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Square-Shaped Fractal Antenna under Metamaterial Loaded Condition for Bandwidth Enhancement

Pushkar Mishra[1, *], Shayam S. Pattnaik[2], and Balwinder S. Dhaliwal[3]

Abstract—In this paper, a metamaterial loaded square-shaped fractal antenna with two iterations is presented and discussed. A metamaterial loading consists of split ring resonators (SRRs) which enhances the bandwidth of the antenna keeping the dimensions and size of the antenna same. The square-shaped fractal antenna, which is in the form of three concentric rings, was simulated and fabricated, and the results were shown and discussed. The antenna resonates at three distinct frequency bands 4.3719 GHz, 7.7437 GHz and 10.6374 GHz with the gains of 1.1974 dB, 4.2745 dB and 4.7233 dB, respectively for resonant frequencies. The bandwidths for the antenna are 185 MHz, 198 MHz and 386 MHz for distinct resonant frequencies. The antenna is fabricated using an FR-4 substrate, and the measured resonant frequencies are 4.08 GHz, 7.545 GHz and 10.24 GHz. In metamaterial loading condition, the antenna resonates at 4.0105 GHz, 6.8474 GHz and 8.0632 GHz with bandwidths of 636 MHz, 347 MHz and 1.33 GHz at resonant frequencies. The appreciable bandwidth is achieved in such a small antenna without changing dimensions and size of the antenna. The simulated, experimental results and comparison are also presented in this paper. The results show that the proposed method can be used to design high bandwidth and compact fractal microstrip patch antennas without increasing dimensions.

1. INTRODUCTION

The miniaturization of antenna design based on fractal geometry is of great interest in today's wireless communication systems. The multiband nature of antennas with a large bandwidth is required in each and every aspect of the communication systems. The size must be small enough so that it can be fixed in communication devices. The researchers have developed many antennas with reduced size and multiband characteristics. Microstrip patch antennas are widely used in these applications due to features such as light weight, high efficiency, and compactness. However, one of the major disadvantages is bandwidth limitations. Multiband characteristics can be obtained by using fractal geometry. The microstrip patch antennas designed using fractal geometry are known as fractal patch antennas which in turn give multiband frequency characteristics with high gain [1, 2].

The representation of fractal sets by means of Iterated Functions System (IFS) is a powerful tool in fractal theory. The number of iterations calculated through Iterated Function System (IFS) is given by Equation (1) [3].

$$Ł = \frac{n}{n+1} \tag{1}$$

where n = number of iterations, and Ł = Iteration Function System (IFS).

Self-similar properties of fractal are the main cause of multiband properties of the antenna. Since fractal is a curve or geometrical figure, each part of which has the same statistical characteristic as the

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* Corresponding author: Pushkar Mishra (pushkarmishra1985@gmail.com).
[1] IKG Punjab Techncial University, Jalandhar, Punjab, India. [2] National Institute of Technical Teachers Training & Research, Chandigarh, India. [3] ECE Department, Guru Nanak Dev Engineering College, Ludhiana, Punjab, India.

whole. They are useful in modelling structures (such as snowflakes) in which similar patterns recur at progressively smaller scales [4]. Another property of a fractal structure is space filling properties which lead to curves which have long electrical length, but fit into a compact physical volume [5]. Several antennas based on fractal geometries have been investigated, including Koch fractal, Sierpinski gasket, Minikowski curve, Hilbert, Cantor and fractal tree in recent years. The simulated and experimental results of these antennas are available in the literature to date [6]. Fractal geometries give narrowband frequencies which in turn give a narrow bandwidth.

Since the bandwidth is an important parameter in modern communication technologies, it must be enhanced with the riders such as small size, compactness, multiband characteristics. There are many technologies established to enhance the bandwidth of microstrip patch antennas [7]. One such technology is metamaterial loading for lowering resonant frequencies and enhancing bandwidth [8].

In 1967, the Russian physicist Viktor Vassalage presented the properties of artificial materials named as metamaterials. Negative permeability (μ) and negative permittivity (ε) were possessed by these materials which supported backward wave propagation of electromagnetic waves [9]. To achieve negative permeability, split ring resonator (SRR) was proposed in 1999 by Pendry et al., which is an LC tank circuit having equivalent inductance L and equivalent capacitance C between two concentric rings [10]. Metamaterial structure consists of SRRs to produce negative permeability and thin wire to generate negative permittivity [11, 12]. The effects of mutual inductance on parameters such as resonant frequency, bandwidth, gain and size have been studied under metamaterial loaded conditions and varied according to the need [5]. This concept is used by the authors to design and fabricate square shaped metamaterial loaded microstrip antenna for wireless communication applications.

In this work, the authors design a microstrip patch fractal antenna to get multiband characteristics, and then metamaterial loading is done to enhance bandwidth characteristics. The main objective of this paper is to design and fabricate a metamaterial loaded fractal patch antenna for wireless communications systems. Concentric square rings are used as fractal geometries with a scaling factor of 2. Three concentric rings are designed, simulated, fabricated, and experimental results are shown. To enhance bandwidth, metamaterial loading is done by splitting middle and outer rings to get SRR characteristics. The metamaterial loaded antenna is then fabricated, and experimental results depict the bandwidth enhancement. The proposed antenna can be employed in various applications such as microwave devices/communications, radio astronomy, mobile phones, wireless LAN, GPS, satellite communications, and radar.

This paper is divided into four sections. The geometrical sketch and antenna configurations are shown in Section 2. Section 3 shows the results of the proposed antenna with fractal geometries and antenna under metamaterial loading conditions. The paper is concluded in Section 4.

2. ANTENNA DESIGN

Figure 1 shows the iterations of the proposed fractal geometry which is utilized to design a fractal antenna of three concentric rings shaped structures. Fig. 2 depicts the designed fractal antenna with 2nd iteration.

The concentric rings used have the dimensions of square geometry. In this composition, the outermost ring patch has the dimensions of length $L_A = 20\,\text{mm}$ and width $W_A = 20\,\text{mm}$. The self-similarity property of the fractal antenna is verified by using scaling factor 2, and two more rings are added to the structure giving rise to the 1st and 2nd iterations, respectively. With the first iteration, dimensions of the middle ring are: Length $L_B = 10\,\text{mm}$ and Width $W_B = 10\,\text{mm}$. For the innermost ring (2nd iteration), the dimensions are: Length $L_C = 5\,\text{mm}$ and Width $W_C = 5\,\text{mm}$. The gap of splits between the rings is $g_1 = g_2 = 1\,\text{mm}$. The antenna is excited by the coaxial feeding technique at the location $x = -4.5\,\text{mm}$ and $y = -8\,\text{mm}$ on the patch. Feeding is done on the outermost ring, which is an appropriate feeding location as it is in the maximum electric field. This is because the fringing E-fields on the edge of the microstrip antenna add up in phase and produce the radiation of the microstrip antenna. The antenna structure is designed, simulated, and fabricated on an FR-4 substrate having thickness $h = 1.5676\,\text{mm}$ and dielectric constant $\varepsilon_r = 4.4$. The structure is simulated using finite element method based High Frequency Structure Simulator (HFSS) of Ansys.

From the antenna structure, it is illustrated that addition of rings gives rise to self-similarity

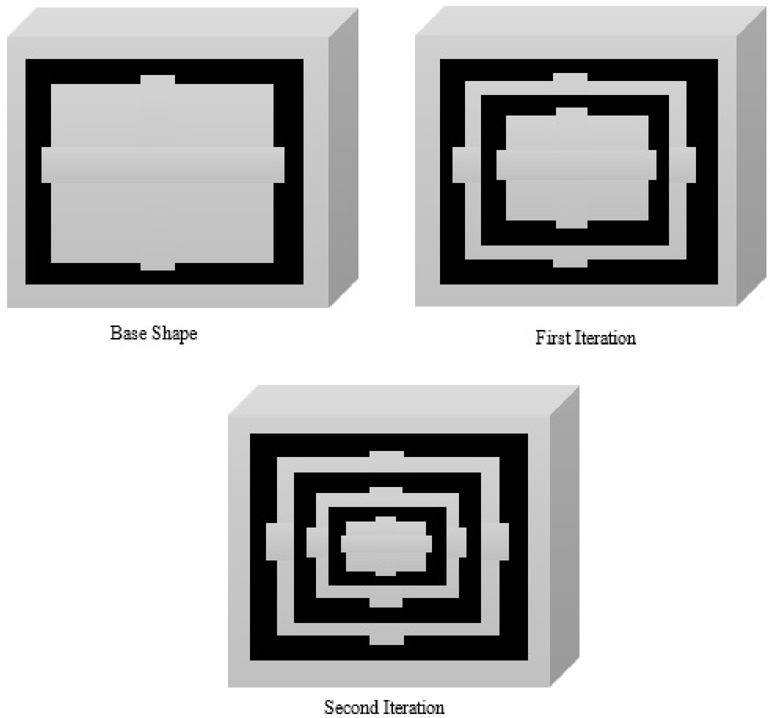


Figure 1. Iterations of proposed fractal geometry.

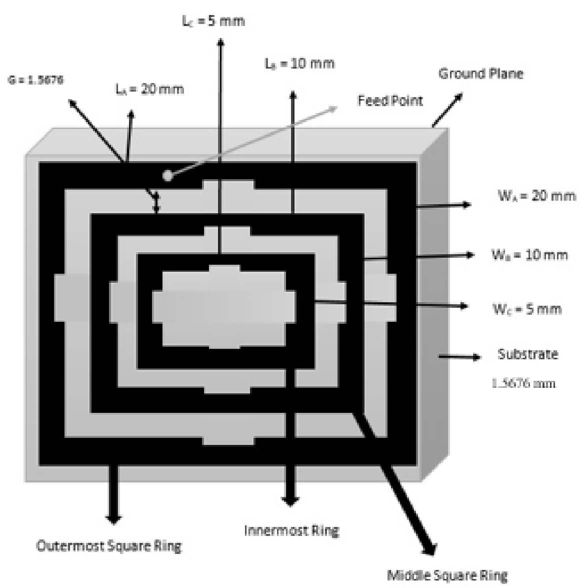


Figure 2. Square shaped fractal antenna with 2nd iteration.

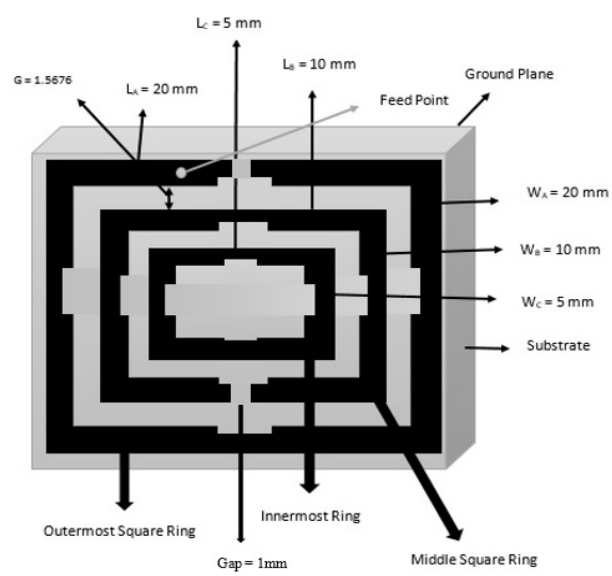


Figure 3. Metamaterial loaded square shaped fractal antenna with 2nd iteration.

property of the fractal geometry which creates multiband frequency characteristics. The slot in the rings further increases the electrical length of the antenna which in turn matches the impedance at lower frequencies compared with the base design of the antenna.

The fractal antenna has bandwidth limitations which is a major constraint of microstrip patch antennas and can be overcome by metamaterial loading on the fractal structure. Fig. 3 depicts the metamaterial loaded square-shaped fractal structure.

The antenna is metamaterial loaded using SRR technique [13]. The gap (having dimension = 1 mm) is created in outermost and middle rings to create an SRR structure on the fractal geometry. These splits are created to give high bandwidth compared to normal fractal geometry as well as to lower resonant frequency.

The actual physical length of the antenna is 20 mm. The antenna design starts with single element using basic square patch microstrip antenna. The base design of the square-shaped fractal antenna is a microstrip antenna for which the design formulas have been widely published in the literature. Balanis describes these design equations as the building block for calculating the length of microstrip patch antennas [14]. The first lower operating frequency is at 4.37 GHz. Length L and Width W can be calculated using Equations (2), (3), (4) and (5) [15].

Width W can be calculated as

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{2}$$

where, W = width, c = velocity of light, f_r = resonant frequency, and ε_r = permittivity.

Effective permittivity is expressed as

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + \frac{12h}{w}}} \tag{3}$$

where, ε_{eff} = effectivity permittivity, h = height of substrate, and W = width.

Since the fringing field is responsible for the radiation in microstrip patch antenna, it must be calculated. The design formula for calculation of fringing field is reported in literature, which can be calculated as [15]

$$\Delta l = \frac{0.412h\left(\varepsilon_{eff} + 0.3\right)\left(\frac{w}{h} + 0.264\right)}{\left(\varepsilon_{eff} - 0.258\right)\left(\frac{w}{h} + 0.8\right)} \tag{4}$$

Δl = effective length due to fringing effect.

Length can be calculated as [15]

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} - \Delta l \tag{5}$$

From the above equations, length of the antenna calculated is 16.14 mm (without seeing the gap, which should be summed to the length of the antenna). The resonant frequency also depends on gap (g). An expression which relates the gap and the resonant frequency is given by Equation (6) [16]

$$g = \frac{c}{\sqrt{2 * \varepsilon_{eff}}} \frac{4.65 * 10^{-12}}{f_0} \tag{6}$$

With the aid of these equations, all the parameters of the antenna are obtained. The gap for resonant frequency is estimated as 1.86 mm. Hence the total electrical length of the square shaped fractal antenna is calculated as 18 mm. All the design equations are valid for microstrip patch antennas and applied to calculation of the outer length of the fractal patch antenna (here, outer ring of square-shaped fractal antenna) for a particular frequency range. The design equations are 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

In this section, the obtained results of both the antenna configurations are presented and discussed.

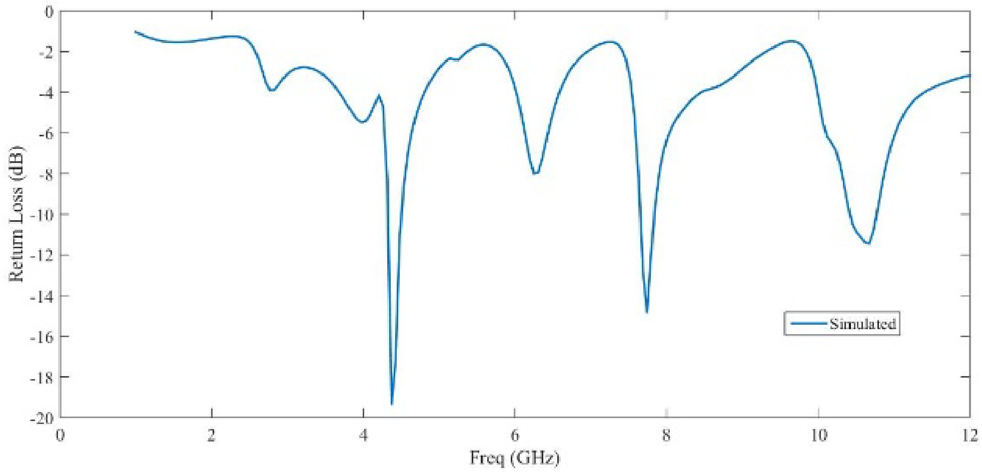


Figure 4. Return loss (S_{11}) of square shaped fractal antenna with 2nd iteration.

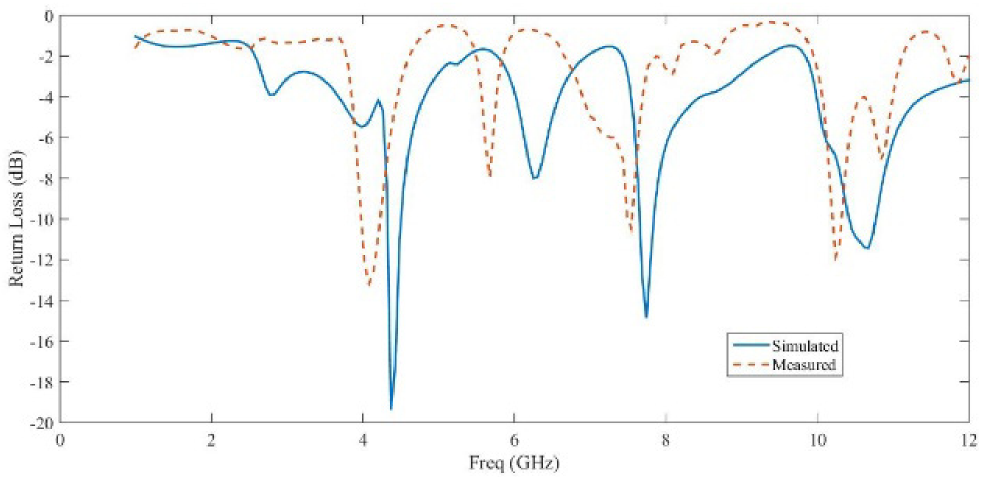


Figure 5. Comparison of simulated and measured return loss of square shaped fractal antenna with 2nd iteration.

3.1. Square Shaped Fractal Antenna with Two Iterations

Figure 4 shows the reflection coefficient (S_{11}) characteristics of square-shaped fractal antenna with the 2nd iteration. The antenna structure resonates at three distinct frequency bands, 4.37 GHz, 7.74 GHz and 10.67 GHz, with bandwidths of 185 MHz, 198 MHz and 386 MHz, respectively. The gains of the antenna are 1.19 dB, 4.27 dB and 4.72 dB at resonant frequencies 4.37 GHz, 7.74 GHz and 10.67 GHz, respectively. It is observed that in this configuration, the antenna structure functions as a fractal antenna as 2 iterations are employed in the form of concentric rings.

Figure 5 shows the comparison of simulated and measured return losses of the square-shaped fractal antenna with the 2nd iteration. The fabricated antenna structure resonates at 4.08 GHz, 7.54 GHz and 10.24 GHz at matching -13.16 dB, -10.46 dB and -11.83 dB, respectively. Figs. 6 and 7 depict photographs of the antenna with fractal geometry.

From Fig. 5, a good matching is observed between simulated and fabricated square-shaped fractal antennas. As seen from the graph, the frequency is shifted towards lower side, due to ohmic losses present in the fabricated antenna. Fig. 4 represents the return loss (S_{11}) characteristics of the unloaded square-shaped fractal patch antenna which resonates at three frequency bands having bandwidths 4.22%, 2.55% and 3.62%. Hence, fractal geometry suffers from low bandwidth which is of importance in present

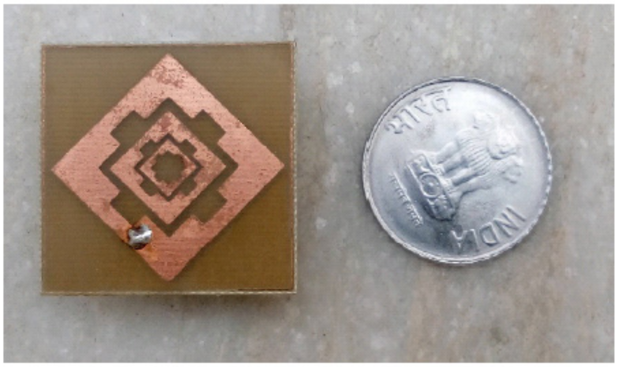


Figure 6. Photograph of fabricated square shaped fractal antenna with 2nd iteration.

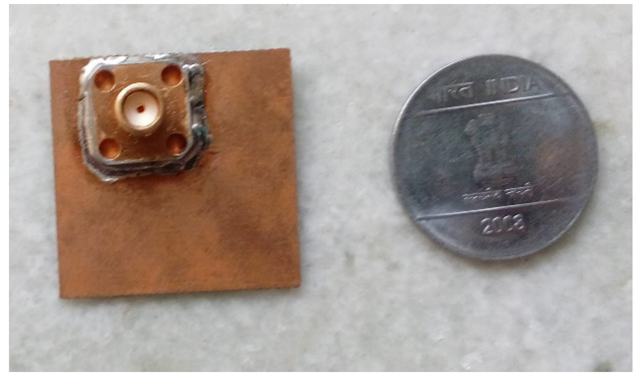


Figure 7. Bottom view of fabricated square shaped fractal antenna with 2nd iteration.

communication system. In order to decrease the resonant frequency and increase the bandwidth in the same dimension of the square-shaped fractal antenna, it is loaded with metamaterial SRRs. Fig. 6 and Fig. 7 depict photographs of the fabricated square-shaped fractal antenna.

3.2. Metamaterial Loaded Square Shaped Fractal Antenna with 2nd Iteration

The comparison of simulated return loss of the square-shaped fractal antenna and metamaterial loaded fractal antenna is shown in Fig. 8. The comparison shows that under the metamaterial loading condition, the frequency bands are shifted to downside, and high bandwidth is obtained compared to fractal geometry, due to metamaterial loading. The loaded antenna resonates at 4.01 GHz, 6.84 GHz and 8.63 GHz at −15.77 dB, −22.01 dB and −32.35 dB, respectively. The corresponding bandwidth percentages at resonant frequencies under loading condition are 5.87%, 5.08% and 16.51%, respectively. This bandwidth is considerably higher in such a compact antenna due to less spacing between the SRRs in the antenna structure, and mutual coupling is increased which in turn increases the bandwidth of the antenna.

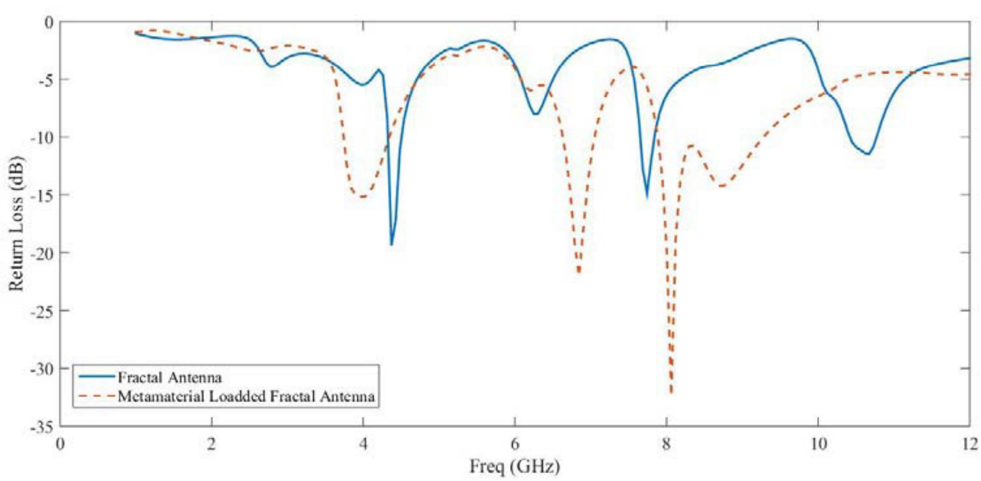
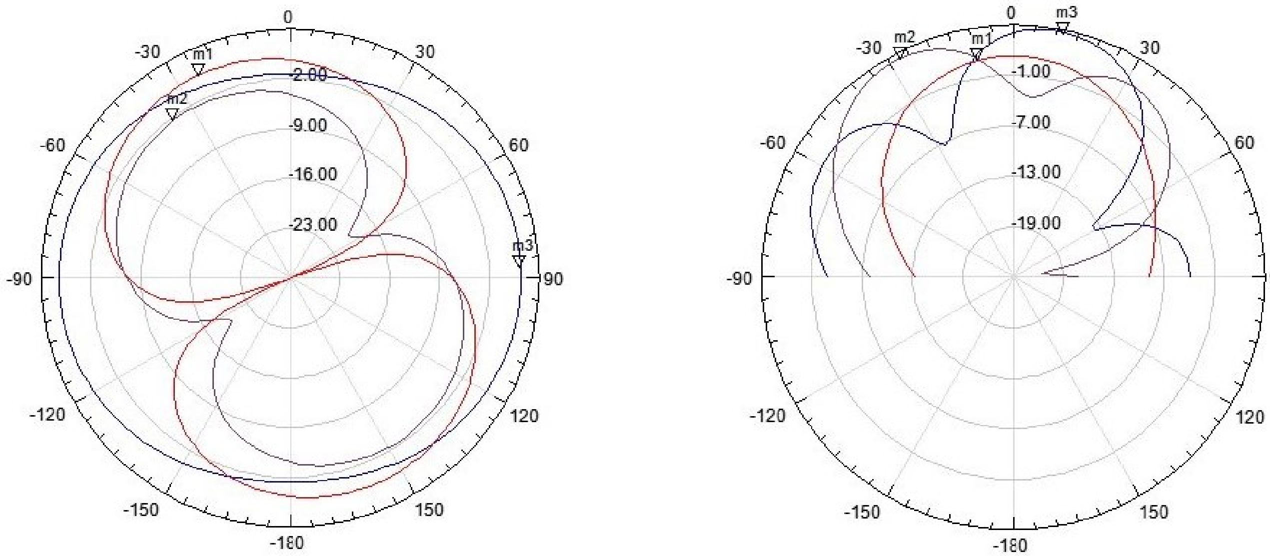


Figure 8. Comparison of simulated return loss of square shaped fractal antenna and metamaterial loaded square shaped fractal antenna with 2nd iteration.

Figure 9(a) and Fig. 9(b) respectively show the azimuth and elevation radiation patterns of the proposed square shaped fractal antenna. Fig. 10 represents the directivity of the square-shaped fractal antenna. Total directivity of the proposed fractal-shaped antenna is shown in Fig. 10. Fig. 11 shows a



Azimuth Pattern Gain Display (dB)

$m1$ = Freq - '4.371 GHz' Theta = '0 deg'

$m2$ = Freq - '7.74 GHz' Theta = '0 deg'

$m3$ = Freq - '10.67 GHz' Theta = '0 deg'

(a)

Elevation Pattern Gain Display (dB)

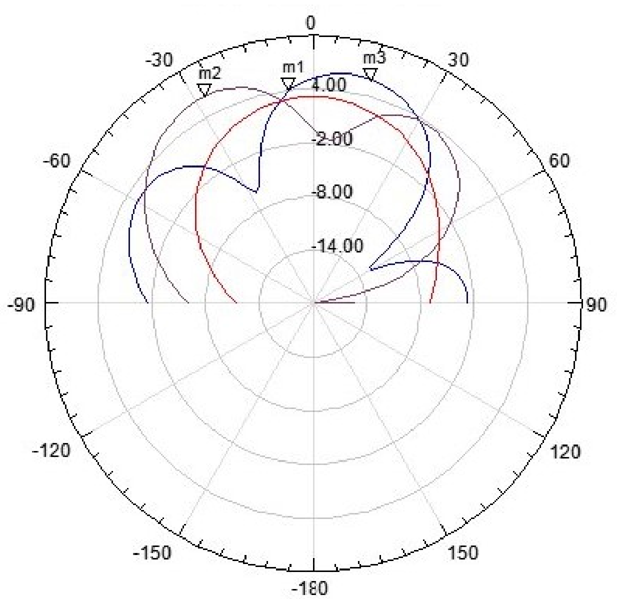
$m1$ = Freq - '4.37 GHz' Phi = '9 deg'

$m2$ = Freq - '7.74 GHz' Phi = '9 deg'

$m3$ = Freq - '10.67 GHz' Phi = '9 deg'

(b)

Figure 9. Radiation patterns of square shaped fractal antenna with 2nd iteration, (a) azimuth, (b) elevation.



$m1$ = Freq - '4.37 GHz' Phi = '9 deg' Mag - 4.08

$m2$ = Freq - '7.74 GHz' Phi = '9 deg' Mag - 6.19

$m3$ = Freq - '10.67 GHz' Phi = '9 deg' Mag - 5.89

Figure 10. Total directivity pattern of proposed fractal antenna with 2nd iteration.

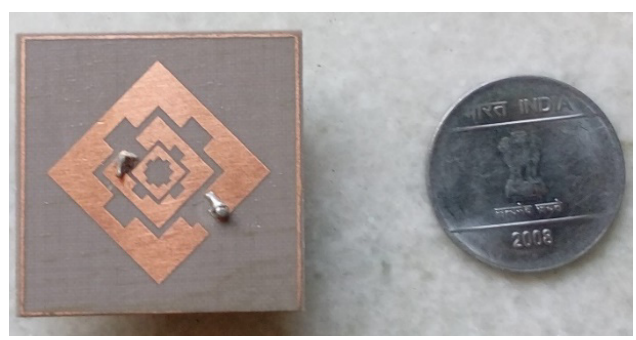


Figure 11. Photograph of square shaped fractal antenna with metamaterial loading.

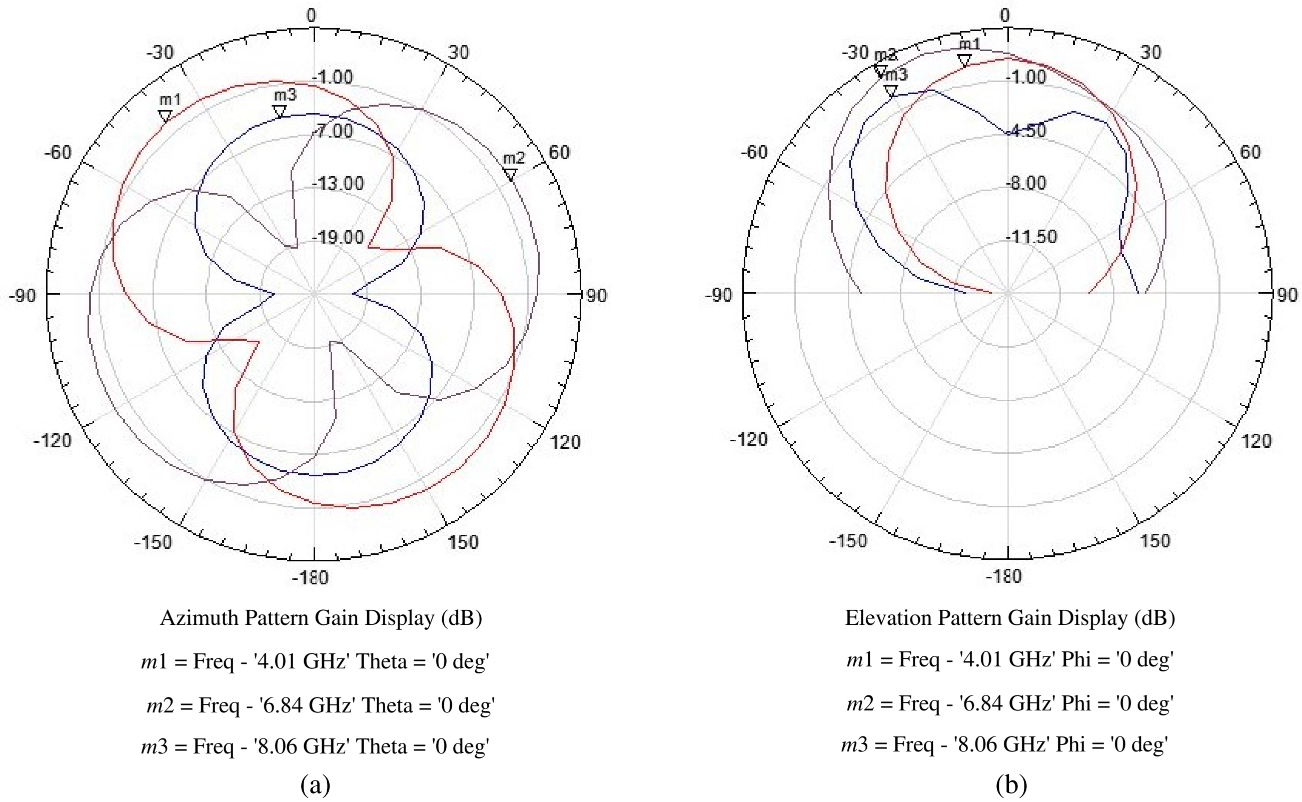


Figure 12. Radiation patterns of metamaterial loaded square shaped fractal antenna with 2nd iteration, (a) azimuth, (b) elevation.

Table 1. Simulated and measured frequency bands of square shaped fractal antenna.

S. No.	Simulated Resonant Frequency (GHz)	Measured Resonant Frequency (GHz)	Gain (dB)	Bandwidth (MHz)
1	4.37	4.08	1.19	185
2	7.74	7.54	4.27	198
3	10.67	10.24	4.72	386

photograph of the square-shaped fractal antenna under loaded condition with metamaterial. Fig. 12(a) and Fig. 12(b) depict the azimuth and elevation patterns of the square-shaped fractal antenna under loading condition.

The fabricated antenna is tested in vector network analyser (VNA). The fabricated antenna resonates at different frequency bands as shown in Table 1. Table 2 describes the comparison of fractal antenna and antenna under loading condition with metamaterial.

As seen from Table 1 and Table 2, the percentage increase in bandwidth is approached with the implementation of metamaterial loading on to the fractal geometry. Metamaterial loading is obtained in the design itself, whereas no major changes is performed on main design except two gaps in the ring, which is advantageous to the design. Moreover, the bandwidth is enhanced by 1.65%, 2.53% and 12.89% for resonant frequencies, respectively. This new hybridization technique of loading metamaterial on to fractal geometry enhances the antenna bandwidth by keeping the geometry intact.

Table 2. Comparison of fractal antenna and metamaterial loaded fractal antenna.

S. No.	Resonant Frequency (Fractal Antenna) (GHz)	Resonant Frequency (Metamaterial loaded fractal antenna) (GHz)	Bandwidth (Fractal Antenna)	Bandwidth Metamaterial loaded Fractal Antenna (MHz)	Percentage Increase of Bandwidth (%)
1	4.37	4.01	185	636	1.65
2	7.74	6.84	198	347	2.53
3	10.64	8.06	386	1331	12.89

4. CONCLUSION

This paper presents a metamaterial loaded square-shaped fractal antenna. Metamaterial loading is an advantageous approach to miniaturize as well as to enhance bandwidth of the antenna without altering the dimensions and size. Multiband characteristics are obtained using fractal structure, and bandwidth is enhanced using split ring resonators on the fractal antenna. The fractal antenna is designed using three concentric rings, and metamaterial loading is done by creating gaps in the outermost ring and middle ring to form split ring resonators. A good agreement is observed in terms of resonant frequencies, and bandwidth is enhanced using metamaterial approach thus validating the concept of using metamaterial loading to fractal antennas. This is an outcome of a hybrid approach to hybridize more than one concept to improve antenna performance. Both the antenna viz. Fractal square-shaped antenna and metamaterial loaded square-shaped antenna are fabricated, and measured results are in good agreement with the simulated ones for ISM band applications.

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