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Design and Assessment of Bio-Inspired Antennas for Mobile Communication Systems

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ABSTRACT- RF front-end system in the mobile communication system consists of an antenna, filter, and amplifier section. Now a day, there is a need to reduce the size of this RF front-end system. Here the challenge is the reduction in the size of the RF front end without degrading the performance. One way to reduce the size is by reducing the size or area of the antenna. This work proposes and simulates three Bio-inspired microstrip (BIMS) antenna designs. They are flower, Butterfly, and leaf shapes presented based on the perturbation method, Gielis super formula, and modified polar transformation models, respectively. These BIMS antennas were printed on fiberglass laminate (FR4) as substrate with a dielectric constant of ε_r = 4.4 and a loss tangent of 0.02. The simulation results cover parameters of the antenna, such as reflection coefficients (S11), surface current density (Jsurf), and radiation patterns. They offer a maximum gain of 14 dBi, 8 dBi, and 4dBi, respectively, and their results are compared with other works. These antennas are less in size, so they occupy less area compared to conventional rectangular or circular patch antenna, which radiates in L and S bands at different frequency ranges.

Keywords: Bio inspired antenna, reflection coefficient, radiation pattern, perturbation method, polar transformation, and Gielis super formula.

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1. INTRODUCTION

In recent years, wireless communication systems have been growing fast, setting new challenges for the research group. The major challenge is reducing the size of the system without degrading its performance of the system. One method to increase the compactness of receiving unit is reducing the size of the components. The antenna is the interfacing wireless communication system with air which is very important. It converts the high-frequency electric signal to radiation and vice versa. It defines the operation bandwidth of the wireless system. The antenna dimensions are inversely proportional to radiating frequency, i.e., the antenna dimension is significant at low frequencies. Most wireless applications like a digital audio radio broadcast, Wi-Fi, ISM band, RFID, satellite navigation, aircraft surveillance, and others are used in the frequency range of 1 to 4 GHz. An antenna design in this range usually occupies a large area and is also significant in size. The compactness improvement leads to the challenge of reducing the antenna size so that the system size can reduce. These antennas are wearable, embedded antennas, flexible antenna, and foldable antennas depending on the applications.

Methods like providing slots on patches, defects in the ground, adding lumped elements, and others are useful to reduce the size. In recent years, physical shapes of antennas are emerging with different shapes inspired by nature. The details of recent works are going to discuss in this paper under *Section 2*. The antenna size can be less than a rectangular patch, and these antenna structures can find in nature. They can follow various models like fractal geometry, polar geometry, perturbation, and the super formula of Gielis. Fractal geometry is a non-uniform structure, so the design is complex. In this work, three antennas are designed and simulated based on the polar geometry, perturbation, and the Gielis super formula using commercial software HFSS.

The orchid flower-shaped antenna design is on the perturbation technique; the butterfly-shaped antenna design is on super formula, and the leaf-shaped antenna is on the polar transformation. *Section 3* outlines the details of antenna design and simulation; *Section 4* is a discussion on simulated results and comparison and finally *Section 5* concludes the paper

2. LITERATURE SURVEY

Bio-inspired antenna structures are natural shapes such as flowers, insects, and leaves. Different authors proposed various methods to design bio-inspired antenna and wearable antennas. These shapes follow mathematical models of polar transformation, super formula, and fractals to have various leaf-shapes, flower, and other shapes [1]. Antenna designs based on these models usually offer narrowband operation. In [2], body wearable antenna designs on denim cloth is designed that offer radiation in 2 to 5 GHz band. The return loss characteristics have multiple ripples. The author in [3] analyzed the fractal structure and compared it with a rectangular patch. In [4], the proposed antenna is a coplanar waveguide (CPW) rose-flower-shaped antenna. A slip ring resonator is a loading element to obtain the required antenna characteristics. The antenna has multiple narrow band radiations from 1 GHz to 18 GHz. A flower-shaped monopole antenna in [5] offers an ultra-wideband application that radiates with centered at 9.75GHz. The authors in [6] design a leaf-shaped monopole antenna with super broadband characteristics.

Parametric analysis is made in this to achieve a super wide band. A spiral-shaped antenna that the snake inspires was present in [7]. A compact dielectric resonating antenna (DRA) is proposed in [8] that radiates at 2.4 GHz, and the compactness is due to the usage of a metal sheet over the antenna. In [9], a spiral seashell-shaped DRA is designed that radiates in 3 to 6 GH. This work presents various parametric analyses to have the sub–6 GHz band operations. Another CPW leaf-shaped antenna in [10] is the fractal-shaped edge leaf antenna loaded with SRR that offers multiple bands of operation up to 20 GHz. A compact antenna for 5G application with a butterfly shape was discussed in [11]. An array of butterfly-shaped radiators based on polar transformation is proposed in [12], which offers a narrow band of 96 MHz operation at 2.4 GHz. Bio-inspired antennas also detect signal transmission ranges and sensors [13]. In [14], a high un gain antenna is proposed. The large gain obtained by making stepped cutting at the edges of the patch. The structure can use different substrates to have different radiation frequencies. However, it offers narrowband operation at respective frequencies. A papaya leaf-shaped dipole antenna in [15] has dual-band operation with one narrow band and the other wideband operation. Butterfly shaped antenna proposed can offer 5G operation and has a center frequency at 15.7GHz and narrow band operation [16], the author used frequency selective surface (FSS). The effect of meta-material, etching ground, and providing a defective ground surface of microstrip on the antenna parameters discussed in [17-20]. The survey shows that the dimension of the antenna is low at high frequency and large dimension at high frequency. This paper proposes three low-profile antennae with bio-inspired shapes and their simulation results compared.

3. BIO INSPIRED ANTENNA DESIGN AND SIMULATION

3.1. Orchid flower shaped antenna

This design follows the perturbation method [13]. Furthermore, the design is a modified form of a circular patch antenna. The radius of the circular patch antenna is usually independent of substrate thickness at microwave frequencies. It is given by

$$R \approx \frac{88}{f_r\sqrt{\varepsilon_r}}\ mm \qquad (1)$$

Where f_r is radiating frequency in GHz and ε_r is the substrate dielectric constant.

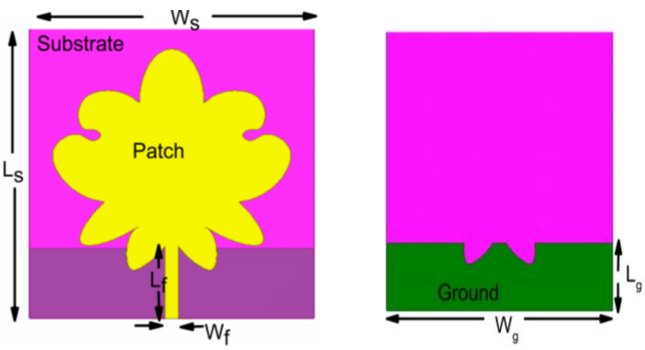
The circular patch is now modified to get the required Orchid flower shape, shown in *figure 1(b)*. The design is symmetric about the origin, so a mirror image of the dimension point's connection will give the proposed model. The dimensions data shown in *table 1*.

(a) (b)

Figure 1: (a) Orchid flower (b) proposed antenna structure

Table 1. Design data for the proposed antenna (each point is calculated from origin (0, 0, 0)

Point	Coordinate values			Distance from origin (millimeter)
	x	y	z	
d1	0	20	0	20
d2	14	10	0	17.2
d3	17.5	0	0	17.5
d4	14	-16	0	21.2
d5	6.5	-20.5	0	21.5
d6	-5	-3	0	139
d7	-10.4	-8.4	0	13.4
d8	-11	4	0	11.7
d9	-5	10	0	11.18



(a) (b)

Figure 2: Orchid flower shaped antenna:(a) Top view (b) bottom view

The proposed model, shown in *figure 2*, uses a 0.8mm thickness FR4 substrate with W_s=W_g= 44 mm, L_s= 54 mm, L_g=13 mm, L_f=15 mm, and W_f=2 mm. small ground parts are etched to improve return loss (S11) and other parameters. The simulated result of the proposed flower model is in *figure 3*.

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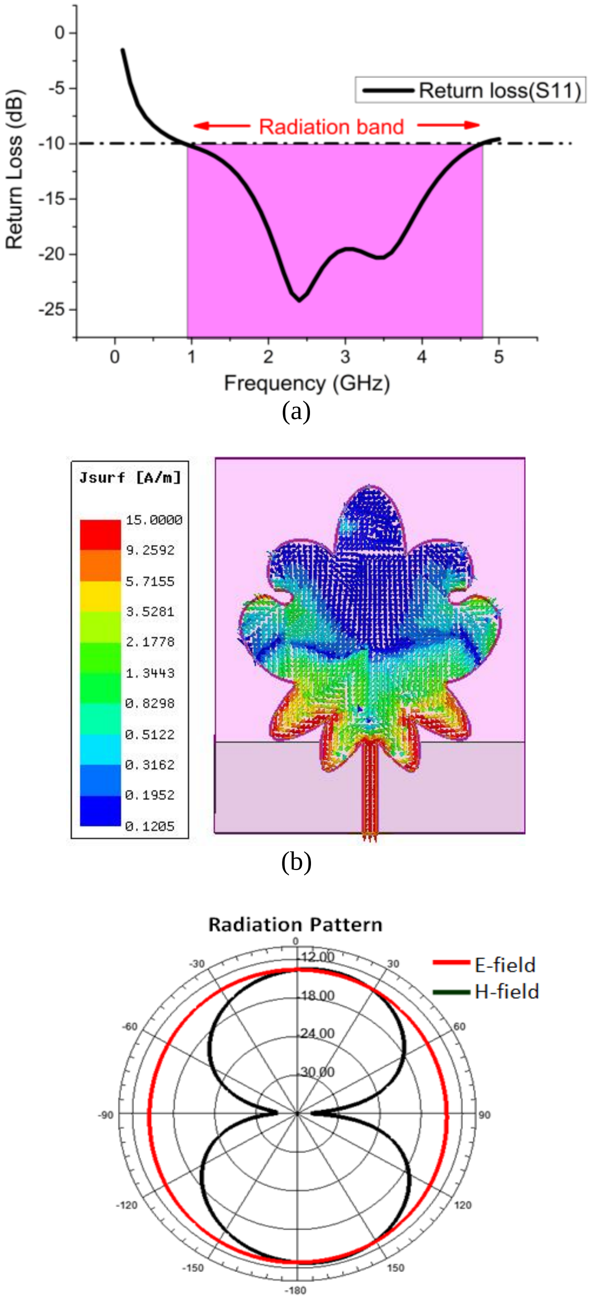


(a) (b) (c)

Figure 3: Simulation results of flower shaped antenna (a) Return loss (S11) (b) J_{surf} distribution (c) Radiation pattern

The simulation results show that the proposed flower-shaped antenna can radiate from 900 MHz to 4.7 GHz shown in Figure 3(a). *Figure 3(b)* is the surface current density along the e-field. It can show that the magnetic field is powerful as the red color indicates 9 to 15 A/m. The distribution is relatively good and shows the best impedance matching. So, the radiation pattern is also intense and maximum radiation at 2.4 GHz 18 dBi as shown in *figure 3(c).*

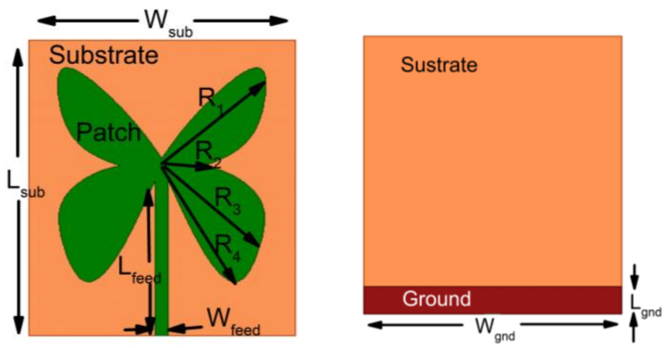
3.2. Butterfly shaped antenna:

This antenna design follows the Gielis super formula [1], which is actually from the super ellipse equations. With this model, leaf-shaped, butterfly-shaped antennas could design. The formula is given by [1]

$$r(\emptyset) = \left[\left(mod\left(\frac{1}{a}cos\left(\emptyset\frac{m}{4}\right)\right)\right)^{n2} + \left(mod\left(\frac{1}{b}sin\left(\emptyset\frac{m}{4}\right)\right)\right)^{n2}\right]^{-\frac{1}{n1}}$$

$$for\ 0 \leq \emptyset \leq 2\pi \qquad (2)$$

Various shapes could obtain by changing the parameter set (a, b, m, n1, n2, n3). The butterfly shape obtains by using the set (1, 1, 4, 0.2, and 0.5). The butterfly-shaped antenna presented in Figure 4 has dimensions of substrate width W_{sub}= 16 mm, substrate length L_{sub}=20 mm, feed line length L_{feed}=11.5 mm, feed line width W_{feed}= 0.8 mm, R_1=8.5 mm, R_2=2.5mm, R_3=7.2 mm and R_4= 8.7 mm. The patch has dimensions of 11.6 X 28 mm^2. In this FR4 substrate with 0.8 mm thickness is used.



(a) (b)

Figure 4: Butterfly shaped microstrip patch antenna (a) Top view with dimension (b) Bottom view

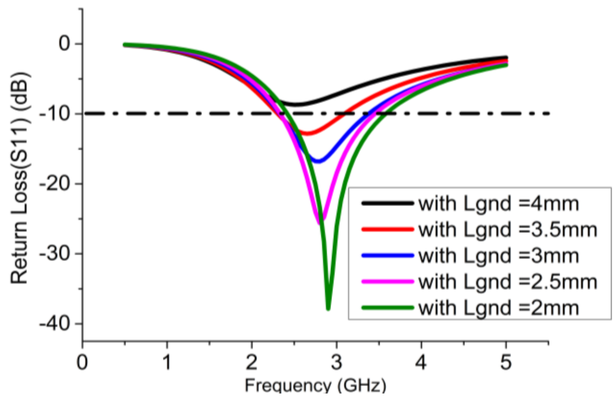
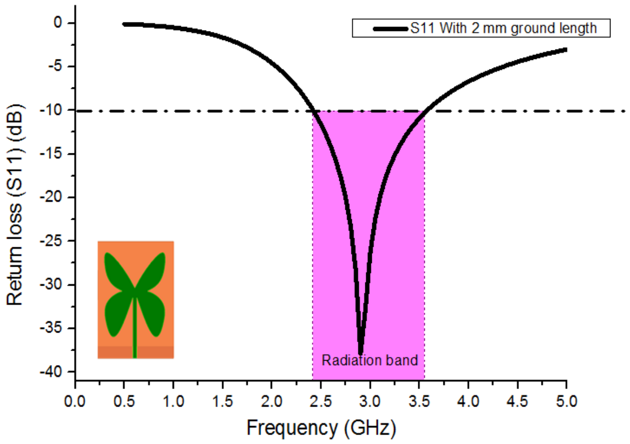
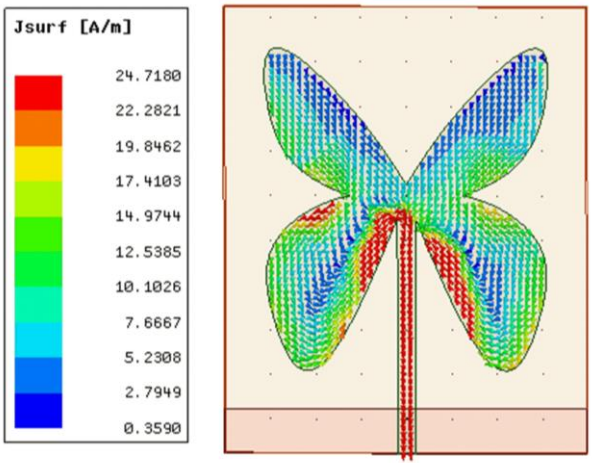


Figure 5: Parametric analysis of ground dimension

The variation S11 was analyzed using parametric analysis by the length of ground Lg. It shows that the bandwidth increases with loss in return loss factor. With a ground length of 2 mm, the antenna radiates efficiently at 2.9 GHz. The return loss plot, surface current distribution, and radiation pattern with a 2 mm ground plane are in *figure 6*.



(a)



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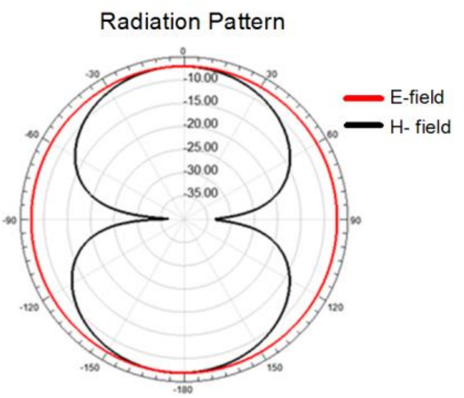

(c)

Figure 6: Butterfly antenna results (a) Return loss (S11) (b) Jsurf distribution (c) Radiation pattern

From the simulation results shown in *figure 6(a)*, the proposed antenna offers a 1.2 GHz bandwidth from 2.4 GHz to 3.6 GHz with a center frequency at 2.9 GHz with a -38 dB return loss. *Figure 6(b)* shows that the current distribution is vital over the patch along the e-field. The magnetic field is near the feed line strong as red shows 22-24 A/m. It is a good radiation field with a maximum gain of 8 dBi, shown in *figure 6(c)*.

3.3. Leaf-shaped antenna:

These leaf-shapes are following the esthetic polar transformation technique. A polar transformation is a vector set representation that gives a variety of shapes, and some of them are close to leaf structures. It follows the mathematical model given by equation (3). Figure 7 shows various structures using this equation.

$$\vec{a} = \left(1 + \frac{\cos t}{2}\right)\left(\cos\left(\frac{2t - \sin t}{k}\right), \sin\left(\frac{2t - \sin t}{k}\right)\right),$$

$$0 \le t \le k\pi \text{ , for all k} \qquad (3)$$

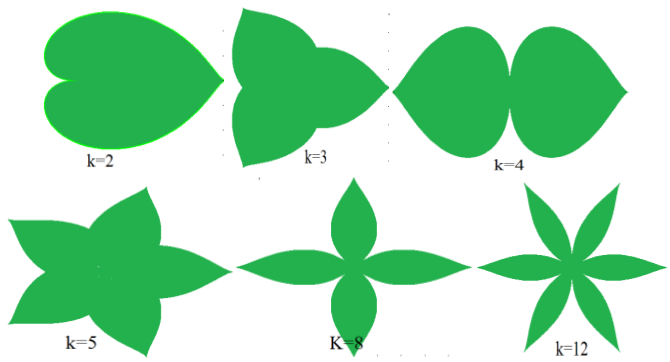

Figure 7: Polar transformation varying up to K=12

Equation (3) is redefined as *equation (4)* in this work to have closer to leaf shape structures.

$$\vec{A} = \left(1 + \frac{\cos t}{2}\right)\left(\cos\left(\frac{2t - \sin t}{k}\right), \sin\left(\frac{4t - 2\sin t}{k}\right)\right),$$

$$0 \le t \le k\pi \text{ , } k = 4,8,12,,16.. \qquad (4)$$

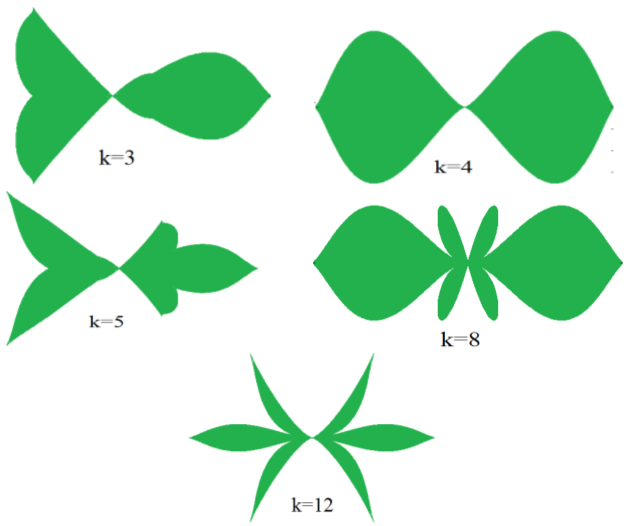

Figure 8: Modified polar transformation varying up to k=12

From the above *equation (4)*, the modified polar transformation with k =3, 4, 5, 8, 12, ..., will structures close to leaves shapes shown in Figure 8. The following *figure 9* shows leaf shaped antenna and the shape of the antenna with k=5. The structure

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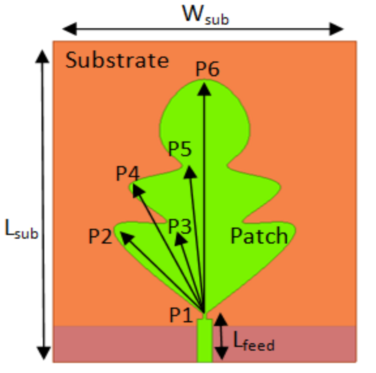
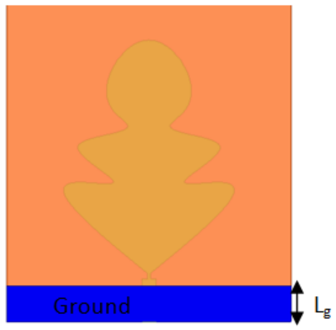
slightly changed for efficient antenna characteristics, and the microstrip patch ground was etched to have a dipole radiation pattern



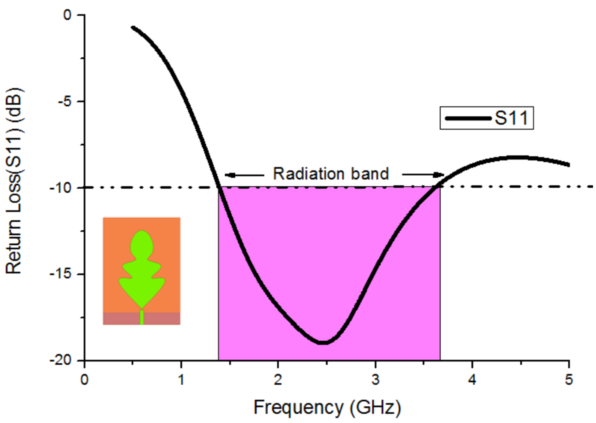
(a)



(b)

Figure 9: Leaf-shaped antenna (a) Top view with dimensions (b) Bottom view

The antenna was printed using a 1.6 mm FR4 substrate with a dielectric constant of 4.4 and a loss tangent of 0.002. The antenna dimensions are W_{sub}= 40 mm and L_{sub}= 45 mm, the feed line dimensions are L_{feed}= 6.2 mm and width are 2 mm, ground dimensions are width is 40mm and L_g=6 mm. As shown in *figure 9*, showing the patch dimensions in terms of radial distance from point 'P1' is convenient. P1-P2 is 16.4 mm, P1-P3 is 14 mm, P1-P4 is 20.5 mm, P1-P5 is 20.2 mm, and P1-P6 is 33 mm. its simulation results are in *figure 10*.



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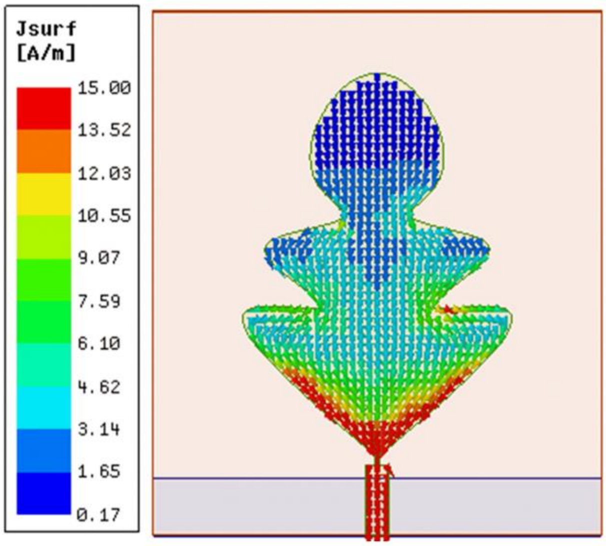

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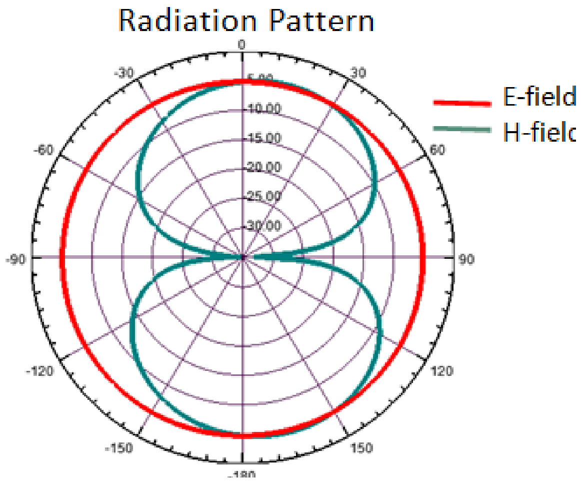


(c)

Figure 10: Simulation results of leaf shaped antenna (a) Return loss (S11) (b) Jsurf distribution (c) Radiation pattern

From the summation results shown in *figure 10(a)*, the antenna operating band is from 1.4 GHz to 3.65 GHz. *Figure 10(b)* is the surface current distribution. The surface currents are high near the feed line as the red color is 13-15 A/m. Due to the partial removal of the ground; the surface current distribution is non-uniform but is good enough to have better radiation. It has a 2.25 GHz bandwidth with a center frequency of 2.4 GHz, and its maximum gain is 11 dBi, shown in *figure 10(c).*

4. RESULTS AND DISCUSSION

All three antennas proposed in this article have shapes inspired by nature. They are Flower shaped antenna, Butterfly shaped antenna, and Leaf shaped antenna. The consolidated results are in *Table 2*. *Table 3* compares these proposed three antennas with bio-inspired antennas listed in the literature.

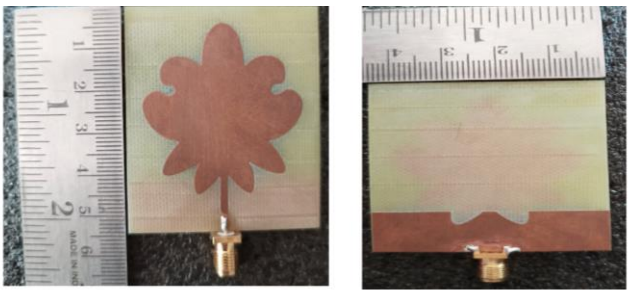
Table 2. Consolidated results of proposed antennas

Proposed antenna	Methodology	Dimensions [Length * width* height (mm^3)]	Maximum Return Loss@ center frequency (dB)	Total gain (dBi)
Orchid Flower shaped antenna	Perturbation method	54*44*0.8	-24 dB @ 2.4 GHz	14
Butterfly shaped antenna	Gielis super formula	20*16*0.8	-38 dB@ 2.9GHz	8
Leaf shaped antenna	Modified polar transformation	45*40*1.6	-18 dB @2.4 GHZ	4

Table 3. Comparison between existing literatures and proposed models

Reference literature	Dimensions [length*width (mm^2)]	Radiation band (GHz)	comment
[4]	12*12	1.03/45/8.28/13.4/17.4	Multi band
[5]	40*42	2.5-13	Ultra-wide band
[6]	42*30	23-12.2	Ultra-wide band
[8]	100*100	3.5/5.3	Dual band
[9]	14*16	1.997/3.19/6.32/8.814/11.87/15.69/18.3	Multi band
[12]	100*60	2.65	Narrow single band
[13]	59.25*35.2	1.99-3.5/5.8-10	Dual band
[14]	60*60	1.47-11.1	Ultra-wide band
Flower shaped antenna (Proposed antenna)	54*44	0.9-4.7	Wide band
Butterfly shaped antenna (Proposed antenna)	20*16	2.4-3.6	Single band
Leaf shaped antenna (Proposed antenna)	45*40	1.4-3.65	Single band

As the frequency of operation increases, the antenna size reduces [4 and 9], as shown in *Table 3*. However, at a low frequency below 5 GHz, proposed antenna models are compact compared to reference models [8 and 12], and their size is considerably small compared to [5,6,13 and14], which are the ultra-wideband and multiple band operating antennas. All three antennas are fabricated using an FR4 substrate and tested for their results. *Figures 11-13* show the fabricated models, measurement setups, and simulated-measured results in a single plot. *Figure 11* is a fabricated orchid flower-shaped antenna and the measurement setup along with results of measured and simulated results. *Figure 12* shows the fabricated butter fly-shaped antenna and the measurement setup, along with measured and simulated results. *Figure 13* shows the fabricated leaf-shaped antenna and the measurement setup, along with the measured and simulated results.



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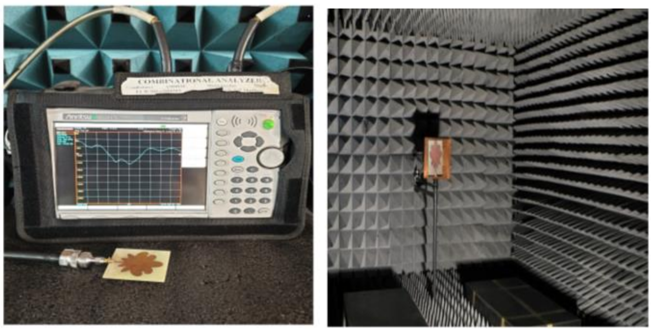

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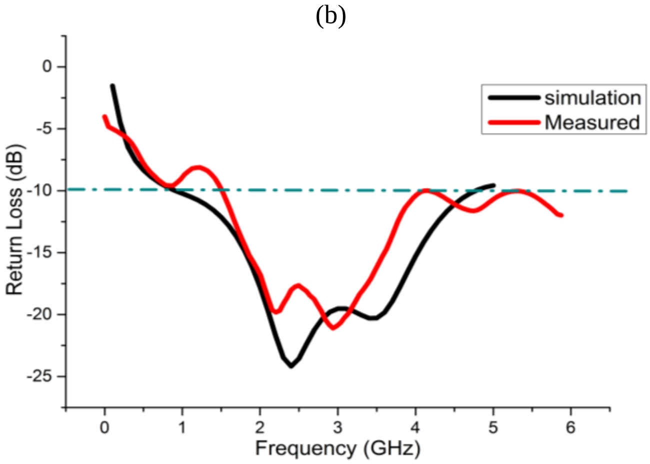

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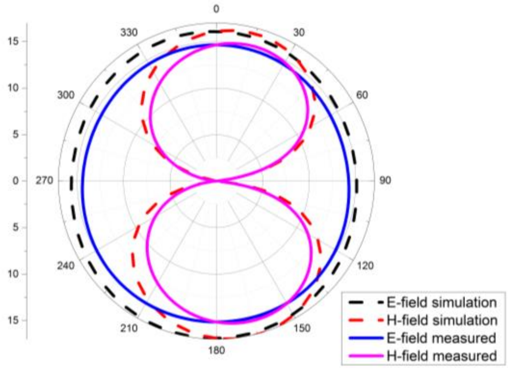
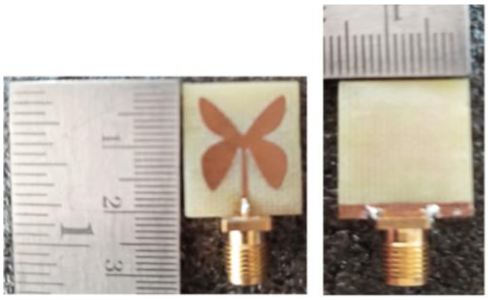


(d)

Figure 11: Orchid flower antenna: (a) Fabricated model (b) Measurement setup (c) Return Loss (d) radiation pattern



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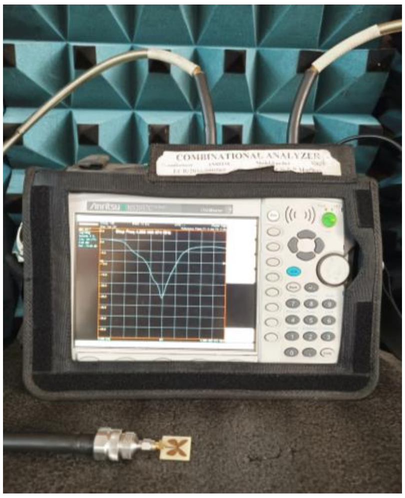

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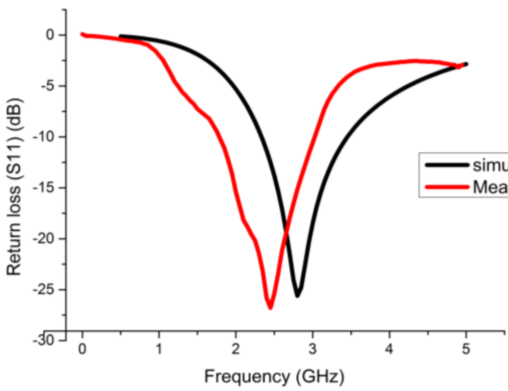

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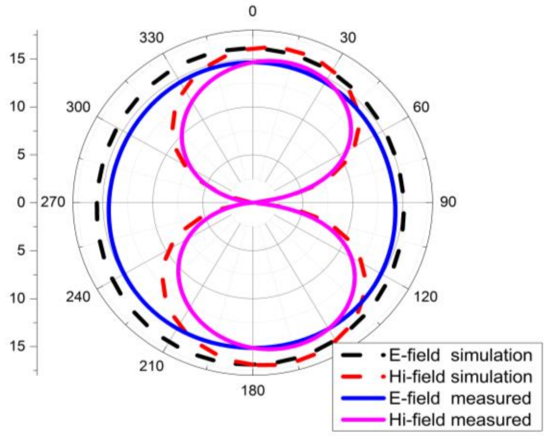
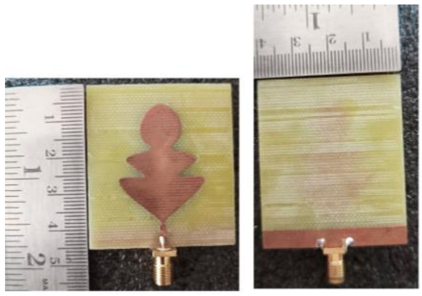


(d)

Figure 12: Butterfly shaped antenna:(a) Fabricated model (b) Measurement setup (c) Return Loss (d) radiation pattern



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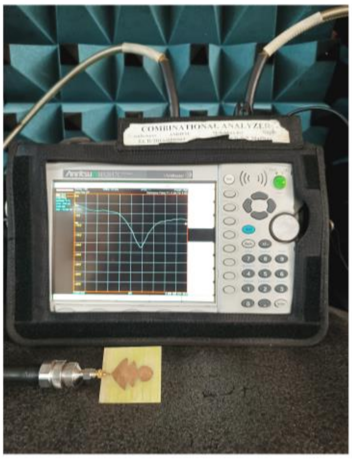

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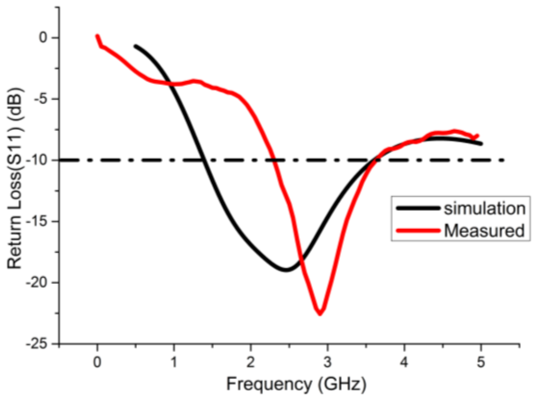

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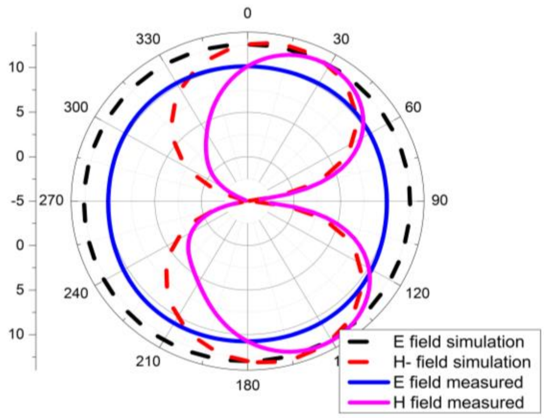

(d)

Figure 13: Leaf shaped antenna: (a) Fabricated model (b) Measurement setup (c) Return Loss (d) radiation pattern

5. CONCLUSION

This work discusses various methods of bio-inspired antenna structures, and three antennas are designed and simulated. In the design, a slight modification in the antenna's shape helped to achieve required objective of the proposal, which is reducing the size without degrading antenna performance. The proposed flower-shaped, Butterfly-shaped, and leaf-shaped antennae return losses are -24 dB, -38 dB, and -18dB, respectively. The flower-shaped antenna radiating frequency range has L and S-band applications. The butterfly-shaped antenna is very compact and targets S-band applications. The prototype offers less bandwidth than the other two models and simulated results. However, the size and return loss is minimal. The leaf-shaped antenna is also a single-band operation in S-band only. The ground is etched to have a dipole radiation pattern in all three models. The antenna design using the perturbation method is easy but requires many trials and errors. The polar transformation and super formula techniques is complex, but they offer many designs with many parameters in the models. In polar transformation, if 'k' is large, the shape beacon is circular, so it is limited to 24. From the above-measured results, the size of the butterfly-shaped antenna is compact, all model's radiation patterns are well matched with simulated results, and return loss measured results are some deviations from simulated results. So, the bandwidth was the loss, but the center frequency was almost identical. The following table shows the bandwidth deviations between simulated and measured results.

Table 4. Bandwidth comparison

Proposed antenna	Simulated		Measured	
	Band range	Band width	Band range	Band width
Orchid flower shaped antenna	1-5 GHz	4GHz	1.8-3.8 GHz	2GHz
Butterfly shaped antenna	2.5-3.5GHz	1GHz	1.8-3.2GHz	1.4GHz
Leaf shaped antenna	1.5-3.5 GHz	2GHz	2.5-3.5GHz	1GHz

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