. An extra capacitance is provided by CLS. The magnetic moment leads to negative values of material parameters for LHM.

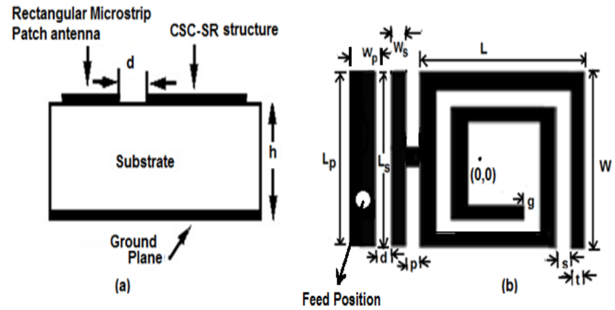

Fig. 1. (a) Cross sectional view of new planar CSC-SR structure loaded MPA, and (b) top view of new planar CSC-SR structure loaded MPA.

Table 1: Dimensional parameters of CSC-SR structure loaded MPA

S. No.	Parameters	Value (mm)
1.	Length of patch (L_p)	4
2.	Width of patch (W_p)	0.5
3.	Length of outermost turn of SR (L)	4.0
4.	Width of outermost turn of SR (W)	4.0
5.	Gap or split of turn (g)	0.2
6.	Spacing between inner turn and outer turn (s)	0.2
7.	Distance between patch antenna and LHM (d)	0.5
8.	Thickness of ring (t)	0.2
9.	Length of CLS (L_s)	4.0
10.	Width of CLS (W_s)	0.2
11.	Distance between CLS and SR (p)	0.3

B. Simulation of CSC-SR unit cell in waveguide

Initially, the proposed CSC-SR unit cell is simulated by putting it in a rectangular waveguide for investigating the metamaterial properties. The proposed CSC-SR unit cell used to load the antenna, is expected to demonstrate the left hand metamaterial properties. For this, the wire is excited by the electric fields, whereas the loop is excited by the magnetic fields. So, perfect electric conductor boundary conditions and perfect magnetic conductor boundary conditions are assigned on the y-direction and z-direction respectively. After applying boundaries, the metamaterial unit cell is applied excitations for field calculations. The CSC-SR unit cell depicted in Fig. 2 is simulated within a waveguide to observe its resonating frequency region and transmission frequency minimum. The proposed unit cell is numerically analyzed with HFSS software which employs adaptive mesh refinement procedures iteratively in high error areas to enhance precision of solution. HFSS recalculates the error on each iteration until the convergence norms are fulfilled for ultimate solution. All the simulations are executed on Intel Core TM i7, 2.67 GHz processor with 4 GB RAM system.

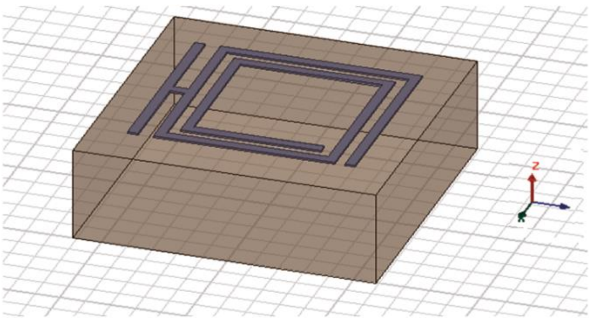

Fig. 2. Proposed CSC-SR unit cell on substrate.

The transmission spectrum of the CSC-SR is extracted from the S-parameter calculations. Further, effective permeability (μ_{eff}) and effective permittivity (ε_{eff}) of an equivalent metamaterial are determined from Nicolson-Ross-Weir (NRW) approach [6] for in-plane incidence to retrieve the effective electromagnetic parameters (μ_{eff} and ε_{eff}) from Scattering parameters, i.e., S_{11} and S_{21}. The reflection parameter (S_{11}) signifies the measure of EM wave reflected due to impedance mismatching in the transmission medium and transmission parameter (S_{21}) indicates the measure of EM wave passed through the conducting element;

$$V_1 = S_{21} + S_{11}, \tag{1}$$

$$V_2 = S_{21} - S_{11}. \tag{2}$$

The values, V_1 and V_2 indicate the summation and difference of S-parameters. The V_1 and V_2 are calculated from Equations (1) and (2):

$$\mu_{eff} = \frac{2}{jk_0 h}\frac{1-V_2}{1+V_2}, \tag{3}$$

$$\varepsilon_{eff} = \frac{2}{jk_0 h}\frac{1-V_1}{1+V_1}, \tag{4}$$

where k_0 is wave number in free space and is equated to ω/c, ω, is radian frequency and is $= 2\pi f$ for frequency f, c is speed of light $= 3\times10^8$ m/s, μ_{eff} is effective permeability of equivalent metamaterial, ε_{eff} is effective permittivity of equivalent metamaterial and h is thickness/height of substrate.

III. RESULTS

A. Simulated results of CSC-SR structure in waveguide

To evaluate the effective parameters of the structure, S-parameters, S_{11} and S_{21} are obtained by simulation of the CSC-SR structure. Figure 3 depicts S_{11} and S_{21} for the CSC-SR structure.

The S_{11} parameter for the proposed structure has a dip at frequency 2.45 GHz and transmission minimum of S_{21} is observed at frequency 2.85 GHz. The phase reversal of S_{11} and S_{21} at resonant frequency is depicted in Fig. 4. The phase reversal exhibited by the novel structure at the resonant frequency verifies its metamaterial behavior.

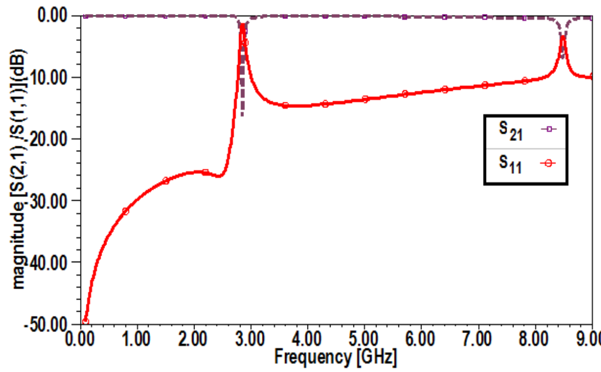

Fig. 3. S_{11} and S_{21} of CSC-SR structure.

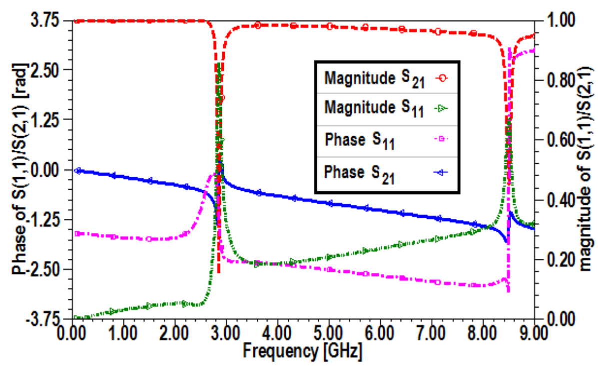

Fig. 4. Magnitude and phase of S_{21} and S_{11} of CSC-SR structure.

The effective parameters of CSC-SR structure are evaluated through S_{11} and S_{21} of new MTM structure. A MATLAB code is used to implement Equations (1) to (4) to demonstrate effective negative permeability and permittivity.

The values of effective electromagnetic parameters of CSC-SR such as effective permeability (μ_{eff}) and permittivity (ε_{eff}) are plotted in Fig. 5 (a) and refraction index (n) in Fig. 5 (b).

The regions of negative permeability and permittivity are clearly evident from the plots. It can be visualized in Fig. 5 (a) that the negative permeability is exhibited for the range 2.85 GHz - 6.15 GHz and the negative permittivity is achieved for the frequency range 2.00 GHz - 6.20 GHz. The negative refraction is thus observed from 2.00 GHz - 6.20 GHz and left hand region is from 2.85 GHz - 6.15 GHz as depicted in Fig. 5 (b). Hence the left hand (LH) bandwidth for the proposed structure is 3.3 GHz which is approximately same as reported in [22]. In addition to the LH bandwidth, the proposed structure provides ease of fabrication as both conductors are on same side of substrate.

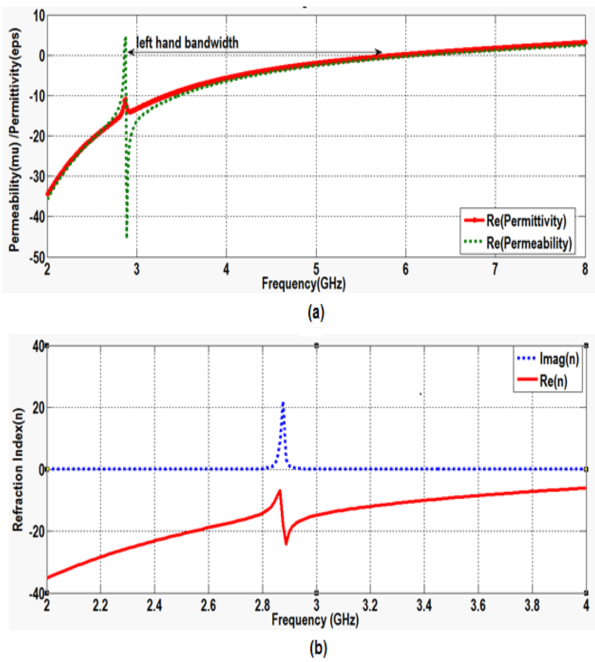

Fig. 5. (a). Effective permeability and permittivity of CSC-SR structure, and (b) refraction index of CSC-SR structure.

B. Simulated results of unloaded MPA and proposed MPA loaded with CSC-SR LHM unit cell

The MPA is placed near the CSC-SR MTM structure and excited by coaxial feed. The SR joined with wire gets excited due to mutual induction of MPA. Hence the complete proposed antenna consists of MPA with LHM unit cell. In the present work, the performance comparison for loaded MPA and unloaded MPA has been done and results are analyzed. The antenna model is initially executed without loading with the CSC-SR structure.

The unloaded antenna resonates at frequency of 27.12 GHz with return loss of 11.8 dB below 0 dB as depicted in Fig. 6. The value of voltage standing wave ratio (VSWR) is 1.69 which indicates high mismatch of impedance. The gain and directivity achieved for the unloaded antenna is 3.7 dB and 3.81 dB respectively. The comparative performance of unloaded MPA and the proposed CSC-SR loaded MPA is given in Table 2.

The novel antenna design is then obtained by loading CSC-SR LHM structure. The loading of SR is preferred for design of electrically small antenna (ESA) because conventional LC resonator uses unit cell area inadequately and so SR loading can be proposed to design ESA [14].

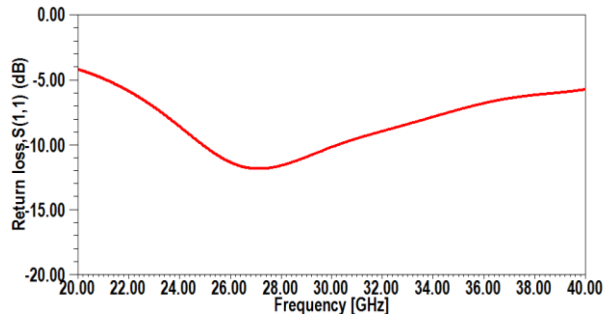

Fig. 6. Return loss of unloaded rectangular MPA.

Table 2: Comparison of proposed CSC-SR loaded MPA with unloaded MPA

S. No.	Parameters	Unloaded MPA	Proposed Antenna
1.	Return loss	-11.8 dB	-47 dB
2.	VSWR	1.69	1.0094
3.	Gain	3.7 dB	7.09 dB
4.	Directivity	3.87 dB	7.17 dB
5.	Antenna dimensions	4 mm × 0.5 mm	4 mm × 5.5 mm

The numerical simulations of the proposed antenna are performed with the intention to conceive the interaction between these conductors with the applied electromagnetic fields. The proposed antenna is also numerically analyzed with HFSS software. The resonant frequency of CSC-SR MTM loaded antenna shifts to low frequency side as compared to resonant frequency of unloaded antenna. This is because of change in capacitance due to geometrical parameters of structure. The loaded antenna resonates at 13.25 GHz with an impedance bandwidth of 1056 MHz as demonstrated in Fig. 7. Its value is 47 dB below 0 dB at resonant frequency, 13.25 GHz and corresponding VSWR value is 1.009 indicating good matching of impedance. The fractional bandwidth (FBW) achieved is 7.96%.

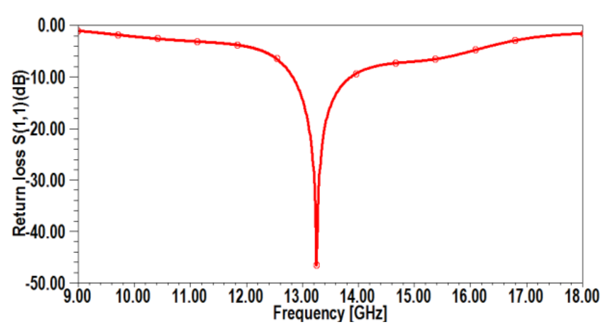

Fig. 7. Return loss of CSC-SR loaded MPA.

A 50 Ω impedance matching is achieved at the resonating frequency of 13.25 GHz as is depicted from the input impedance variation over frequency sweep in Fig. 8.

Figure 9 displays 3D polar plot of gain with peak value 7.09 dB and 3D plot of directivity with maxima of 7.17 dB at resonant frequency. The elevation and azimuth gain radiation patterns are shown in Fig. 10 for proposed antenna.

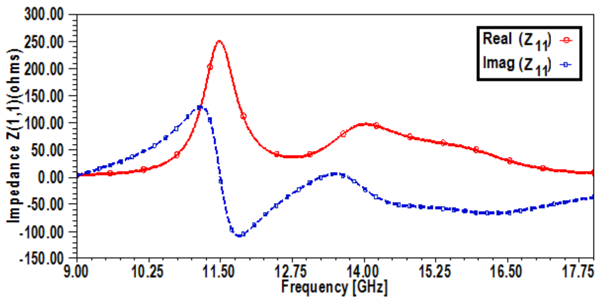

Fig. 8. Input impedance characteristics of CSC-SR structure loaded MPA.

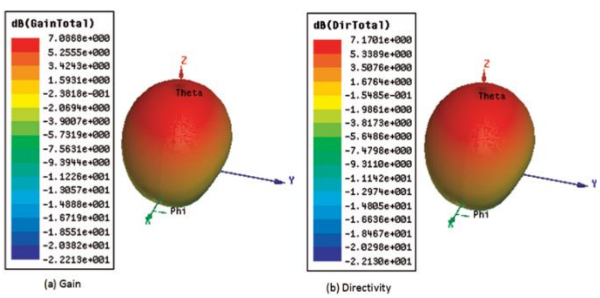

Fig. 9. 3D polar plot of gain and directivity of CSC-SR structure loaded MPA.

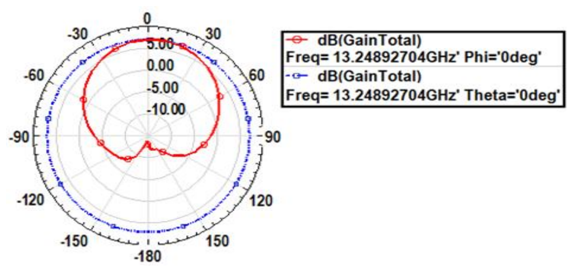

Fig. 10. Simulated radiation pattern of MPA loaded with CSC-SR.

The essential condition for being an electrically small antenna, the largest dimension of the proposed antenna must fit inside an imaginary sphere, termed as 'radian sphere' of radius 'a', and should satisfy the condition in Equation (5) [23,24]:

$$ka < 1, \tag{5}$$

where ka=(2π/λ)a and λ is operating wavelength. For the proposed antenna, ka=0.943 which is less than 1.

A relationship between minimum quality factor (Q_{chu}) and the radiation quality of an ESA was derived by Chu which is given by Equation (6) [25]:

$$Q_{chu} = \frac{1}{(ka)^3} + \frac{1}{ka}. \tag{6}$$

According to Chu limit, an antenna would experience poor efficiency at a size below Chu limit (Q_{chu}). The minimum calculated radiation factor (Q_{rad}) from equation (7) for the proposed antenna is 2.25. For an antenna to be ESA, its radiation factor, Q_{rad} should be > 10 [26]. The value of Q_{rad} can be calculated as:

$$Q_{rad} = \frac{1}{fractional\ BW}. \tag{7}$$

The value of Q_{rad} for proposed antenna is 12.7 and is >> Q_{chu}. Thus, the proposed ESA structure is practically realistic with stated parameters.

C. Experimentally measured results of proposed fabricated antenna

The proposed antenna is fabricated on Rogers Duroid substrate 5880 of dielectric constant 2.2 and height 2.361 mm. The photographs of two sides of fabricated antenna are shown in Fig. 11.

The return loss for the fabricated antenna is shown in Fig. 12 measured with Agilent N5222A PNA Microwave Network Analyzer. The measured value of return loss for the fabricated antenna is 24 dB below 0 dB and impedance bandwidth is 1085 MHz at resonant frequency 13.2 GHz as compared to simulated value of 47 dB below 0 dB with impedance bandwidth 1056 MHz. The observed difference of experimental results from simulated results is due to cable loss between the connector and antenna and soldering.

Figure 13 compares the simulated 2D gain for the CSC-SR loaded antenna with the measured values. The antenna shows good response in the frequency range from 10.25 GHz to 17.25 GHz with maximum gain at 13.25 GHz. It is also observed that measured results for return loss are close to numerically evaluated results.

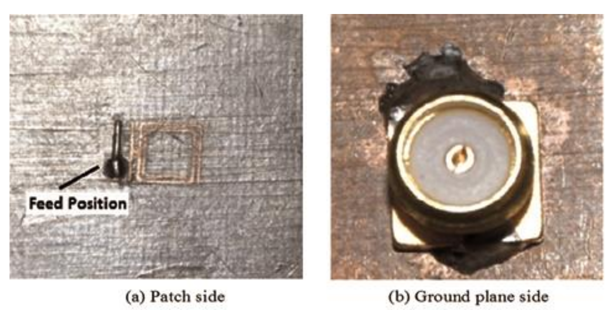

Fig. 11. Photographs of fabricated CSC-SR structure loaded MPA on Rogers Duroid substrate.

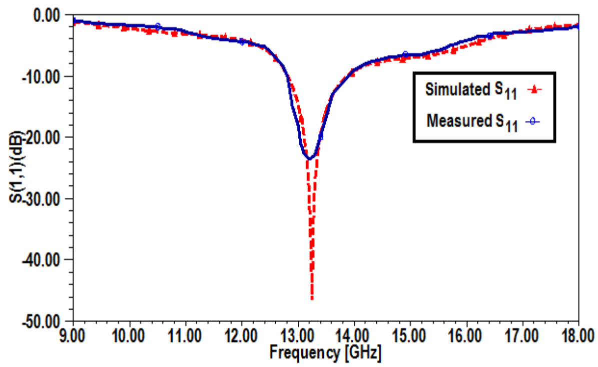

Fig. 12. Simulated and measured return loss of CSC-SR structure loaded MPA.

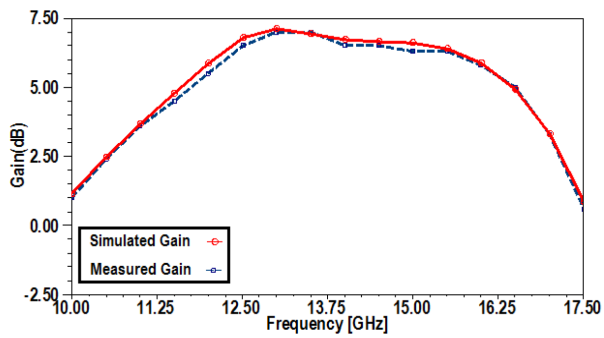

Fig. 13. Simulated and measured gain of CSC-SR structure loaded MPA as a function of frequency.

The proposed metamaterial antenna offers better performance characteristics along with miniaturization than the design reported in [7] as summarized in Table 3.

Table 3: Comparison of proposed antenna with ESA antenna reported in [7]

Antenna	Parameters	Joshi et al. [7]	Proposed Antenna
Simulated antenna	Return loss	-34 dB	-47 dB
	Gain	3.2 dBi	7.09 dB
	Directivity	7.8 dBi	7.17 dB
	Bandwidth	512 MHz	1056 MHz
	Electrically small antenna	ka=0.775 < 1	ka=0.943 < 1
	Electrical size	0.161λ × 0.192λ	0.177λ × 0.243λ
	Antenna dimensions	5 mm × 6 mm	4 mm × 5.5 mm
Fabricated antenna	Return loss	Not measured	-24 dB
	Gain	Not measured	7 dB
	Bandwidth	Not measured	1085 GHz

IV. CONCLUSION

In this work, a new planar CSC-SR metamaterial structure based planar antenna has been proposed. It is observed that proposed CSC-SR structure exhibits a very wide frequency band of 3.3 GHz with negative permittivity and negative permeability. Hence this metamaterial structure would have great prospects in designing broadband microwave devices. Further this new structure loaded MPA of size 0.177λ × 0.243λ is presented resonating at 13.25 GHz whereas the unloaded MPA was resonating at a frequency of 27.12 GHz. The resonant frequency of the antenna gets lowered with improved magnetic permeability of dielectric material by metamaterial loading. Thus it is concluded that the resonance of antenna can be controlled according to the desired application. Good impedance matching is demonstrated with S_{11} value reaching to -47 dB. The proposed antenna achieves high gain of 7.09 dB, an impedance bandwidth of 1056 MHz with fractional bandwidth of 7.96%. Measured results obtained are in good agreement with the simulated results. The proposed antenna satisfies the condition of ESA with good radiation factor and is practically feasible with stated parameters.

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15 M.Tech. thesis, 04 Ph.D. thesis and 05 thesis are in progress. She has more than 75 publications to her credit in International and National Journals in the area of antenna design, bio-electromagnetics and in micro-scale and nano-scale structures.