The design of a multi-band bionic antenna for mobile terminals

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Abstract
This article proposes and designs a multi-band antenna that imitates banana leaves structurally. The edge structure of the antenna radiator is a mirror-symmetrical trapezoid, and four patches of different sizes are used as leaf veins inside. The feeding mode is coplanar waveguide feeding with a trapezoidal structure. The electromagnetic simulation software HFSS is used for antenna modeling and parameter optimization. The test results show that the antenna can cover 0.79 to 3.18 GHz, 3.29 to 3.98 GHz, and 4.98 to 7.62 GHz and produce six main frequency points: 0.9, 1.5, 2.4, 3.8, 5.6, and 6.9 GHz. The antenna has omnidirectional radiation characteristics and can be widely used in the future mobile communication network coverage field.

KEYWORDS
bionic, coplanar waveguide, mobile communication, multi-band

1 | INTRODUCTION
Nature has been the source of various technological ideas, engineering applications, and major inventions for humans. In long-term observation and practice, humans continue to imitate biological behaviors and benefit from them.1 Bionics is a science that imitates biological construction technology. The main idea of bionics is to imitate, create and invent advanced technologies based on the principle of biological structure and function, such as new equipment, new tools, and new technologies, to better serve human learning and production.2,3

The working principle of the antenna and many working performances are very similar to those of animals in nature. In the process of studying, analyzing and utilizing nature, the research on plant structure and animal organs can bring to new antenna concepts and facilitate the production of new antenna designs.4 Bionic antennas are an application of bionics in antenna design. Designing the antenna geometry by imitating the biological model can achieve a better performance.5,6 Examples include the antenna with the RCS reduction effect simulating sunflower and animal antennae,7,8 the antenna with a slotted shape simulating the dark areas of butterfly wings in the sun,9,10 the L-band monopole antenna simulating the shape of an octopus,11 the miniaturized broadband antenna simulating the ginkgo leaf shape,12 and the fractal ultra-wideband antenna array simulating bat wings.13
In recent years, the miniaturization and multi-functionalization of communication devices require that the internal antenna has strong integration capabilities. Meanwhile, owing to the lack of wireless spectrum resources, the demand for multi-band antenna has increased. Many methods have been studied to obtain multi-band antenna, such as coupling feed technologies, slot-loaded technologies, and reconfigurable technologies. Unfortunately, these methods require complex calculation, and the antenna structures are difficult to manufacture. Thus, new designs should be explored to simplify the structure and theoretical analysis.

This article proposes and discusses the design of a banana leaf antenna with multi-band characteristics using bionics principles. The banana leaves is very beautiful plant in nature, which have a regular shape and a multi-node structure. Inspired by the shape of banana leaves, this study realize the design of a multi-band bionic antenna. The designed antenna can cover three frequency bands: 0.79 to 3.18 GHz, 3.29 to 3.98 GHz, and 4.98 to 7.62 GHz. It can be widely used in WLAN, WiMAX, Bluetooth, GPS, and other communication systems.

1.1 Design and structure of banana leaf antenna

The antenna design is derived from the image of a banana leaf, as shown in Figure 1. In order to obtain more sunlight energy, plants in nature continue to grow to make full use of space and exhibit obvious genetic fractal characteristics in appearance. For antennas in a limited space, in order to improve the efficiency of radiating and receiving electromagnetic waves, the spatial filling of the fractal geometry can be used to increase the length of the radiator in a limited space. Generally, the shape of the patch antenna is relatively regular, which is convenient for analysis with transmission line or cavity model. The overly complex graphic is difficult to analyze and realize, and there will be greater errors during the process of manufacture. The thickness of the patch is very thin, so the bionic object should be flat. The structure of banana leaves is regular and flat, which is easy for simulation calculation and physical processing. Banana leaves
also have many branches, theoretically it should be able to produce multiple frequency bands. The gap in the banana leaf extends the current path and realize the antenna miniaturization. Therefore, banana leaf is choosen as the bionic model.

The design of the antenna consists of four procedures. Firstly, the main radiator is constructed with a hexagon structure. The feeding method is coplanar rectangular conductor, as shown in Figure 2A. This antenna is a common monopole without any deformation or slot. The simulation return loss $S_{11}$ in Figure 3 have two frequency bands: 1.9 to 4.0 GHz and 6.0 to 8.1 GHz. However, the current common applications are below 6 GHz. Only one band meets the requirement. Second, to realize the band 6.0 to 8.1 GHz also below 6 GHz, the solid radiator structure is changed to a hollow radiator structure, as shown in Figure 2B. The hollow structure extend circuit path, which will lower the work frequency. The simulation result shows that both resonance frequencies move to the left, which is consistent with the theoretical analysis. Thirdly, to realize multi-band property, patches of different sizes are introduced to disturb the current path. A rectangular patch is used to connect the veins and the feeder from top to bottom, as shown in Figure 2C. Figure 3 displays that the introduction of veins increases the number of resonance points. Last, the rectangular coplanar waveguide is changed to trapezoidal waveguide. Compared with rectangular structure, trapezoidal structure can make the mode conversion from feeder to radiator a gradual process, which makes the bandwidth more stable. The final antenna model is shown in Figure 2C.

The electromagnetic simulation software HFSS is used to optimize the antenna parameters, such as the length and width of the leaf veins, the width and height of the coplanar waveguide, the position of the leaf veins, and the length of the feeder line. The final antenna structure model is shown in Figure 4. The size parameters are given in Table 1. The dielectric plate is a PTFE glass cloth board (G10/FR4) with a dielectric constant $\varepsilon_r = 4.4$, thickness $h = 1.6$ mm, and dielectric loss tangent $\tan\delta = 0.02$. The physical size of the dielectric board is $50\times45\times1.6$ mm$^3$.

![Figure 4](Image)

**TABLE 1**  Antenna parameters

| Parameter | W | w1 | w2 | w3 | w4 | H | H1 | H2 | H3 | h1 | h2 | h3 |
|-----------|---|----|----|----|----|---|----|----|----|----|----|----|
| Value (mm)| 45| 19 | 3.47| 10 | 0.5| 50| 17 | 42 | 49 | 26 | 38 | 18 |
| Parameter | h4 | h5 | h6 | h7 | l1 | l2 | l3 | l4 | l5 | l6 | l7 | h |
| Value (mm)| 4.1| 5.1| 8  | 6  | 7  | 14 | 4.7| 17.8| 19.1| 12.1| 19.4| 1.6 |

![Figure 5](Image)

**FIGURE 5**  Return loss characteristics of the designed antenna

![Figure 6](Image)

**FIGURE 6**  Current intensity distribution on the antenna surface

(a) 1.4 GHz  (b) 2.4 GHz  (c) 3.8 GHz  (d) 5.7 GHz
1.2 Antenna simulation results and parameter analysis

The return loss characteristic of the antenna is shown in Figure 5. Clearly, the antenna can cover four frequency bands, that is, 1.0 to 1.22 GHz, 1.25 to 3.03 GHz, 3.50 to 4.05 GHz, and 5.36 to 7.64 GHz, and produce six frequency points: 1.1, 1.4, 2.4, 3.8, 5.7, and 7 GHz. Since no main application at 7 GHz exists, no further discussion will be made here. The return loss $S_{11}$ values at the five main frequency points, that is, 1.1, 1.4, 2.4, 3.8, and 5.7 GHz, are $-20$, $-22$, $-31$, $-15$, and $-29$ dB, respectively, indicating that the return loss characteristics are good.

To study the operating principle and the relationship between resonant frequencies and important parameters of the antenna, the simulated surface current distributions are plotted at the sample frequencies of 1.4, 2.4, 3.8, and 5.7 GHz, which are shown in Figure 6. For the 1.4 GHz operation (see Figure 6A), one can find that the strong surface current concentrates on the middle main branch and the longer vein on the right. Therefore, it can be understood that the 1.4 GHz resonance occurs due to the middle main branch and the longer vein on the right. From Figure 6B,D, it is observed that the resonance occurs due to hexagon ring. The third resonant mode of the antenna, by considering the current distribution of the antenna as shown in Figure 6C, arises from the currents on two longer leaf veins and part of the hexagonal ring.

The first resonance in the proposed antenna is excited due to the middle main branch and the longer vein on the right. At the resonance, this length would be half of the wavelength in the medium. The boundary condition for the first resonance can be seen from Figure 6A, in which the maxima of the current occur at the middle main branch and the longer vein on the right. Therefore, the length of the radiating patch responsible for first resonance can be calculated as:

$$L_1 \approx h_3 + h_4 + h_5 + h_6 + l_2$$  \hspace{1cm} (1)

From the data presented in Table 1, $L_1 = 49.2$ mm, at the resonance, $L_1$ should be $\lambda_g/2$. Therefore,

$$f_1 = \frac{c}{2L_1 \sqrt{\varepsilon_r}} \approx 1.45 \text{ GHz}$$  \hspace{1cm} (2)

The second resonance is excited due to the hexagon ring. The electric field maxima occur on the right half of the hexagon as shown in Figure 6B. From the data given in Table 1, the maximum current path length is $L_2$, as:

$$L_2 \approx l_6 + l_5/2 + l_7/2 = 31.35 \text{ mm}$$  \hspace{1cm} (3)

FIGURE 7  3D antenna pattern
The full simulation shows that the resonance is occurred at 2.4 GHz, which is much close to the predicted value.

The third resonance occurs due to the two longer leaf veins. This can be established by studying the current distribution as shown in Figure 6C. In this figure, it is
clearly shown that one of the current minima occurs at the two longer leaf veins. At resonant frequency, the length of the current path would be half of the guided wavelength. Therefore,

\[ L_3 \approx l_2 + h_5 = 19.1 \text{ mm} \tag{5} \]

\[ f_3 = \frac{c}{2L_3\sqrt{\varepsilon_r}} \approx 3.75 \text{ GHz} \tag{6} \]

The fourth resonance in the proposed antenna is excited due to the bottom half of the hexagon ring. The maximum current path length is \( L_4 \), as:

\[ L_4 \approx 2\frac{l_5}{3} = 12.7 \text{ mm} \tag{7} \]

\[ f_4 = \frac{c}{2L_4\sqrt{\varepsilon_r}} \approx 5.63 \text{ GHz} \tag{8} \]

The 3D pattern of the antenna is shown in Figure 7. The polarization of the E/H-plane is shown in Figure 8. The blue solid line represents the main polarization, and the red dashed line represents the cross polarization. For the entire frequency range, the antenna maintains good radiation characteristics, and the pattern has no sidelobes. The E-plane and H-plane have good omnidirectionality. However, as the frequency increases, the cross polarization becomes significantly larger. From the pattern, the antenna has the most ideal gain at 3.8 GHz, with a maximum gain of 7.3 dBi, followed by a better gain at 5.7 GHz, with a maximum gain of 7.1 dBi. The maximum gain at 2.4 GHz is 5.4 dBi, while the gain at 1.4 GHz is only 3.8 dBi. The performance at 1.4 GHz is not particularly ideal and thus needs to be improved.

### 1.3 | Test results of banana leaf antenna

To verify the correctness of the design scheme, the antenna shown in Figure 9 was manufactured. The size of the antenna is 50 mm*45 mm*1.6 mm. The antenna is printed on a 1.6 mm thick polytetrafluoroethylene glass board (G10/FR4), its dielectric constant \( \varepsilon_r = 4.4 \), and the dielectric loss tangent \( \tan\delta = 0.02 \). The feed line is directly connected to the 50 \( \Omega \) SMA adapter for connection testing.

Figure 10 shows the antenna return loss comparison between the simulation and the test. The first resonance point 1.1 GHz moves left to 0.9 GHz. The other resonance points remain basically unchanged.

### TABLE 2 | Commercial frequency bands covered by banana antennas

| Frequency band | Bandwidth | Commercial band coverage |
|----------------|-----------|--------------------------|
| 1              | 0.79-3.18 GHz (117.1%) | GSM900 (880-960 MHz), CDMA2000 (885-960 MHz), TD-LTE (B-Trunc) (1.447-1.467 GHz), LTE33-37 (1.9-2.025 GHz), TD-SCDMA (1.88-2.025 GHz), DCS1800 (1710-1820 MHz), WCDMA (1755-1880 MHz), ISM2.4G (2.4-2.4835 GHz), WLAN (802.11b/g/n: 2.4-2.48 GHz) |
| 2              | 3.29-3.98 GHz (18.9%) | LTE42/43 (3.4-3.8 GHz), WiMAX (3.3-3.8 GHz) |
| 3              | 4.98-7.62 GHz (41.9%) | WLAN (802.11a/n:5.15-5.35 GHz), 5G (5725-5825 MHz) |
The return loss $S_{11}$ values at the center resonance frequency 0.9, 1.5, 2.4, 3.8, 5.6, and 6.9 GHz, are $-17.3$, $-27.6$, $-30.5$, $-15.9$, $-26.2$, and $-22.3$ dB, respectively. The test results show that the final optimized antenna design can cover the following frequency bands: 0.93-3.18 GHz, 3.29-3.98 GHz, and 4.98-7.62 GHz. The relative bandwidth for each is 117.1%, 18.9%, and 41.9%. Specific applications are shown in Table 2. The simulation and measured results are basically consistent. However, due to the interference factors such as antenna manufacturing accuracy, excuse deviation, and test environment, there is a certain deviation between the test and the simulation results. The substrate thickness of the antenna is only 1.6 mm, and the influence of the dielectric thickness change during the processing on the performance of the antenna cannot be ignored. The connection method of SMA between the feeder and the signal is solder connection. The solder increases the thickness of the dielectric board, which has a certain impact on the test results. The error is within the allowable range.

Figure 11 shows the radiation pattern of the antenna at four main resonance frequencies of 1.5, 2.4, 3.8, and 5.6 GHz. From the figure, the peak gains at 1.5, 2.4, 3.8, and 5.6 GHz can reach 3.45 dBi, 4.55 dBi, 5.22 dBi, and 6.14 GHz, respectively. In the working frequency band, the antenna has omnidirectional radiation characteristics and can be widely used in mobile communication terminals. However, when testing the antenna pattern in the dark room, it is inevitable to connect the antenna to the test equipment with radio frequency cables and connectors. These RF cables and connectors are very close to the antenna, and their radiation will affect the pattern test.

Compared with other bionic antennas, the antenna designed in this article have many advantages. The proposed antenna is microstrip patch antenna, which is easier to process than the antenna in Reference 25. The banana leaf structure is simple and regular, which is easier to model than the butterfly bionic antenna in Reference 26. The designed antenna have three ultra-widebands, which has better bandwidth characteristics than the antenna in References 27 and 28.

2 | CONCLUSIONS

Based on the principle of bionics, a microstrip antenna with multi-band characteristics is designed by simulating the shape of banana leaves. A comparison of the
simulation and test results verifies the rationality of the design. The antenna has a beautiful appearance and good performance. The antenna size is 50 mm*45 mm*1.6 mm. The test results show that the S11 values at the central resonance points 1.5, 2.4, 3.8, and 5.6 GHz reach −22, −28, and −30 dB, respectively, and the maximum gain is 3.45, 4.55, and 5.22 dBi, respectively. The banana leaf antenna has three frequency bands, that is, 0.79 to 3.18 GHz, 3.29 to 3.98 GHz, and 4.98 to 7.62 GHz with relative bandwidths of 117.1%, 18.9%, and 41.9% respectively, and has omnidirectional radiation characteristics within each bandwidth. In general, the antenna can be applied to CDMA2000, WCDMA, Bluetooth, etc., and to TD-LTE (B-TrunC) (1.447-1.467 GHz), WLAN (802.11a/n: 5.15-5.35 GHz), and 5G (5.725-5.825 GHz) communication.

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CONFLICT OF INTEREST
The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT
The data that supports the findings of this study are available in the supplementary material of this article.

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