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Metamaterial Loaded Fractal Based Interdigital Capacitor Antenna for Communication Systems

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Abstract—This paper presents a metamaterial loaded interdigital capacitor antenna having fractal geometry. The antenna consists of multiple split ring resonators (MSRR) with shorted ground. The metamaterial loading is achieved by MSRR that enhances the gain. Furthermore, multiband characteristics are obtained by two L-shaped rings providing the fractal geometry. The antenna has the physical dimension of 27 × 39.20 mm for the outer ring and in terms of wavelength has the dimension of $0.486 \times 0.707\lambda$. This antenna structure is designed and simulated on an FR-4 epoxy substrate of thickness $h = 1.56$ mm and dielectric constant $\varepsilon_r = 4.4$. The antenna resonates at multiple frequencies, i.e., 1.5 GHz, 2.2 GHz, 2.70 GHz, 4.20 GHz, 4.9 GHz, 5.3 GHz, 7.2 GHz, 7.5 GHz and 8.8 GHz at different return loss values with gains of 9.5 dB, 14.5 dB, 11.9 dB, 3.6 dB, 4 dB, 1.5 dB, 3.8 dB and 6.5 dB. The comparison of the simulated and measured return losses shows a good agreement. The antenna finds its applications in GPS, space and satellite communication, radar, body area network (BAN) communication system.

1. INTRODUCTION

New era of mobile communication demands for small size antennas with multiband operation. In the past, a number of antennas have been reported for multiband operations [1]. The demand for high amplification is of extreme importance in these frequency bands that can be accomplished by loading antenna with metamaterial spilt ring resonator structures [2, 3]. The term metamaterial has been used among researchers working on different types of media [4].

In 1967, Vassalage described an interesting material having a negative permeability (μ) and permittivity (ε) termed as metamaterials [5]. Metamaterials possess negative permeability (μ) and/or negative permittivity (ε). Hence, metamaterials are termed as a double negative (DNG) or single negative materials (SNG). In single negative metamaterial, the permeability (μ) negative materials are mu negative (MNG), and permittivity (ε) negative materials are termed as epsilon negative (ENG) metamaterials. Split ring resonators in metamaterial structure give rise to negative permeability, and negative permittivity can be obtained from thin wire elements in the metamaterial split ring structure [6]. The refractive index is negative of metamaterials which is opposite to Snell's Law, hence called as negative index material (NIM). To enhance gain, directivity and bandwidth of the antenna, metamaterials play a prominent role by satisfying the condition of miniaturization.

The electrical dimensions of the antenna can be increased through various physical aspects including multiple split ring resonators (MSRR) [7]. MSRR consists of concentric split rings which in turn increases the capacitances between the strips, keeping the area of the antenna intact. The need of designing transmissive and radiating microwave components leads to employing artificial metamaterials [8, 9].

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The most common type of resonator is split ring resonator which gives normal values of permeability at microwaves [10].

Conventional multiband antennas exhibit half and one wavelength modes at lower and higher frequencies. So to get quarter wavelength modes at these frequencies, printed antennas are in demand, which gives better isolation with system ground plane [11]. However, good impedance matching is difficult to attain at quarter wavelength, which creates limitation of miniaturization. The impedance matching can be attained by using composite right/left-handed (CRLH) approach of the metamaterials. CRLH comprises both positive phase constant and negative phase constants at specific regions of frequencies [12]. With the advancement of CRLH transmission line theory, loading of metamaterials leads to rapid development to increase the gain and bandwidth of the resonator. In order to impose CRLH properties on a patch antenna, the antenna includes an interdigital capacitor for series capacitances and complementary split ring resonators for shunt inductances. With the use of interdigital capacitor, which acts as a part of resonator, the antenna size can be reduced which contributes to achieve high gain and high directivity [13].

Multiband response with greater miniaturization can be obtained by using fractal based geometry to fully exploit the electrical length of the antenna. Researchers have developed many antennas with reduced size and multiband characteristics. One of the antennas is fractal antenna [14, 15]

Fractal structures are generated by an iterated function system (IFS) [16], which is determined by Equation (1)

$$\pounds = \frac{n}{n+1}, \tag{1}$$

where $\pounds$ = iterated function, and n = number of iterations.

In this communication, an interdigital capacitor antenna designed with the fractal approach and loaded with a metamaterial split ring resonator (SRR) is presented. Due to the interdigital capacitor design, good impedance is obtained at quarter wavelength frequencies. Metamaterial loading as split ring resonators enhances the gain and directivity of the antenna, and capacitances and inductances obtain the anomalous values. The antenna has been designed in order to take advantages of DGS, metamaterial and fractal geometries. This is an outcome of a hybridization approach to hybridize more than one concept to improve antenna performance.

The paper is organized as follows. Section 2 describes the design of the interdigital capacitor antenna with meta-fractal approach. The detailed geometrical structure with SRR implementation is shown in this section. In section 3, the characteristics of the interdigital capacitances, fractal design and metamaterials loading are discussed. The results of the IDC meta-fractal antenna are also presented and discussed. Finally, the paper is concluded in Section 4.

2. ANTENNA DESIGN

Figure 1 depicts the geometry of the proposed metamaterial loaded interdigital capacitor multifractal antenna. The antenna has parasitic monopoles with a spiraled split ring and an etched interdigital capacitor. The interdigital capacitor antenna has a spiraled split ring structure with a T-shaped inter digital capacitor (IDC) which describes the metamaterial loading on the antenna. This proposed composition of implementing two L-shaped patches will introduce a new fractal geometry having metamaterial loaded interdigital capacitance effect. The two L-shaped patches are placed at the distance of 2 mm from the outer ring of the interdigital capacitor. The dimensions of the interdigital capacitor are side length = 39.2 mm and width = 27 mm. The dimensions of two L-shaped patches are length = 30 mm and width = 8 mm. The thickness of each copper patch strip is 2 mm which is excited by a coaxial feed at $x = 1$ mm and $y = 10$ mm. This antenna structure is designed and simulated on an FR-4 epoxy substrate with thickness $h = 1.5676$ mm and dielectric constant $\varepsilon_r = 4.4$. The gap at the split of two interdigital capacitor rings is 1 mm, and the gap between interdigital capacitor outer ring and L-shaped patch is 2 mm. This structure is simulated using finite element method based High Frequency Structure Simulator (HFSS) of Ansys.

The metamaterial loaded interdigital capacitor patch antenna is simulated as a base antenna for the new proposed fractal antenna. The fractal antenna is designed by implementing two L-shaped patches on the base design and later simulated.

Previously designed base antenna simulation results locate the resonant frequency values on which metamaterial characteristics can be verified. During the loading test simulation, metamaterial antenna is coaxially fed at $x = 1\,\text{mm}$ and $y = 10\,\text{mm}$, $x_1 = 38.18\,\text{mm}$ and $y_1 = 16.98\,\text{mm}$ on the two interdigital capacitor rings. The SRR is in the shape of the interdigital capacitor design, hence can be verified using FEM method. The patch of the proposed interdigital capacitor antenna has two parasitic elements with a monopole shorted to ground with similar L-shaped parasites forming a defective ground structure (DGS).

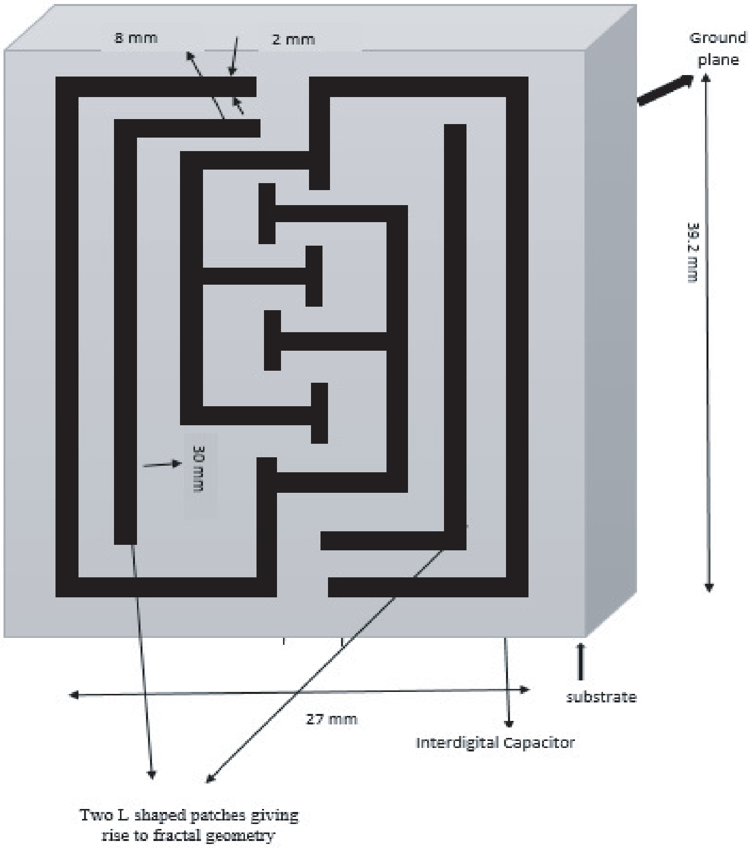


Figure 1. Metamaterial loaded interdigital capacitor fractal antenna.

Defected ground further increases the bandwidth and multiband behavior of the proposed metamaterial loaded interdigital capacitor fractal antenna. Fig. 2 illustrates the bottom view of the antenna in which L-shaped strips have been isolated from the ground by a distance of 0.5 mm. The isolated L-shaped strips are connected to L-shaped parasites elements at the top of the patch. By using L-shaped parasites, high gain has been achieved in addition to metamaterial loading.

The actual physical length of the antenna is 26.98 mm. The gap across the length of the antenna generates the capacitance which is considered for calculating the frequency. After consideration of the gap capacitance, the length of the antenna is 25.86 mm. Using Equation (2), fringing field calculated is 0.68 mm from Equation (2).

$$\Delta L = \frac{.412h(\in_{\mathit{eff}} +.3)\left(\frac{w}{h} + 0.264h\right)}{(\in_{\mathit{eff}} -.258)\left(\frac{w}{h} + 0.8\right)}. \tag{2}$$

After introduction of fringing field, the physical effective length of the proposed interdigital capacitor meta-fractal antenna is 28.34 mm. After using Equations (3), (4) and (5), the calculated electrical length of the antenna is 27.22 mm which in turn gives 2.7 GHz as resonant frequency of the antenna.

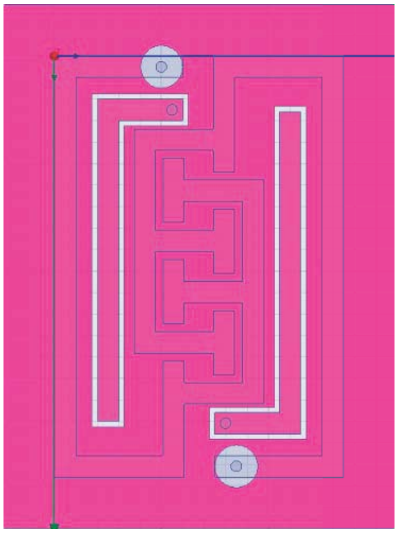


Figure 2. Bottom view of proposed antenna.

Length of the antenna

$$L = L_{\mathit{eff}} - \Delta L. \tag{3}$$

where L = length of the proposed antenna, L_{eff} = effective length of proposed antenna, and ΔL = fringing field.

The effective length of the proposed antenna can be calculated as

$$L_{\mathit{eff}} = \frac{c}{2f_o\sqrt{\in_{\mathit{eff}}}}, \tag{4}$$

where c = speed of light in vacuum = 3×10^8 m/sec, f_o = resonant frequency, and E_{eff} = effective permittivity.

Effective permittivity is expressed as

$$\in_{\mathit{eff}} = \frac{\in_r +1}{2} + \frac{\in_r -1}{2\sqrt{1+\frac{12h}{w}}}, \tag{5}$$

where ε_r = relative permittivity, h = thickness of substrate, and w = width.

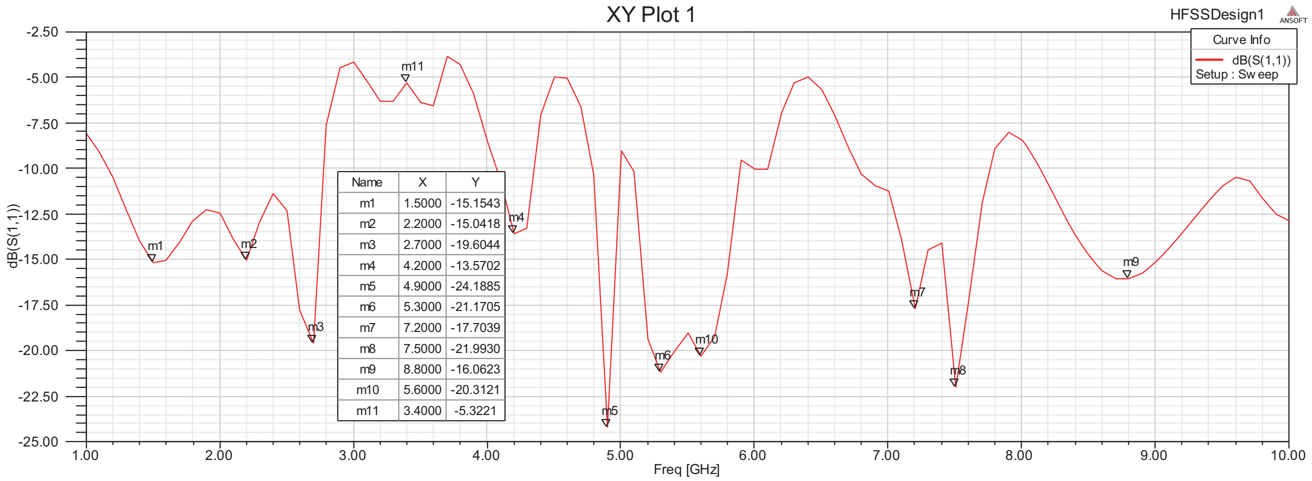
With the aid of these equations, all the parameters of the antenna are obtained. Hence the total electrical length of the square shaped fractal antenna is calculated as 27.22 mm. All the design equations are valid for microstrip patch antennas and are applied to calculation of the outer length of the fractal patch antenna (here, outer L shaped design of fractal antenna) for a 2.7 GHz frequency range. The design equations have been enforced only for base design or 0th iteration process of fractal geometry. Parameters calculated by mathematical analysis match the simulated and experimental outcomes.

3. RESULTS AND DISCUSSION

3.1. Simulated and Measured Results

In this section, fractal and metamaterial characteristics of the interdigital capacitor antenna are verified. The results of meta-fractal interdigital capacitor antenna with simulated and fabricated geometries are presented, compared and analyzed. Fig. 3 shows the reflection coefficient of the simulated interdigital capacitor antenna.

The antenna resonates at multiple frequency bands as described in Table 1. As seen from the graph (Figure 3), the bandwidth of the antenna is 663 MHz and 615 MHz for the resonant frequencies ranging between 5–6 GHz and 615 MHz for 7–8 GHz frequency band range due to defective ground structure and



Name	X	Y
m1	1.5000	-15.1543
m2	2.2000	-15.0418
m3	2.7000	-19.6044
m4	4.2000	-13.5702
m5	4.9000	-24.1885
m6	5.3000	-21.1705
m7	7.2000	-17.7039
m8	7.5000	-21.9930
m9	8.8000	-16.0623
m10	5.6000	-20.3121
m11	3.4000	-5.3221

Figure 3. Simulated return loss of proposed antenna.

Table 1. Simulated and measured frequency bands.

S. No.	**Simulated Resonance Frequency ($\mathbf{S_{11}}$)**	**Return Loss (dB)**	**Measured Resonance Frequency ($\mathbf{S_{11}}$)**	**Return Loss (dB)**
1	1.50	-15.1543	1.50	-10.264
2	2.2	-15.0418	2.18	-11.794
	2.70	-19.6044	2.48	-10.551
3			2.7	-14.087
4	4.20	-13.57	4.94	-13.4124
5	4.9	-24.1885		
6	5.3	-21.1705	5.36	-24.1843
7	5.60	-20.3121	5.7	-15.2409
8	7.2	-17.7039	7.12	-11.595
9	7.5	-21.993	7.5	-10.8772
10	8.8	-16.0623	8.72	-12.2126

two L-shaped parasites. For frequency bands 2.70 GHz, 4.20 GHz, 4.9 GHz, 7.2 GHz and 7.5 GHz, the bandwidth is low as compared to other frequency bands because the antennas loaded with metamaterials have low bandwidths [17]. The simulated highest bandwidths are 663 MHz for the resonant frequencies ranging between 5–6 GHz and 615 MHz for 7–8 GHz frequency band range.

In this work, HFSS is used as a simulator to get S-parameters. The antenna is fabricated using an FR-4 substrate. A photograph of fabricated antenna is shown in Fig. 4.

The measured two-port S-parameters of metamaterial loaded interdigital capacitor fractal antenna are plotted in Fig. 5. Fig. 6 depicts the comparison of simulated and measured return loss (S_{11}) characteristics of the metamaterial loaded interdigital capacitor fractal antenna. In this antenna, good matching has been identified as can be seen from Fig. 7.

Figure 7 demonstrates the simulated reflection coefficient (S_{11}) and transmission coefficient (S_{21}) characteristics of the proposed antenna.

The fabricated antenna is tested in vector network analyzer (VNA). The fabricated proposed antenna resonates at different frequency bands as shown in Table 1.

Figures 8(a) and 8(b) respectively show the elevation and azimuth radiation patterns of the proposed metamaterial loaded fractal based interdigital capacitor antenna. Gains of 9.5 dB, 14.5 dB, 11.9 dB, 3.6 dB, 4 dB, 1.5 dB, 3.8 dB and 6.5 dB are achieved with different bands.

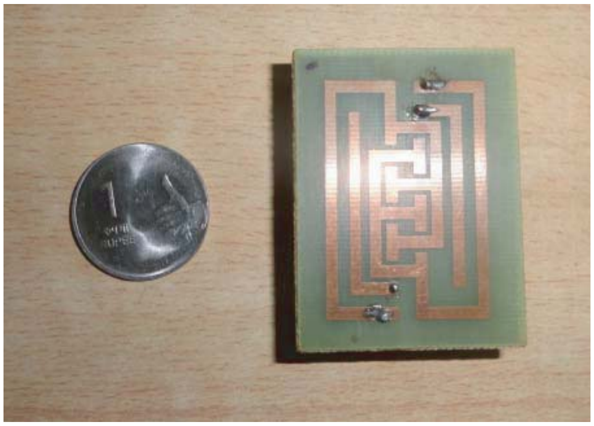


Figure 4. Photograph of fabricated antenna (radiating patch).

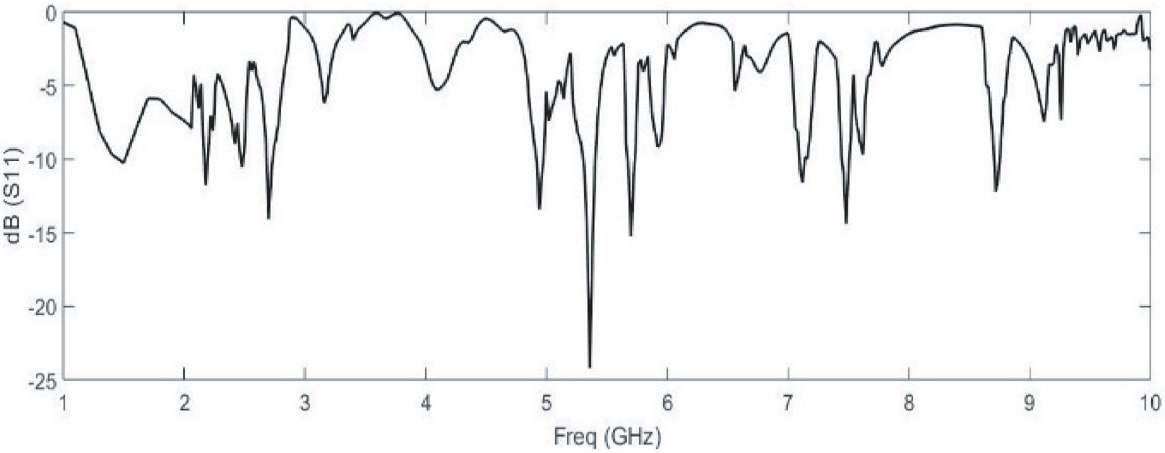


Figure 5. Measured return loss of the proposed antenna.

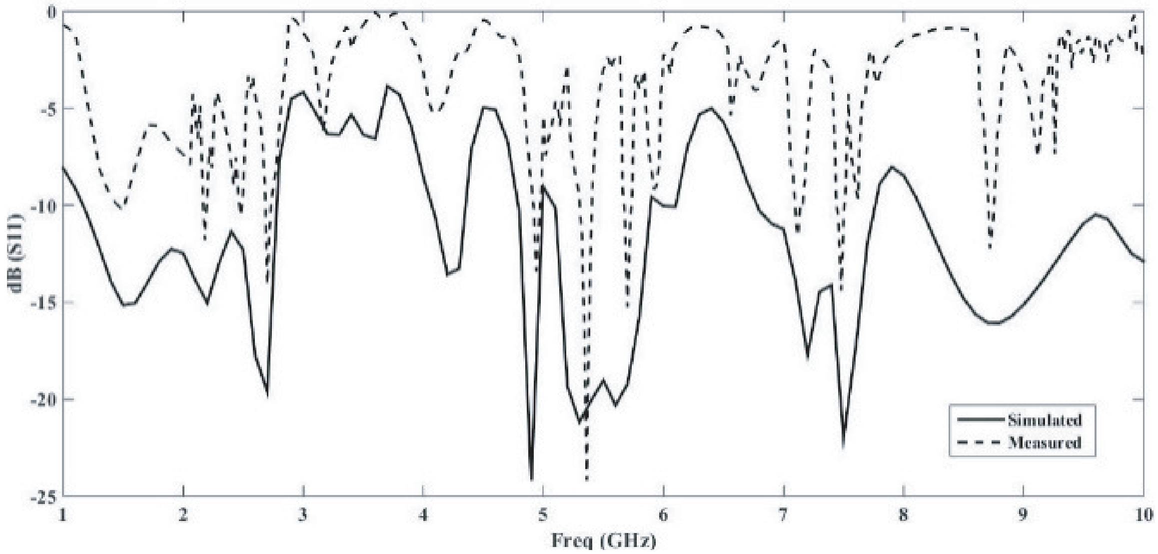


Figure 6. Comparison of simulated and measured return loss (S_{11}) characteristics of Meta-Fractal Interdigital capacitor antenna.

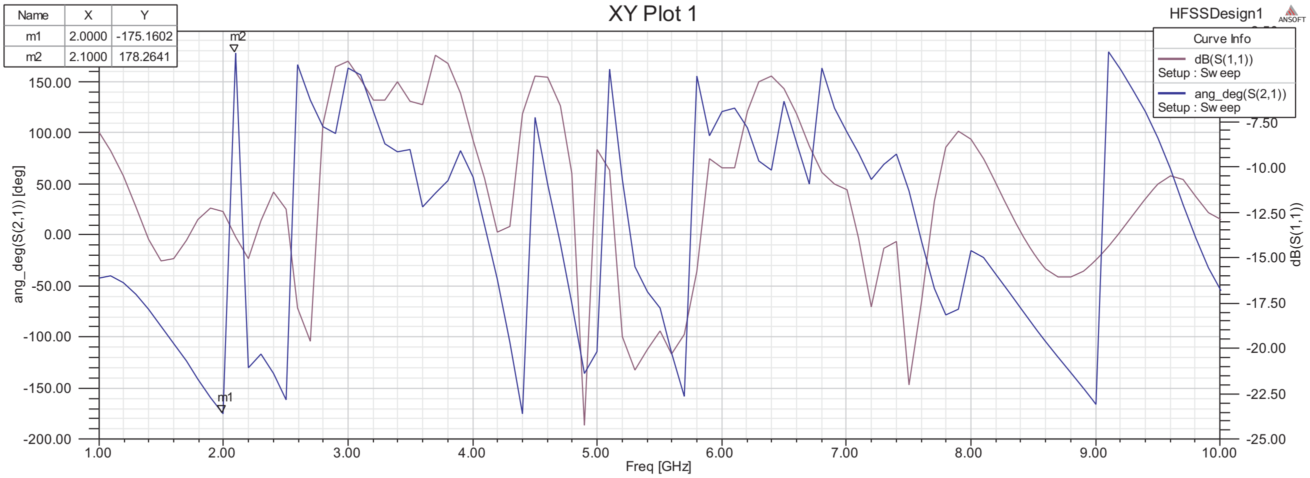
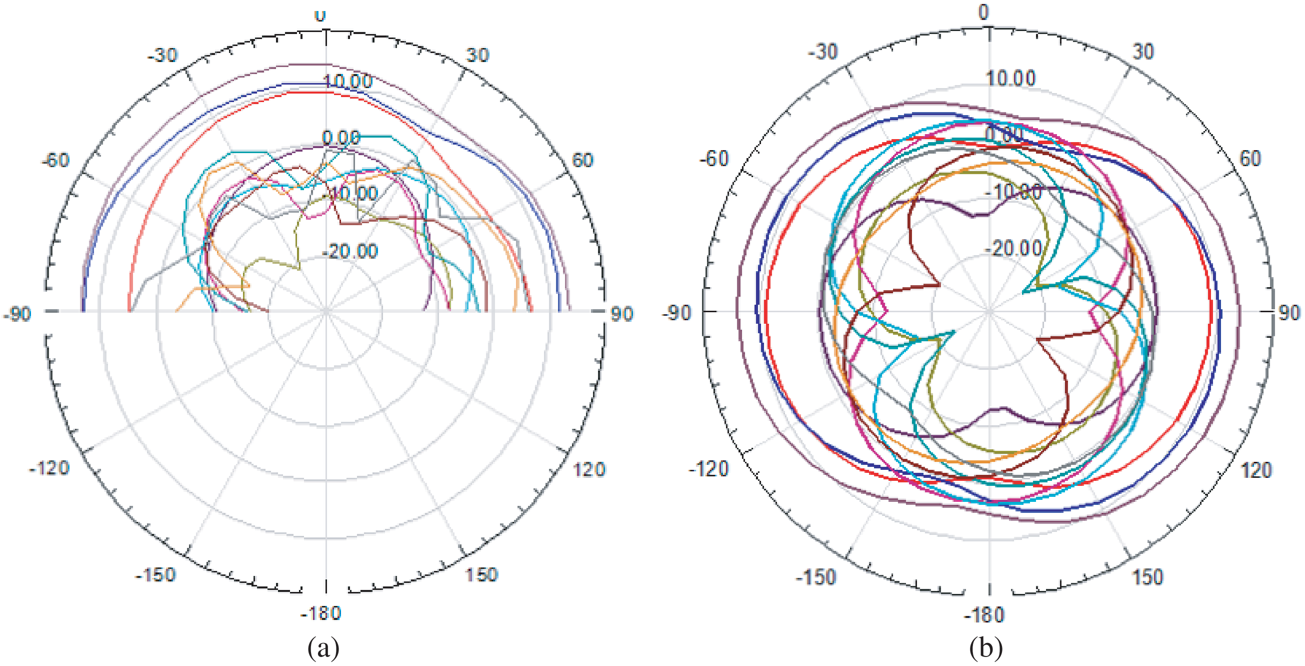


Figure 7. Simulated reflection coefficient (S_{11}) and transmission coefficient (S_{21}) characteristics of the proposed antenna.



(a)

(b)

Figure 8. (a) Elevation pattern gain display. (b) Azimuth pattern gain display.

4. CONCLUSION

This paper presents a meta-fractal interdigital capacitor antenna. Metamaterial loading is an advantageous approach to miniaturize and leads to achieving reasonable gain and better bandwidth. Multiband characteristics are obtained using a fractal structure design. The geometry is equivalent to interdigital capacitor, so the gap capacitance effect is taken into account to solve the antenna analytically, and its results show good agreement with measured and simulated ones of the antenna. The antenna has been designed in order to take advantages of DGS, metamaterial and fractal geometries. This is an outcome of a hybridization approach to hybridize more than one concept to improve antenna performance. In further studies, by inserting more rings antennas frequency behaviors can be varied which will in turn increase more different applications.

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