Aesthetic wideband dielectric resonator antenna based on fractal slot with two independently controllable resonant frequencies

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Abstract An aesthetic wideband dielectric resonator antenna (DRA) based on the Minkowski fractal slot is firstly presented. The proposed DRA consists of a glass dielectric resonator (DR) with the laser engraving pattern, the ground with the Minkowski fractal slot, the fork-shaped microstrip line, and the substrate. By employing the Minkowski fractal slot, the TE₁₁₁ mode of the DR and an additional hybrid mode are excited to realize the wideband characteristics. A parametric study is performed to analyze the wideband DRA performance. The simulated results show the hybrid mode and TE₁₁₁ mode can be controlled independently. To achieve the aesthetics of the DRA, a school badge is engraved inside the glass DR. Finally, the proposed DRA is fabricated and measured. A wide impedance bandwidth of 38.4% and the peak gain of 6.5 dB for S₁₁ < -10 dB are achieved.

key words: wideband, dielectric resonator antenna, fractal slot, aesthetic

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Since the dielectric resonator antenna (DRA) was proposed by Long in 1983 [1], it has been studied extensively because of its compact size, low loss, low weight, and ease of excitation [2, 3, 4, 5]. Recently, the decorative DRAs have been reported [6, 7, 8, 9, 10], which use the glass as the dielectric resonator (DR) for fabrication DRAs, simultaneously serve as glass artworks and the radiator. The apple-shaped DRA and the swan-shaped DRA are proposed in [6], which are available in the commercial market. In [7, 8, 9], the dual function DRA simultaneously works as an antenna and light covers. A new idea using a transparent DR as the socket panel is reported [10]. These decorative DRAs are aesthetic and practical. However, these irregular DRAs have the disadvantages of complex structure and difficulty in establishing theoretical models.

With the rapid development of high-speed wireless communication, the demand for wideband antennas has dramatically increased. In recent years, several techniques have been proposed to enhance the impedance bandwidth of the DRA. They generally can be divided into four categories. The first technique is to decrease effective permittivity [11, 12, 13, 14, 15]. In [14], combining a strip dielectric resonator (DR) and four DRs with different permittivity, the DRA can be excited to form a wide operating bandwidth. Drilling holes inside the DR to taper the effective permittivity, a 26.7% impedance bandwidth of the DRA has been presented [15]. The second technique is to change the shape of the DR. In this way, the wide impedance bandwidths are achieved by employing a super-shaped DRA [16], the cup-shaped hemispherical DRA [17], a triangular-shaped DRA [18], and a Minkowski fractal shaped DRA [19]. However, multiple DRs, drilling holes, and irregular DRAs increase structural complexity and manufacturing costs. Moreover, these techniques destroy the shapes and aesthetics of the DRAs. The third technique is to excite multiple modes of the DRA [20, 21, 22]. In [21], a wideband DRA is proposed by merging the adjacent bands corresponding to TE₁₂₁ and TE₂₁₁ modes. Fang proposes using the strip-fed excitation TE₁₁₁ and TE₁₁₁ mode of DRA, which results in a wide impedance bandwidth of 30.9% [22]. The fourth technique is the hybrid DRA. The hybrid DRA provides an additional resonance mode through the feeding ring [23], radiating slots [24], monopoles [25], or other structures nearby the DRA mode, so a wide impedance bandwidth is achieved. These techniques are widely applied to expand the DRA bandwidth, while the resonant frequency in-band can not be independently controllable.

In this letter, an aesthetic wideband DRA with two independently controllable resonant frequencies is studied. The proposed DRA comprises a square DR, a fork-shaped microstrip line, and the ground with a Minkowski fractal slot. The bandwidth is improved by the Minkowski fractal slot that excites and merges two resonant modes, the TE₁₁₁ mode of DR and the hybrid mode. By adjusting the two resonant modes, the bandwidth of the DRA can be flexibly controlled. Compared with the conventional wideband DRAs, the proposed DRA has the advantages of simple structure, low cost, and two independent controllable resonance frequencies.

2. Antenna design

Fig. 1 shows the structure of the proposed DRA. The wideband DRA consists of a square DR with the laser engraving
pattern, the ground with the Minkowski fractal slot, the fork-shaped microstrip line, and Rogers 4350B substrate ($\varepsilon_r = 3.48, \tan \delta = 0.0037, h = 1.524$ mm). The square DR is made of the K9 glass ($\varepsilon_r = 6.85$). The ground with the Minkowski fractal slot and the microstrip line is on the top and the bottom of the substrate, respectively. The DR is fed by the fork-shaped microstrip line coupled to the Minkowski fractal slot.

The side length of the DR can be analyzed and calculated by using the dielectric waveguide model. When the DRA is mounted on a ground plane, the resonant frequency of fundamental mode $TE_{111}$ can be calculated quickly by using equation (1) and equation (2) [26]. Where $f_0$ is the resonant frequency of $TE_{111}$ mode, $c$ is the speed of the light, $k_0$, $k_x$, $k_y$, and $k_z$ are wavenumbers of the free space and the DR along with $x$, $y$, $z$ three directions, respectively. $a$ and $\varepsilon_r$ are the length and the permittivity of square DR, respectively. Finally, the side length $a$ of the square DR is designed as 29 mm.

$$f_0 = \frac{c}{2\pi\sqrt{\varepsilon_r}}\sqrt{k_x^2 + k_y^2 + k_z^2} \quad (1)$$

$$k_x = \frac{\pi}{a}, \quad k_z = \frac{\pi}{2a}, \quad k_y \tan \left( \frac{k_y a}{2} \right) = \sqrt{\varepsilon_r - 1} k_0^2 - k_z^2 \quad (2)$$

### 2.1 Minkowski fractal slot design

The fractal geometry is formed by iterating in multiple directions [27]. With the increase of the number of fractal iterations, the self similarity of fractal structure effectively increases radiation path and radiation length, so fractal geometry is widely used to design wideband DRAs [28, 29]. In [28], a spidron fractal DRA with a reflection bandwidth of 37.29% is presented. A wideband DRA combines the Sierpinski and the Minkowski fractal DR in [29]. However, these DRAs enhance bandwidth through the fractal DR, which are difficult to manufacture. In this letter, a Minkowski fractal slot is proposed for the first time to improve the impedance bandwidth of the DRA. The geometric construction of the Minkowski fractal slot starts with a square slot, called the initiator. The side length $l_1$ of the square slot is close to a quarter of wavelength [30], as shown in equation (3). Where $f$ is the central resonant frequency, $c$ is the speed of the light and $\varepsilon_{eff}$ is the effective permittivity. Taking the square slot as the iterative initiator, $l_2$ and $l_1$ are iterated in the ratio of 1:2:5. The iterative construction process is shown in Fig. 2. Considering the manufacturing accuracy and deviations, the number of iterations $N=2$ is designed.

$$l_1 = \frac{c}{4 \times f \times \sqrt{\varepsilon_{eff}}} \quad (3)$$

To achieve wideband impedance matching, a fork-shaped microstrip line is used as the feeding structure. Fig. 3 shows the structure of the fork-shaped microstrip line and the Minkowski fractal slot. The design parameters are as follows, $l = 75$ mm, $w = 85$ mm, $l_1 = 17$ mm, $w_1 = 3.3$ mm, $l_2 = 6.8$ mm, $w_2 = 3$ mm, $l_3 = 31.6$ mm, $l_4 = 36.1$ mm, $l_5 = 10.5$ mm. Compared with the ordinary microstrip line, the fork-shaped structure has more adjustable parameters, which makes it easier to match the wideband impedance.
2.1 Parametric study

Fig. 6 shows the simulated reflection coefficients with different side lengths of a square DR. As the side length of the DR increases, the higher resonant frequency approaches the lower resonant frequency. Moreover, the side length \( a \) of the DR only affects the higher resonant frequency, which has almost no effect on the lower frequency. Thus, the higher resonant frequency can be controlled independently based on the above characteristics.

Similarly, the lower resonant frequency changes with changing Minkowski initiator slot length \( l_1 \), as shown in Fig. 7.

What's more, the slot length \( l_1 \) only affects the lower frequency, which has almost no effect on the higher resonant frequency. Based on the above characteristics, independent adjustment of two resonant frequencies can be achieved by changing the side length \( a \) and the slot length \( l_1 \). In this way, the proposed DRA bandwidth can be easily adjusted. In addition, it can be extended to a dual-band and multi-band antenna based on two independently controllable frequencies.

The impedance matching of the proposed DRA can be adjusted by the scaling ratio \( s \). The scaling ratio \( s \) is the ratio of the length \( l_2 \) and \( l_1 \). As shown in Fig. 8, the scaling ratio \( s \) can easily adjust the impedance matching characteristics of the DRA. What’s more, the scaling ratio does not affect the impedance bandwidth. It greatly simplifies the design complexity of the DRA.

2.3 Aesthetic DR with the engraving pattern

The glass DR has the advantages of low \( Q \) factor and low permittivity, which are beneficial to improve the bandwidth of the DRA. Furthermore, glass is a suitable material for...
laser engraving. The internal engraving in glass uses a laser machine to shoot the laser into the glass interior. The laser pulse is generated in a very short time, which can produce the white dots at the required positions. The white dots are combined into a preset shape inside the glass, while the rest of the glass remains intact. Fig. 9 shows the DR with laser engraving and without laser engraving. The glass DR with a laser engraving pattern is aesthetic, which can be used as a glass artwork and the radiator. The aesthetic DRA has great commercial potential due to its low cost and high performance.

Fig. 9. The glass DR with laser engraving and without laser engraving.

3. Prototype fabrication and measurement

To verify the simulation design, the aesthetic DRA based on the Minkowski fractal slot is fabricated as shown in Fig. 10. The measured and simulated reflection coefficients of the DRA were performed in Fig. 11. Good agreement between the simulation and measurement is observed. Moreover, the engraving pattern has no effect on the impedance bandwidth of the DRA. The measured reflection coefficient of the aesthetic DRA is less than -10 dB in the frequency bands from 2.02 GHz to 2.98 GHz, whose fractional bandwidth is 38.4%.

Fig. 10. Photograph of the fabricated DRA.

The gain and efficiency of the aesthetic DRA are shown in Fig. 12. The peak gain and efficiency of the proposed DRA are 6.5 dBi and 88.1%, respectively. The measured gain is slightly lower than the simulated gain. This is because the dielectric loss of the DR is not considered in the simulation.

Fig. 12. The gain and efficiency of the proposed DRA.

In order to understand the performances of the proposed DRA, the comparisons of various wideband DRAs are carried out listed in Table I. As observed from Table I, the proposed DRA achieves aesthetics and broadband characteristics.

Table I. Performance comparison.

| Works | Permittivity of DR | BW (GHz) | BW (%) | Gain (dBi) | Aesthetics |
|-------|--------------------|----------|--------|------------|------------|
| [14]  | 45, 69             | 8.99–11.43| 24     | 7.9        | No         |
| [22]  | 10                 | 1.83–2.50 | 30.9   | 7.0        | No         |
| [24]  | 9.4                | 5.90–7.32 | 21.5   | 6.4        | No         |
| [31]  | 9.5                | 2.14–2.56 | 17.8   | 7.4        | No         |
| [32]  | 2.5, 6.85          | 2.87–3.96 | 31.9   | 2.2        | Yes        |
| Proposed | 6.85           | 2.02–2.98 | 38.4   | 6.5        | Yes        |
4. Conclusion

Aesthetic wideband DRA based on the Minkowski fractal slot is presented in this letter. The $TE_{111}$ mode and a hybrid mode were excited to realize the wideband characteristics. Two modes of the DRA can be controlled independently, so the bandwidth of the DRA can be easily adjusted. There are decorative patterns inside the DRA based on laser engraving. Moreover, the engraving pattern has no effect on the impedance bandwidth of the DRA. The proposed DRA is fabricated within the operating frequency band 2.02–2.98 GHz. The DRA has the advantages of low cost, wide bandwidth, and aesthetics, which is a good candidate for WLAN applications.

Acknowledgments

This work was supported by National Natural Science Foundation of China (No. U1831201) and National Key Research and Development Project (No. 2017YFE0128200).

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