Experimental Verification of Gain and Bandwidth Enhancement of Fractal Contoured Metamaterial Inspired Antenna

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ABSTRACT The performance of any antenna cannot be completely assessed purely on the basis of simulation results. All simulations are made by assuming an ideal environment where the fabrication tolerances and practical losses are not accounted for. Therefore, evidencing the performance experimentally becomes a crucial step. In this work, the experimental validation of a fractal contoured square microstrip antenna with four ring metamaterial structure, hereon referred to as optimized metamaterial inspired square fractal antenna has been presented. It is an extension to previously designed antenna and aims to experimentally verify the enhanced gain and bandwidth of this antenna. The design and simulation of the proposed antenna was accomplished by using Ansys HFSS v18.2. The end-to-end antenna spread area is 23 mm x 23 mm on a 46 mm x 28 mm x 1.6 mm FR4 substrate with ε_r of 4.4. The simulated design was fabricated using Nvis 72 Prototyping Machine and measured in an anechoic chamber facility using vector network analyzer. The antenna resonates with the deepest S_{11} of -39.5 dB in a broad bandwidth of 2.53 GHz from 2.265 GHz to 4.79 GHz with experimental verification. The proposed antenna provides an enhanced gain of 8.81 dB at the most popularly used frequency of 2.5 GHz. The simulation and experimental results of resonance, gain and radiation pattern are found to agree maximally. The fractional bandwidth offered by this proposed antenna is 72.28%. The experimental validation confirms enhanced gain-bandwidth performance in a wide resonance band. Hence, this antenna is well recommended for wireless, energy harvesting rectenna and sub-6 GHz (2.5 GHz to 4.20 GHz) 5G applications.

INDEX TERMS Broadband, Energy harvestment, Fractal Gain, Metamaterial, Radiation pattern, S_{11}

I. INTRODUCTION

THE evolution of technology has introduced and still demands sophistication of handheld devices. Therefore, research on making these devices and microstrip antenna (MSA) compact, is rigorous. The miniaturization of an antenna involves a trade-off between gain and bandwidth. This compromise does not bode well for applications like RF energy harvesting, where the gain and radiation performance play a pivotal role. Thus, to overcome the performance degradation while accomplishing the challenges of miniaturization, techniques like fractal geometries and metamaterials (MTM) have proved useful. The fractal concept, introduced by Mandelbrot in 1983, remains the most popular and widely employed method of antenna miniaturization. The space-filling and self-similarity features of fractal geometry in the MSA design offer enhanced bandwidth (BW) and multiple resonances without compromising the antenna spread area.

The concept of MTM was introduced by Veselago (1968) [1, 11-12]. He proposed that a material may be artificially enhanced to exhibit negative permeability (μ) and permittivity (ε) at some selected frequencies. Such materials are called double negative materials (DNG). Nearly 32 years later, John Pendry extended the MTM research by practically proposing these structures in 2000 [32]. Since then, MTM structures have proven to be a versatile technology with enormous research scope. The utilization of MTM is reported to be diverse ranging from application in microwave, antenna design, filters, couplers, object cloaking to count a few. The conventional characteristics of an MSA can be improved by using MTM as a superstrate, DNG complementary cells, DNG [7-9], graded MTM [18] and water-based MTM [19]. A variety of designs [2-3, 21-25, 27-31, 33-35] illustrate the methods like truncating the ground, incorporating a split ring resonator (SRR) as a MTM loading, enhance the gain and directivity of the antenna. Other techniques like incorporating asymmetric patch structures can be used to enhance the impedance BW [5, 17].

This article is an extension of the authors' previously accomplished work with simulation results of resonance and radiation characteristics as reported in [4]. A novel idea of parametric optimization was adapted to sufficiently enhance the BW and gain of the antenna. A conventional square MSA was designed for 2.5 GHz using closed form analysis on FR4 substrate of size 46 mm × 28 mm. The comparison between CPW and microstrip feed showed better S_{11} for microstrip feed. A square shaped fractal geometry at its fourth iterated stage was then introduced around the circumference of this square MSA. This iterative structure increases perimeter of the patch and the electrical size of the antenna in the same overall area. This enhances the resonance without compromising the size of the antenna. This is technique and design steps are better illustrated in Fig.1. A square shape is used as the initiator. It is further modified by removing square tab elements which are 1/4th the size of the initiator at all the four corners in the first iteration. Two sets of squares are removed at each corner to get the second iteration. This obtained structure is repeated four times to obtain the third iteration. The center portion is filled with metallic structure for continuity. Similarly, four copies of the third iteration are repeated to obtain the fourth iteration. This iteration is then halted here, as the size of the smallest square becomes 1mm x 1mm. This is done in order to meet the practical requirements, for fabricating extremely intricate patterns becomes restrictive.

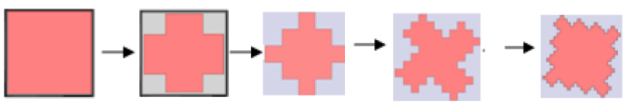


FIGURE 1. Iteration stages for developing square fractal geometry

To further enhance the performance, the ground was truncated in steps of 1/4. A truncation at ground length of 20mm gave better resonance characteristics. Finally, this antenna was loaded with a passive four ring SRR structure at the rear side. This square MSA with fractal contouring and four ring SRR structure is henceforth considered the optimized metamaterial inspired square fractal antenna (OMSFA). In this article, the fabrication of antenna with full ground, truncated ground and SRR structure as well as experimental testing for resonance and radiation characteristics have been discussed for validating the simulated results.

II. ANTENNA FABRICATION AND MEASUREMENTS

The OMSFA consists of a The OMSFA was designed to resonate at a frequency of 2.5 GHz on a 46 mm x 28 mm x 1.6 mm FR4 substrate with a dielectric constant of 4.4.

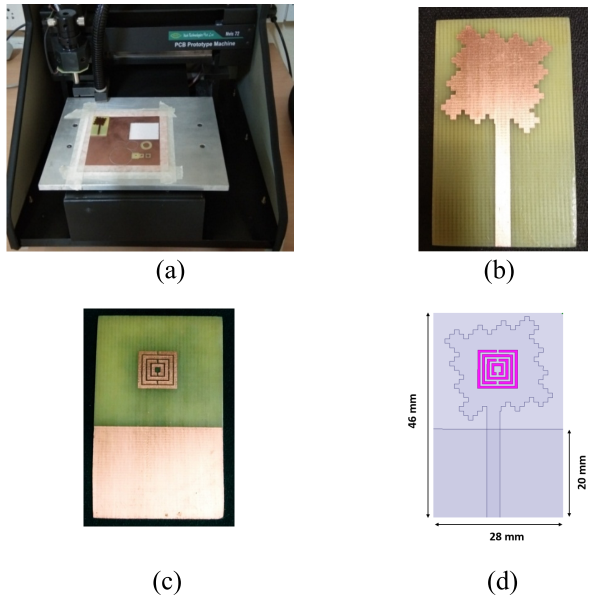
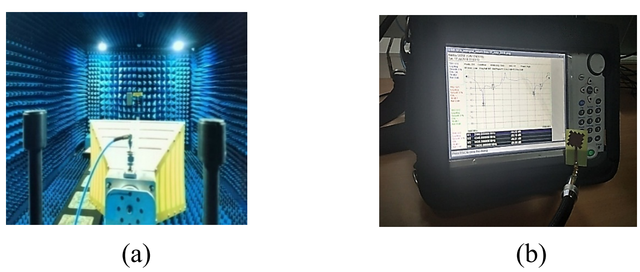
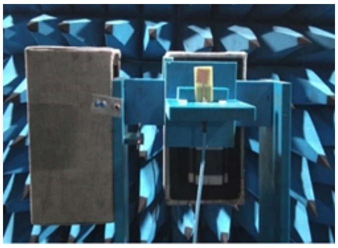


FIGURE 2. Fabricated OMSFA (a) during fabrication process in PCB machine (b) front side (c) rear side and (d) Schematic of the OMSFA

The complete design details [4] are available in Table 1, thus, are not repeated in this paper. A printed circuit board (PCB) process is employed to etch and fabricate the proposed OMSFA, which is depicted along with the front and rear views in Fig. 2. The antenna testing facility reported in [26], including the anechoic chamber (AC) with a broadband horn antenna and a Vector Network Analyzer (VNA) (Model: Anritsu Site Master S820E), has been utilized for characterizing the proposed antenna. The VNA was setup for a sweep range of 1 GHz to 12 GHz during the calibration and measurement processes. The AC installed with an automated three axis rotating motor system has been used to rotate the antenna in all the desired angles for performing radiation pattern measurement. The snapshots of the measurement setup are shown in Fig. 3. The subsequent sections deal with the measured results of the proposed OMSFA. The AC, installed with an automated three axis rotating motor system has been used to rotate the antenna in all the desired angles for performing radiation pattern measurement. The snapshots of the measurement setup are shown in Fig. 3. The subsequent sections deal with the measured results of the proposed OMSFA.





(c)

FIGURE 3. View of measurement setup (a) reference horn antenna (800 MHz to 18 GHz) (b) OMSFA connected with the VNA (1 MHz to 40 GHz) (c) OMSFA mounted on a rotating stand

TABLE I. Dimensions of the proposed OMSFA

Design Parameter		Dimensions
Microstrip Patch Antenna	*Radiating Patch*	23 mm × 23 mm
	Substrate	46 mm × 28 mm × 1.6 mm
	Ground	20 mm × 28 mm
	Microstrip Feed	25 mm × 2.75 mm
SRR Structure	*Width of the SRR (w)*	0.5 mm
	Spacing between the rings (s)	0.5 mm
	Gap width (g)	0.5 mm

III. RESULTS AND DISCUSSIONS

The parametric optimization with ground truncation, evolving stages of the square fractal antenna, design aspects of MTM and the simulation results of the OMSFA are thoroughly discussed in [4]. The experimental validation of [4] has been taken up in this section. The fabricated antenna resonates at 2.98 GHz and 9.58 GHz with deepest S_{11} covering a broad bandwidth. Since, a plethora of wireless devices operate in the range of frequencies close to 2.5 GHz, the results and discussions are focused on 2.5 GHz along with the other resonant frequencies observed during measurement, highlighting the versatility of the proposed antenna. The measurement and the simulation results are found to comply in the frequency range of interest. However, a slight deviation can be observed from the simulation results. When making simulations, the connector losses are not taken into account. Thus, the experimental results might slightly deviate due to fabrication tolerance and losses in SMA connector.

A. S_{11} CHARACTERISTICS

A comparison of the measured S_{11} exhibited by the antenna with full ground, truncated ground and SRR structure is shown in Fig. 4. The fabrication and experimental testing were performed for the three developmental stages of the proposed antenna. Hence, experimental results are compared. The dashed green line represents antenna with full ground, the red dotted line represents antenna with truncated ground and the solid blue line represents OMSFA. It is evident from the graph that the antenna resonates in two bands that cover S-band and X-band. However, the deepest S_{11} of -39.5 dB is offered in S-band at 2.98 GHz. The antenna with truncated ground and the OMSFA shows enhanced performance as compared to the antenna with full ground. The OMSFA exhibits two resonances at 2.98 GHz and 9.58 GHz within the resonant bandwidth. In comparison to full ground and truncated ground variations, the proposed OMSFA offers deeper S_{11} of -39.5 dB at 2.98 GHz, while providing a broader operational BW of 2.53 GHz ranging from 2.26 GHz to 4.79 GHz.

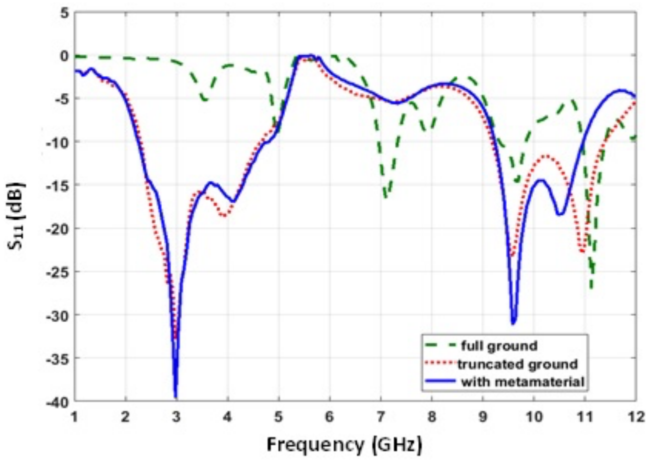


FIGURE 4. Comparison of measured RL in three stages (full ground, truncated ground and OMSFA)

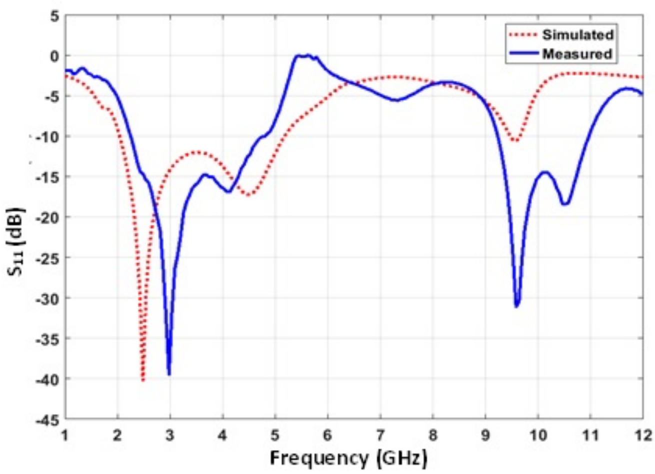


FIGURE 5. Comparison of simulated and measured S_{11} of OMSFA (Simulation data courtesy: [4])

It can be observed that at the most often employed frequency of 2.5 GHz, the antenna resonates with S_{11} of -14.7 dB within the same broad BW. These parameters are listed in Table 2, depicting superior performance of the OMSFA. It may be noted that all the data in this table comprises of the values extracted from the experimental results of the developmental stages of the proposed antenna. The simulated and measured S_{11} of the OMSFA are compared in Fig. 5.

TABLE II. Comparison of measured results

Antenna Type	f_r (GHz)	S_{11} (dB)	Resonance BW (GHz)	FBW (GHz)
Full ground SFA	7.01	-16.8	0.31 (6.99 GHz to 7.30 GHz)	4.34
	11.12	-26.9	0.40 (10.95 GHz to 11.35 GHz)	3.58
Half ground SFA	2.98	-32.8	2.31 (2.32 GHz to 4.63 GHz)	66.57
	10.99	-29.9	2.15 (9.19 GHz to 11.34 GHz)	20.95
Proposed OMSFA	2.50	-14.7	2.53 (2.26 GHz to 4.79 GHz)	72.28
	2.98	-39.5	2.53 (2.26 GHz to 4.79 GHz)	72.28
	9.58	-31.1	1.70 (9.25 GHz to 10.95 GHz)	16.83

The dotted red line represents the simulated S_{11} while the solid blue line represents measured S_{11}. Although the characteristic curves agree in shape, the resonance point observed at 2.5 GHz in simulation shifts to 2.98 GHz with a S_{11} of -39.5 dB when measured. This shift might be due to the practical issues such as quality of SMA connector, soldering, connecting cables and fabrication process. However, the resonance at the expected frequency of 2.5 GHz still falls within the first resonance BW. The corresponding fractional bandwidth (FBW) obtained in the first band is 72.28 % which is much higher than the normally expected 20 %. The measured results illustrate that the OMSFA also shows resonance in another broad bandwidth from 9.25 GHz to 10.95 GHz with resonance point at 9.58 GHz. The S_{11} at 9.58 GHz is also appreciably deep at -31.1 dB.

B. GAIN CHARACTERISTICS

An investigation on the square fractal antenna (SFA) without SRR and OMSFA with the SRR was carried out to observe the influence of SRR on the performance. Accordingly, the gain characteristics have been compared in Fig. 6. The gain of the SFA is found to be 4.7 dB whereas it is 8.81 dB for OMSFA. It is evident that the incorporation of SRR structure has significantly enhances the gain of the antenna. Hence, parametric retrieval and validation have not been reprised in this manuscript. The detailed works in [2, 38] can be referred for further clarity.

The OMSFA exhibited enhanced performance in the simulation. This was further verified through experimental verification. The gain characteristics of simulated and measured OMSFA are plotted and compared in Fig. 7. The dotted red line represents simulated gain and the solid blue line represents measured gain.

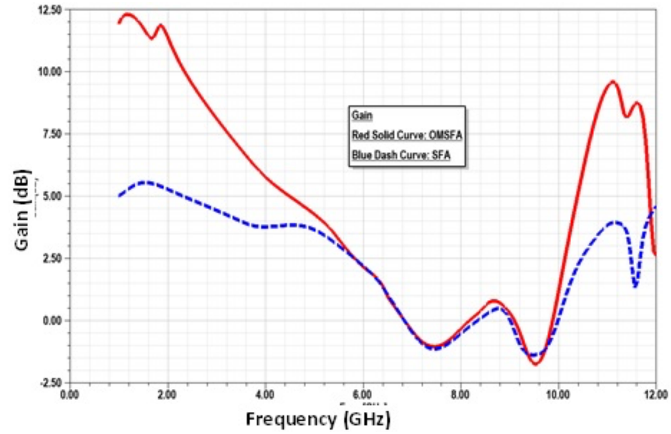


FIGURE 6. Comparison of simulated gain of SFA and OMSFA (Simulation data courtesy: [4])

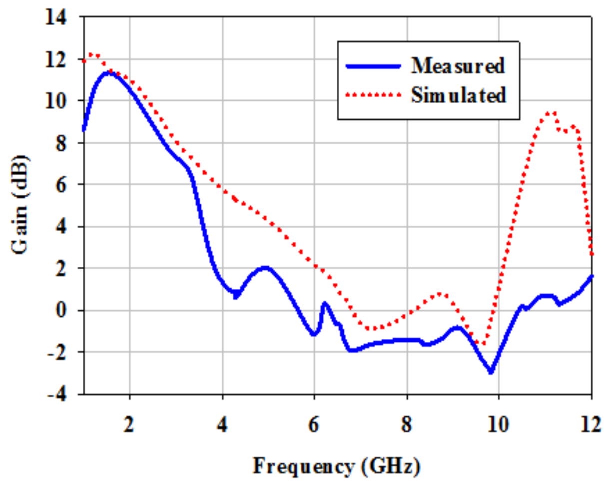


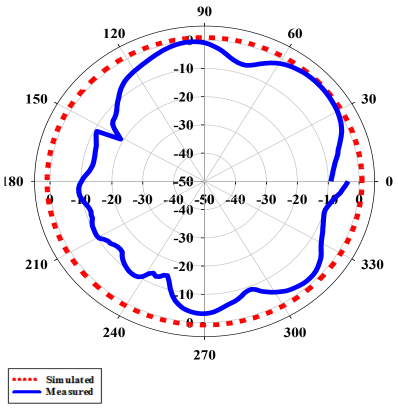
FIGURE 7. Comparison of simulated and measured gain of the proposed OMSFA (Simulation data courtesy: [4])

The variation of gain in both the cases is almost similar. It can be noted that the gain at 2.5 GHz is 8.85 dB whereas it is 7.28 dB at the first resonant frequency of 2.98 GHz. In the first resonance band a maximum gain of 9.64 dB is observed at 2.26 GHz and it falls to a minimum of 1.96 dB at 4.79 GHz. In the second resonance band, the maximum gain of 0.82 dB occurs at 9.25 GHz and drops down to -1.053 dB at 10.95 GHz.

C. RADIATION PATTERN

Even though the antenna resonates at two larger BWs, the radiation patterns were measured at 2.5 GHz and discussed in this section. The Cross-polarization (X-pol) radiation is usually much more substantial at θ=90º or the H-plane and the Co-polarization (Co-pol) radiation is usually significant at θ=0º or the E-plane [36, 37]. The radiation patterns at 2.5 GHz for studying the Co-pol (θ=0º and φ= 0º to 360º) and the X-pol (θ=90º and φ= 0º to 360º) were measured and plotted in Fig. 8. It can be observed from Fig.8(a) that the maximum radiation occurs at a larger solid angle and the radiation reduces slightly between 130º to 250º direction.

Fig.8(b) depicts the X-pol radiation pattern, where maximum gain is much lesser as compared to the Co-pol radiation pattern.



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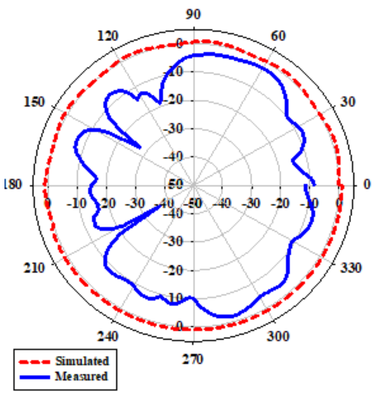


(b)

FIGURE 8. Comparison of simulated and measured radiation patterns at 2.5 GHz (a). Co-Pol (E-Plane) (b). X-Pol (H-Plane) (simulation data courtesy: [4])

Hence, the Co-pol and X-pol are acceptable. In the measurement setup, the installed stepper motor in the AC moves in steps of 9° instead of the conventional steps of 10°. Hence, the measured radiation patterns plotted in Fig 8. do not make a perfect loop and the angles 0° and 360° appear unconnected. The extracted gain values at different φ angles have been listed in Table 3. The radiation pattern analyses at other frequencies may be carried out in future works as required.

TABLE III. Extracted gain from radiation pattern at various angles

Azimuth angle at φ	Extracted Gain (dB) at 2.5 GHz	
	Co-polarization	Cross-polarization
0°	-9.10	-8.66
90°	-0.95	-4.20
180°	-10.20	-15.04
270°	-3.13	-10.00
360°	-3.58	-11.50

TABLE IV. Comparison of measured results with literature

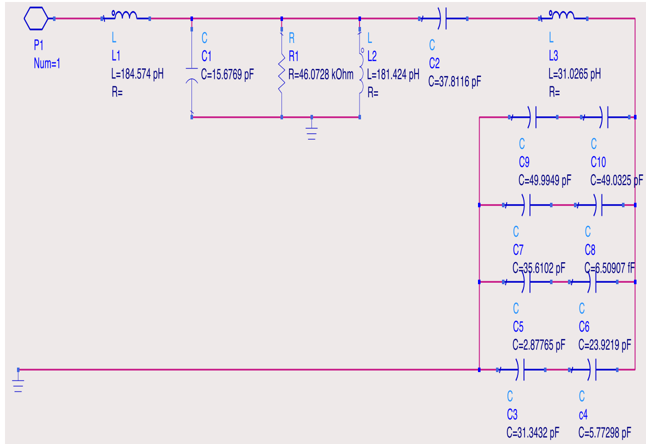
Ref.	Specification	f_r (GHz)	S_{11} (dB)	BW (GHz)	FBW (GHz)	Gain at f_r (dB)
Proposed OMSFA (measurement)	Substrate: FR4 Feed: Microstrip Ground: Truncated Antenna type: Fractal Antenna Dimension: 46 mm x 28 mm x 1.6 mm	2.50 2.98 9.58	-14.7 -39.5 -31.1	2.53 2.53 1.70	72.28 72.28 16.83	9.50 8.24 -1.73
[4] Proposed OMSFA (simulation)	Substrate: FR4 Feed: Microstrip Ground: Truncated Antenna type: Fractal Antenna Dimension: 46 mm x 28 mm x 1.6 mm	2.5	-38.9	3.2	126	9.80
[10] (simulation)	Substrate: FR4 Feed: Microstrip Ground: Full Antenna type: Fractal Antenna Dimension: 70 mm x 70 mm x 1.6 mm	3.41	-20	2.35	68.91	2.30
[13] (measurement)	Substrate: Neltec Feed: Microstrip Ground: Full Antenna type: Multiband MSA Antenna Dimension: 19 mm x 19 mm x 0.20 mm	3.2 5.4 5.8	-21 -24 -23.8	0.08 0.06 0.12	2.49 1.11 2.06	3.28 2.76 3.10
[15] (measurement)	Substrate: FR4 Feed: CPW Antenna type: Monopole Antenna	2.47	28	0.10	4.04	1.76

	Dimension: 27.4 mm x 12 mm x 1.6 mm					
[16] (measurement)	Substrate: FR4 Feed: microstrip Ground: Truncated Antenna type: Fractal Antenna Dimension: 19.7 mm x 17 mm x 1.6 mm	5.2	13.0	1.60	31.37	4.00

In Table 4, the performance of the proposed antenna has been compared with various antennas reported in the literature [10, 13, 15, 16]. The simulated OMSFA [4] offers nearly 5.7 GHz wider fractional bandwidth and 7.5 dB more gain than the design in [10] while the measured OMSFA results show deep resonances covering multiple bands. It also measures at least 4 dB better gain to that of the design in [13] and 7 dB better gain than [15] in the 2.5 GHz band. Unlike [16], the OMSFA offers enhanced fractional bandwidth performance with resonances in two bands. This makes the OMSFA a suitable candidate for a wider range of applications. It is evident that the proposed antenna shows significantly better performance.

D. EQUIVALENT CIRCUIT MODEL

The proposed OMSFA consists of a fractal radiating element and a truncated ground with an SRR structure incorporated as a passive gain enhancing element. The capacitances involved in the fractal geometry are by the virtue of the several iterative cuts made in the perimeter. However, the gaps closer to the geometry account for the major capacitive contribution. These capacitances have been marked as $C_1 - C_{12}$ in Fig. 9 (b). An inductance can also be identified by the virtue of continuous conductive patch which can be identified as L_1. The MTM structure also adds to the overall capacitance and inductance. This is governed by the dimensions of the structure which involve width (w), spacing (s), gap width (g), side length of the outer ring (l) and the number of rings (n) as referred in [38]. An equivalent circuit representation of the OMSFA is depicted in Fig. 9 (a). The circuit implementation and fine tuning has been done using ADS software. As shown in the S_{11} (dB) vs frequency plot in Fig. 9 (c), the circuit resonates at 2.9 GHz. This is in agreement with the simulated and measured resonance frequency band as shown in Fig. 5. The circuit can further be fine-tuned to achieve the second resonance at 9.58 GHz. This however is not covered in this paper and can be taken up in the future works.



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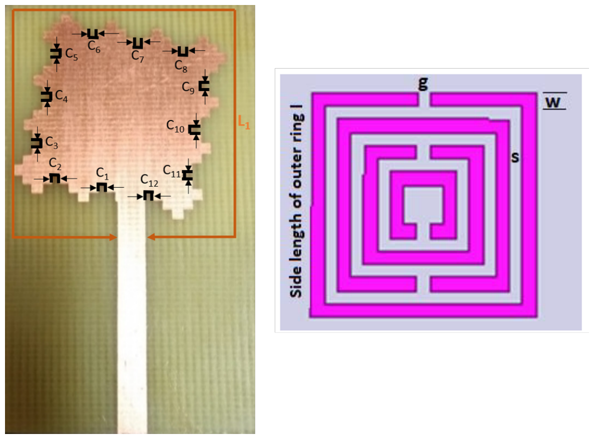

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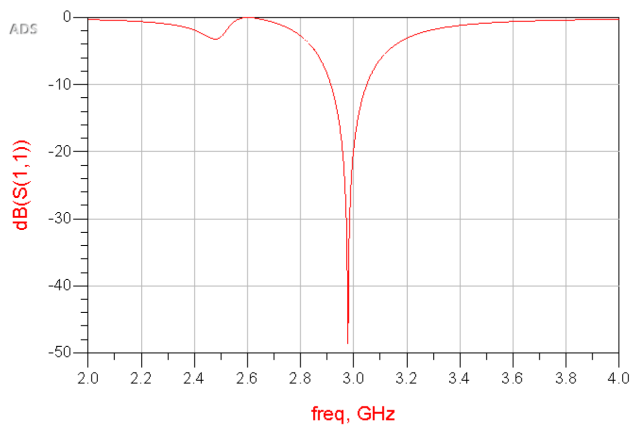

(c)

FIGURE 9. (a) Equivalent circuit design for the proposed OMSFA. (b) Depiction of inductances and capacitances involved (c) S_{11} (dB) vs Frequency (GHz) plot for equivalent circuit design

IV. CONCLUSION

This article is an extension of the research work reported previously. It covers the realization, experimental study, and performance analyses of the OMSFA. The proposed fractal contoured metamaterial inspired antenna offers superior performance as compared to other geometries reported in literature. The novelty lies in the amalgamation of fractal structure with truncated ground and the multi-ring SRR loading. The experimental work validates the unique pairing of the fractal radiating element and SRR structure notably enhances the gain and BW performance. The optimized iterative fractal design helps reduce the overall size of the antenna while maintaining the electrical performance. The proposed OMSFA experimentally outperforms the conventional MSA. Contrary to the space occupying antenna arrays, it exhibits an appreciable gain of 8.81 dB at 2.5 GHz with a substantial FBW of 72.28 %. It also offers resonances at 2.98 GHz and 9.58 GHz within the broad bandwidth of 2.53 GHz and 1.70 GHz, respectively. The substantial gain and wide resonance bandwidth of the proposed antenna makes it a well-suited candidate for a diverse range of wireless applications in the S-band. Since, majority of wireless and mobile communication devices operate at about 2.5 GHz, there is abundant unexplored ambient RF energy available in this range. Thus, this antenna can also be deployed for energy harvesting. The design and integration of the matching and rectifier circuits for harvesting energy is reserved as an extended work for future. The advancement of 5G communication in the sub-6 GHz band also opens up new avenues for the employment of the proposed OMSFA. Even though the OMSFA exhibits appreciable S_{11} and wide bandwidth in the X-band it shows inadequate gain performance. This can be further overcome with innovative gain enhancement techniques. Analyses of radiation pattern at other frequencies and fine tuning of the equivalent circuit design for additional resonant frequencies are beyond the scope of this paper and can be focused upon in the future work.

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