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A Kagome Crest Fractal Optimized Quad-Band Antenna for Wireless Applications

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ABSTRACT

The design of multiband antenna plays a vital role and enhances the functionality of mobile equipment for various wireless services over the last decade. This paper presents a sophisticated quad-band fractal microstrip patch circular monopole antenna with a star shaped slot. The proposed structure is iterated two times to have a Kagome crest fractal antenna. In the paper, optimization of quad band antenna using the Quasi newton Optimizer (QNO) is also presented. Optimizing various design parameters for the proposed antenna in HFSS is simulated. The antenna dimensions are 100mmx100mmx1.6mm occupying an area of 100cm^2. Model simulation and experimental validation is done for three frequency ranges, 2.8-3.5GHz, 4.8-7.5GHz and 8.1-9.4GHz, resonating at 3.1GHz, 5.2GHz, 6.8GHz and 8.7GHz respectively. The proposed antenna operates for several wireless applications including RF Energy harvesting, dedicated short range communication, Satellite communication, wireless power transfer to a micro aerial vehicle, etc. can be covered with these band of frequencies. VSWR, return loss, radiation pattern, gain is some of the parameters considered to prove the performance of the fabricated design prototype.

1. INTRODUCTION

The rapid increase of wireless services and applications, antenna designers are very much interested in combining different wireless communication protocols into a single device. Moreover, multiband antennas are extensively used in smart portable devices, mobile communications, WLAN, WiMAX operate with multiple bands of frequencies. In general, WLAN operates with 2.4, 5.2, 5.4, and 5.8 GHz and 3.3-3.8 GHz for WiMAX. Printed technology proved at its best place in designing the antennas providing reduction in hardware complexity with better performance. The fabrication of these antennas is very simple with compact size. These antennas are made up of a solid dielectric substrate with a conducting material (thin sheet of metal) produced on both sides. Patch refers to the metallic sheet placed on top of the substrate which is connected with the ground plane via a feed network [1]. Patch is the radiating part of antenna and ground plane provides increased bandwidth [2]. The performance of antenna can be enhanced with increase in thickness of the substrate or by decreasing its dielectric constant. Some of the advantages of these antennas are smaller size, low weight, cost effective, easy to integrate on the substrate etc. whereas the limitations include low gain, low efficiency, low power handling capacity [3, 4]. To overcome these limitations, Fractal antenna geometry can be used. The primary benefit of fractal antennas is multiband application with higher gain and reduced size [5-8]. The use of fractals also helps in the improvement of antenna features.

Various multiple-band antennas are proposed for RF energy harvesting using CPW, microstrip line and coaxial feeding techniques [9-12]. Table 1 compares the proposed antenna's size, operational bands, and average peak gain to antennas mentioned in the literature [13-22]. The proposed quad band antenna is proven to be effective at 2.8-3.5GHz, 4.8-7.5GHz and 8.1-9.4GHz frequency bands resonating at 3.1GHz, 5.2GHz and 6.8GHz and 8.7GHz respectively. The most attractive application for the designed antenna can be seen at RF energy harvesting and short range communication. These multiband antennas are also used in MIMO and OFDM [23, 24].

The gain of these antenna should be precisely large so that the reduction in power requirements would ultimately increase the battery life. This can be achieved by using optimization techniques. Basically, they are classified into two types: evolutionary and gradient based algorithms to update the antenna design parameters. Some of the evolutionary algorithms include Genetic algorithm, Simulated annealing, PSO (Particle Swam Optimization) which optimize the antenna using natural or collective behavior of the variables. They are not frequently used as they are inefficient with the increase of design variables [25-29]. However, gradient based algorithms such as Quasi Newton Optimizer can handle for large no. of design variables. They converge fast to the local optima with low computational cost. Solving the objective function is a little complex, hence can be computed using first order methods. In the paper, QNO based optimization is performed and analyzed in the next sections.

Table 1. Comparison of different parameters for various applications

Ref	Size (mm^3) & Area(cm^2)	Substrate Material & Its Dielectric Constant	Feed Type	Bandwidth/ Frequency Range	Application
[13]	20.1x16.6x1.58 &3.3366cm^2	RT duroid 5880,2.2	Inset feed	5.8-5.95 GHz	DSRC
[14]	37x40x1.6 &14.8 cm^2	Neltec NX9240,2.4	Coaxial feed line	2.39-2.43 GHz	RF Energy Harvesting
[15]	53.038x46.676x1.6 & 4.576cm^2	FR4 Epoxy, 4.4	MS line feed with inset feed	60 & 200 MHz at 2.45 GHz & 5.8GHz	RF Energy Harvesting
[16]	23.2x31x1.6 &7.192 cm^2	FR4 Epoxy, 4.4	MS feed line	5.69-5.89 GHz	Wireless power transfer to a MAV
[17]	100x100x1.6 &100 cm^2	FR4 Epoxy, 4.4	CPW	0.88-8.45 GHz	RF Energy Harvesting
[18]	25x40x1.6	FR4 Epoxy, 4.4	MS line feed	2.27 GHz–2.6GHz and 3.0 GHz-20 GHz	WLAN/ WiMAX and UWB
[19]	70x70x1.6 & 49 cm^2	FR4 Epoxy, 4.4	Inset feed	2.35 & 3.7 GHz	RF Energy Harvesting
[20]	205x275x1.6 &563.75 cm^2	3 layers: FR4-air-FR4,4.4	MS line feed	1.526-1.626 GHz	RF Energy Harvesting
[21]	28x28x1.6 &5.76 cm^2	FR4 Epoxy, 4.4	Co-axial probe feed	3.3, 4.7 and 6.7GHz	Wi-Max
[22]	123.39x83.6x1.6 & 103.154cm^2	FR4 Epoxy, 4.4	MS line feed with inset feed	6.85-7.15 GHz	Satellite Communication

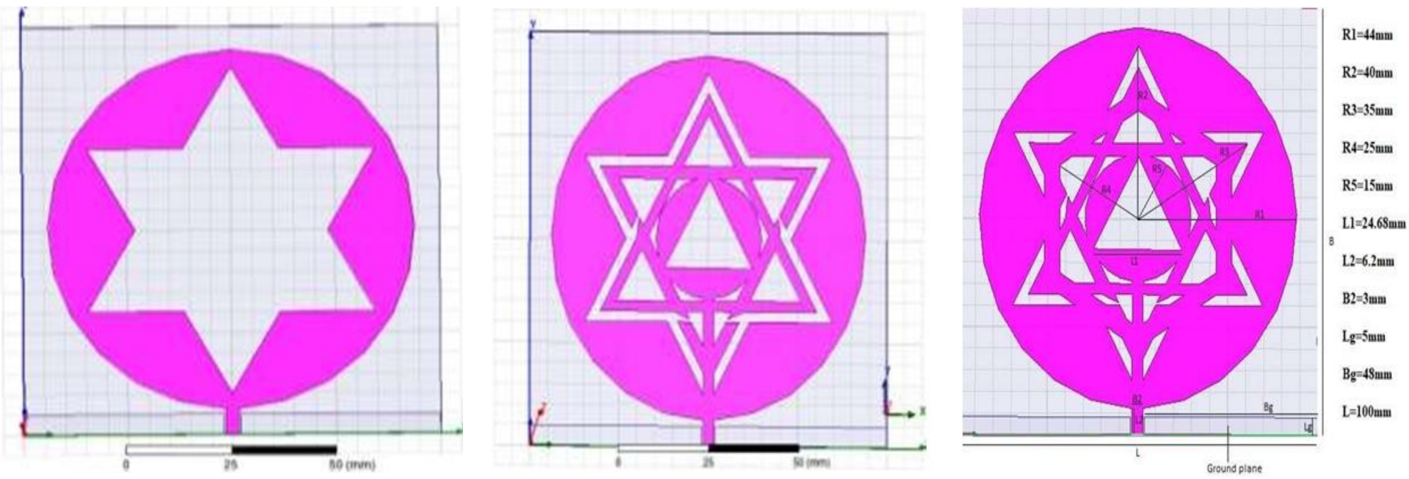
2. FRACTRAL ANTENNA DESIGN

The proposed antenna design and geometrical structure of various iterations of the antenna are discussed here. The Kagome crest is a star shaped design. It is generally viewed as a six coned star or as an eight coned star. The iterations are based on the fractal design keeping all the other parameters same such as substrate height, material and feeding technique. The performance of the antenna largely depends upon its geometrical parameters and dielectric constant of substrate. The recommended antenna uses the substrate of FR4 epoxy having dielectric constant of 4.4.

The substrate has 0.02 dielectric loss tangents with 1.6 mm thickness. Also, the type of feeding used and the feeding point are important parameters to decide the overall performance of antenna. Feed used in the design is provided with 50-ohm microstrip transmission line. The antenna size considered is 100mm x 100mm x 1.6mm along with the ground plane.

The 0th- iteration of the proposed antenna is depicted in Figure 1 (a), in which there is a circular patch with star pattern is slotted on it [19]. To be precise, there are 2 concentric equilateral triangles of same size and opposite direction that are slotted from the circular patch.

The first iteration of the antenna is obtained as shown in Figure 1 (b), where the notch (rectangular strip connected to the feed) is expanded and connected to another star shaped strip in which a circle is added in the middle and a small equilateral triangle is slotted from that circle. It is to be noted that all the triangles and circle are concentric. To obtain the second iteration proposed antenna, a hexagonal strip is added [28]. The dimensions are given along with the geometrical structure in Figure 1(c). Thus, the Kagome crest fractal antenna is designed which exhibits better radiation and gain. Figure 2 clearly depicts the bottom view (ground plane) of the design for all iterations.



(a) (b) (c)

Figure 1. Geometrical structure of the antenna: (a) 0-iteration, (b) 1-iteration, (c) 2-iteration

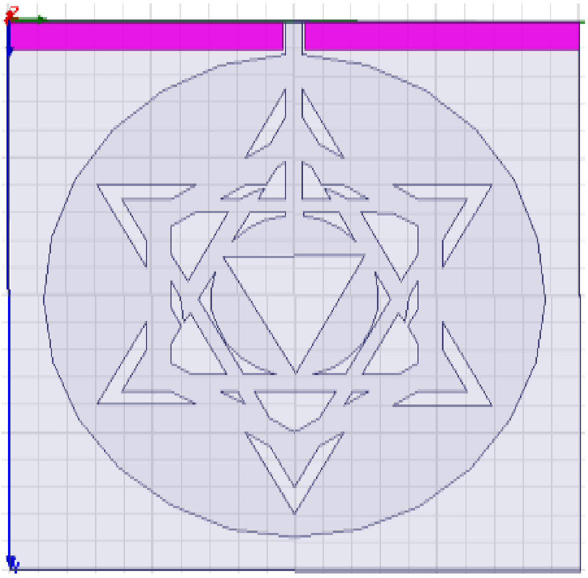
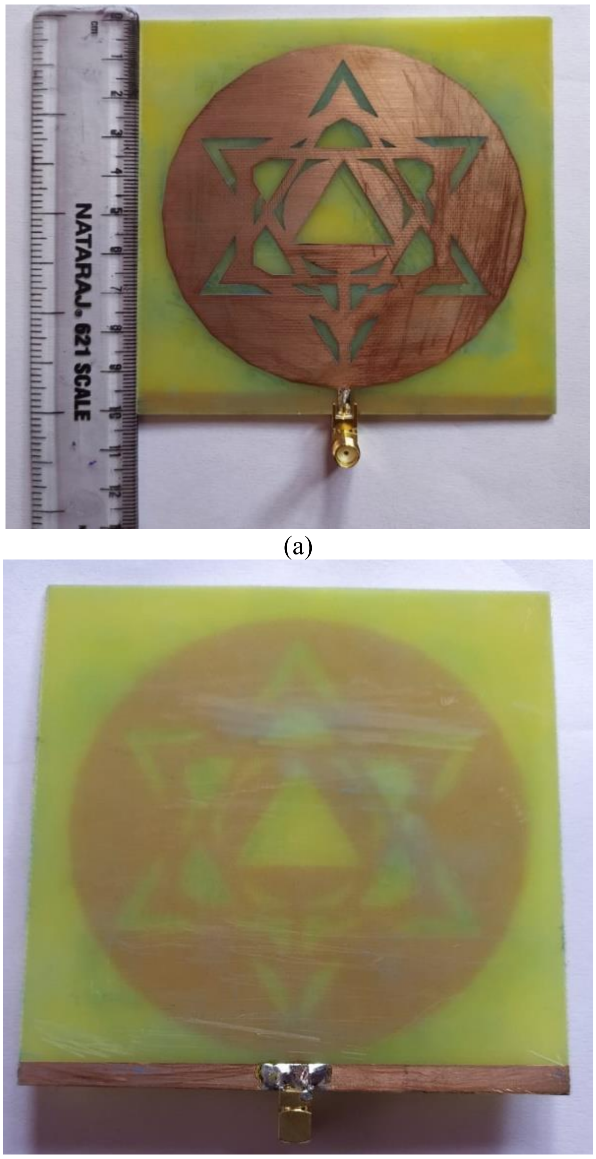


Figure 2. Bottom view of the proposed antenna with ground plane



(a)

(b)

Figure 3. Fabricated proposed antenna (a) Kagome crest star shaped patch for radiation (b) Ground substrate

The radius of the circle in the middle is updated using an optimization method. Quasi Newton optimizer (QNO) is one of the gradient based algorithms [29]. The objective function is optimized to the local minima. It finds the updated variables of the given function. The objective function is related to the design parameters of the antenna including thickness, radius, power or force, etc. The QNO is used to find the zeros or local maxima or minima values of the design variables using first order method. This has the advantage of antenna having large number of variables to optimize the design. The function is Hessian matrix which is asymmetric matrix calculated by a quadratic method and solved for zeros. This matrix is updated by computing successive gradients of the variables. In the optimization process, the gradients and Hessian are calculated as

$$\nabla g(x_k + \Delta x) = \nabla g(x_k) + H\Delta x \qquad (1)$$

where, ∇g is the gradient and H is the Hessian matrix. The unknown variable x_k is updated using the current approximate Hessian matrix at each iteration. Thus, the optimization is done by varying the radius of the circle from 41mm to 42.51mm. Figure 3 shows the fabricated antenna after optimization.

3. PERFORMANCE ANALYSIS

The proposed antenna's properties, such as return loss, VSWR, radiation pattern, and gain, are defined and performance at various iterations are discussed in this section. An antenna's return loss is a percentage of the total amount of power transmitted to the antenna. The lower the return loss, the more power transmitted, and the more efficient the antenna can be. For microstrip antennas, return loss must be less than -10dB, which implies that 90% of the available power is delivered to antenna. Figure 4 clearly depicts the return loss for various iterations. The 0^{th} iteration has 4 resonant frequencies at 3.1, 5.2, 6.8 and 8.7GHz respectively, with lowest return loss value of -23.48dB occurring at 5.2 GHz. The 1^{st} iteration has better impedance matching property than the 0^{th} iteration as inferred from the graph. Although, it also has 4 frequency bands around similar frequencies but there is an improvement in return loss which is -38.42dB at 5.3GHz. Hence more power is delivered to the antenna making it more efficient. The 1^{st} iteration has return loss value around -15dB at other 3 resonant frequencies and hence is not much useful at these frequencies. The 2^{nd} iteration, which is the proposed antenna design overcomes this with significant return losses at all the 4 bands. The parameter analysis of resonant frequencies, bandwidth obtained and the simulated return loss at the resonant frequencies for the proposed design is given in Table 2. The proposed antenna's simulated and measured return loss using a network analyzer demonstrated in Figure 5. Manufacturing tolerances, thickness uncertainty, FR4 substrate dielectric constant, and SMA connector quality all contribute to the variance between simulated and measured values.

The impedance matching among the antenna and connected transmission line is signified by VSWR. The VSWR value between 1 and 2 is considered good for patch antenna performance. VSWR values obtained for the optimized antenna are 1.2893, 1.1160, 1.1056 and 1.1250 at resonant frequencies of 3.1GHz, 5.2GHz, 6.8GHz and 8.7GHz respectively. The VSWR is depicted in Figure 6 with different markers showing the value of the VSWR at the resonant frequencies.

Figure 7 demonstrates the strength of radio waves radiated by the antenna in different directions. The proposed optimized antenna measured radiation pattern at four resonant frequencies indicates the efficiency of the antenna for various 5G applications. The optimized quad-band antenna's radiation patterns are predicted with E-plane and H-plane under HFSS environment. Also measured in an anechoic chamber with in-house antenna measuring equipment. The patterns are measured with a reference antenna generally horn antenna. Radiation patterns in the E-plane are bidirectional, but those in the H-plane are omni directional (dumb bell shaped). Furthermore, the measured and simulated results are nearly identical, with slight differences due to measurement and alignment problems.

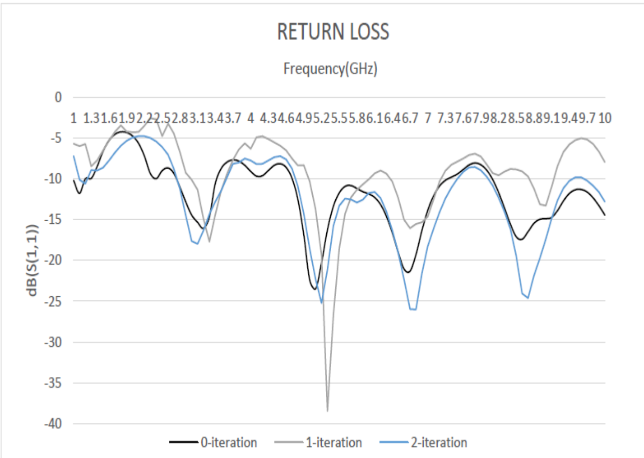


Figure 4. Performance of the antenna in terms of return loss curves at various iteration

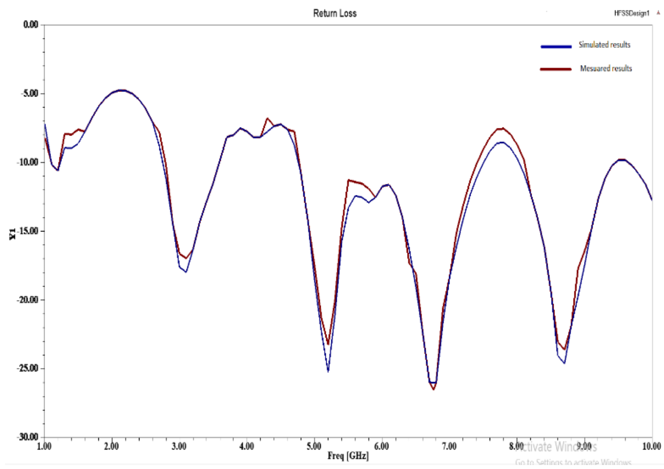


Figure 5. Analysis of simulated and measured return loss of proposed antenna

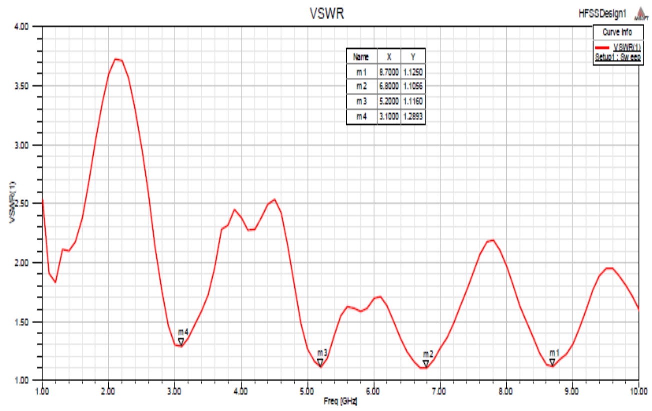
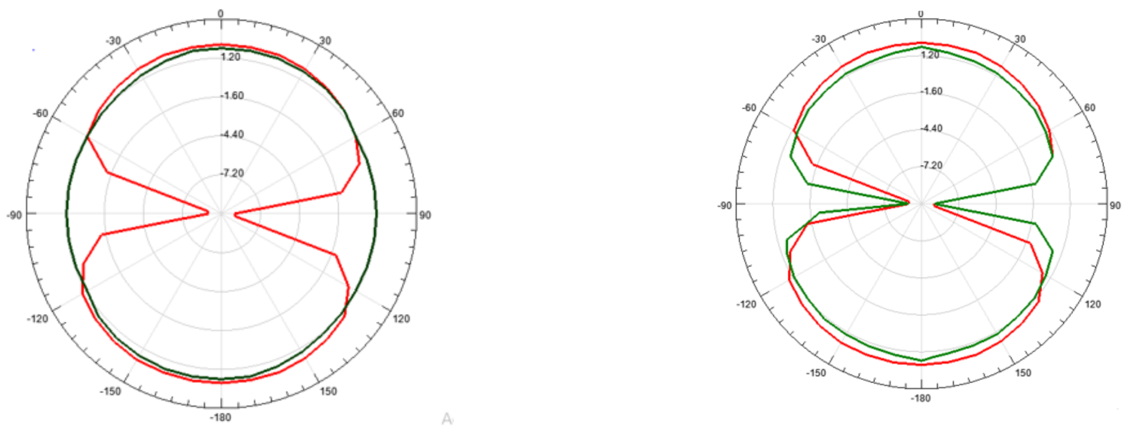


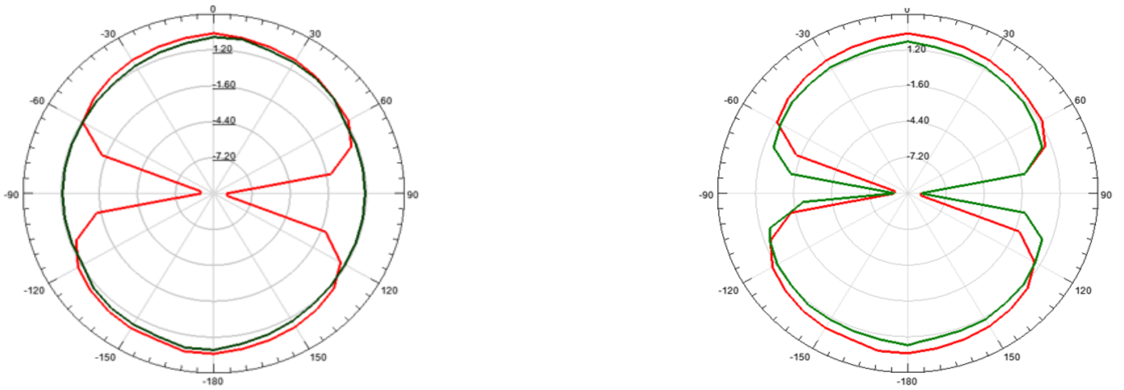
Figure 6. Simulated VSWR at multiband frequencies of the antenna

Table 2. Parameter analysis of the proposed antenna at multiband frequencies

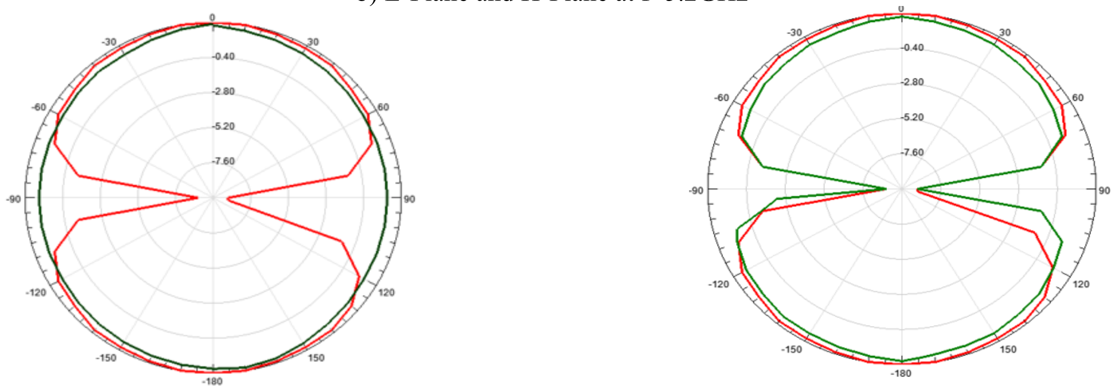
Frequency	Bandwidth	Resonant Frequency	Percentage Bandwidth	Return Loss
2.8-3.5GHz	700MHz	3.1GHz	22.58%	-17.96dB
4.8-7.5GHz	2700MHz	5.2GHz &6.8GHz	51.92% &39.7%	-25.21dB &-26dB
8.1-9.4GHz	1300MHz	8.7GHz	14.94%	-24.6dB



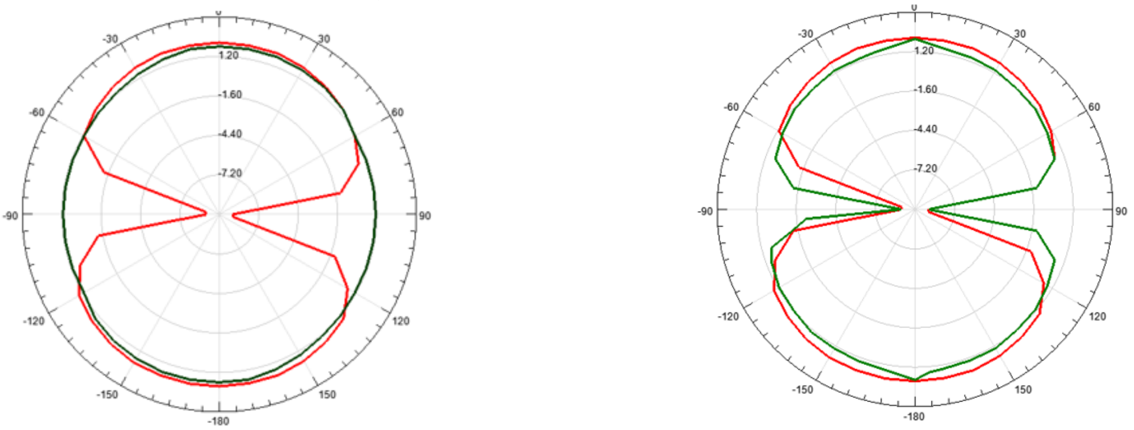
a) E-Plane and H-Plane at f=3.1GHz



b) E-Plane and H-Plane at f=5.2GHz



c) E-Plane and H-Plane at f=6.8GHz



d) E-Plane and H-Plane at f=8.7GHz

Figure 7. Stable radiation patterns of the proposed quad-band Antenna at resonating frequencies of a)3.1GHz, b) 5.2GHz, c) 6.8GHz and d) 8.7GHz

The simulated and measured radiation patterns of the proposed quad-band fractal antenna is represented in Figure 7. E-plane and H-plane patterns at different resonating frequencies of 3.1GHz, 5.2GHz, 6.8GHz and 8.7GHz proved the performance antenna. Figure 8 illustrates the antenna's total gain at the four resonant frequencies where it is found to be the highest. The CPW feeding technique is an effective technique achieves wide frequency ranges. The feeder is connected with both sides of the ground plane. At 50-ohm, CPW is found to be more lossy than Microstrip line and the coupling efficiency along with the quality factor (Q) is less. Therefore, impedance bandwidth is more in CPW feed. In this work, microstrip line feed is employed and hence this antenna incurs reduced losses.

Table 3 compares the proposed antenna with [18-22] for substrate type, antenna size, number of frequency bands, bandwidth and return loss. As the optimized antenna achieves highest number of frequency bands are obtained with return loss less than -10dB and hence it can be used for variety of applications such as RF energy harvesting, satellite communication etc. The proposed optimized antenna performance in terms of reflection coefficient is depicted in Figure 9. It was observed that Kagome Crest Fractal antenna has low losses and wide bandwidth when it was optimized with the Quasi newton algorithm. Figure 10 represents the parametric analysis of the proposed antenna with variation in radius of the patch. After optimization, it achieves better performance at 44mm of radius.

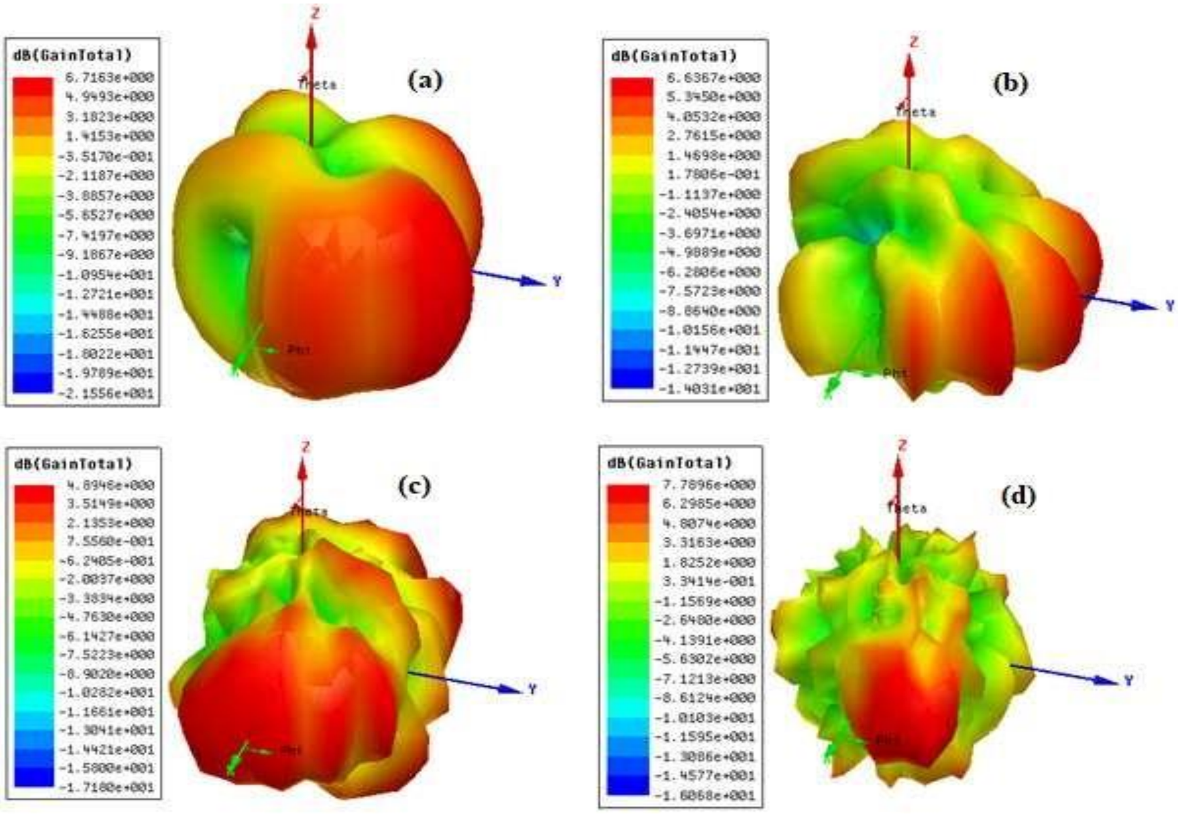


Figure 8. Gain of the proposed antenna at (a) 3.1GHz(b) 5.2 GHz (c) 6.8GHz(d) 8.7GHz

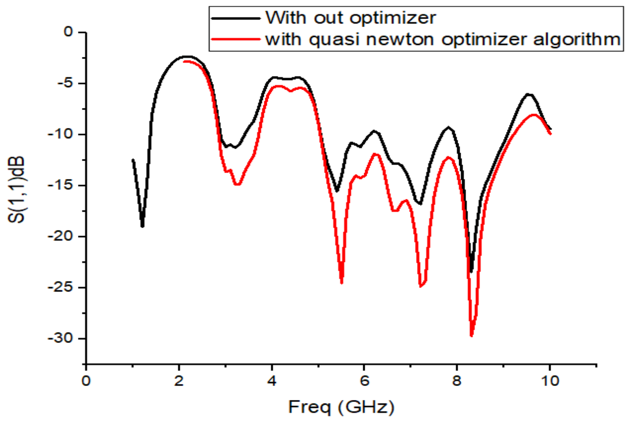


Figure 9. Proposed antenna using optimization

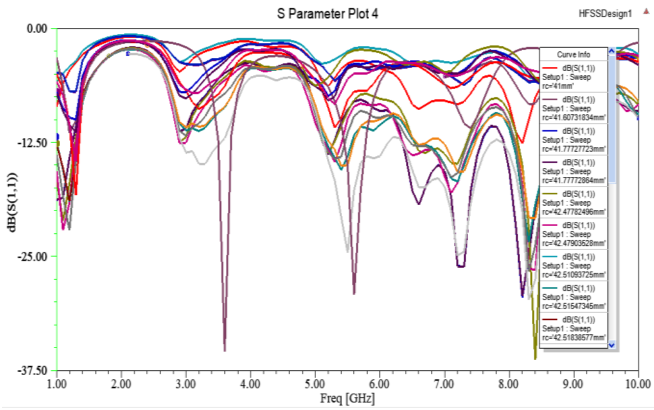


Figure 10. Optimization results by varying the patch radius

Table 3. Comparative analysis of different parameters of the proposed antenna

Ref	Type of Substrate	Size (mm^3)	Frequency Bands (GHz)	Bandwidth (MHz)	Return Loss(dB)	Antenna Purpose
Proposed Antenna	FR4 Epoxy	100x100x1.6	2.8-3.5 4.8-7.5 8.1-9.4	700 2700 1300	-17.96 at 3.1 -25.21 at 5.2 -26 at 6.8 -24.6 at 8.7	RF Energy harvesting, DSRC, Satellite comm.
[18]	FR4 Epoxy	25x40x1.6	2.27 GHz–2.6GHz and 3.0 GHz-20 GHz	7500	-18 at 2.4	WLAN/WiMAX & UWB
[19]	FR4 Epoxy	70x70x1.6	2.35 and 3.7	-	-23.23 at 2.35 -21.6 at 3.7	RF Energy harvesting
[20]	FR4-air-FR4	205x275x1.6	1.526-1.626	100	-13.449 at 1.575	RF Energy harvesting
[21]	FR4 Epoxy	28x28x1.6	3.3, 4.7 and 6.7	-	-15.68 at 3.3 -17.71 at 4.7 -33.82 at 6.7	WiMAX
[22]	FR4 Epoxy	123.39x83.6x1.6	6.85-7.15	300	-27.533 at 7	Satellite comm.

4. CONCLUSION

In this paper, a novel design of Kagome crest quad band fractal geometry antenna including a star shaped slot is proposed and it is optimized using a gradient based algorithm of Quasi Newton optimizer. Antenna design at various iterations is examined and optimization improved the operational performances of the designed antenna. This antenna is simulated and fabricated prototype was analyzed with the network analyzer. It resonates at quad frequencies of 3.1, 5.2, 6.8 and 8.7GHz. The antenna offers a bandwidth of 51.92% (4.8-7.5GHz) & a peak gain of 7.78dB providing better impedance matching and stable radiation characteristics. The optimized antenna improved the return loss at frequencies 2.8-3.5GHz, 4.8-7.5GHz & at 8.1-9.4GHz. The proposed antenna has multiple bands with high bandwidth was observed with the maximum gain of 7.7896dBi. The simulations and practical measured results proved that the antenna is preferable for WLAN, RF Energy harvesting, mobile and wireless applications.

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