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A Circular Quasi-Isotropic Dielectric Resonator Antenna for Bluetooth

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Abstract—A quasi-isotropic dielectric resonator antenna (DRA) is proposed under the 5.8 GHz industrial, scientific, and medical (ISM) standard. The antenna consists of a hollow cylinder and and a coaxial probe which feeds electricity. By digging a large hole in the cylindrical dielectric resonator, the $HEM_{11\delta}$ mode and TM_{10} mode of the floor are excited, the two modes are orthogonal, and the radiation characteristics are equivalent to orthogonal magnetic dipoles and electric dipoles, so as to achieve quasi-isotropic radiation characteristics. The large hole can also reserve space for other electronic components for Bluetooth devices with small space, such as capsule endoscope, mobile phone, and Bluetooth headset. The characteristics of the antenna are simulated and analyzed by HFSS, and the optimized antenna structure parameters are obtained. The antenna is made for experimental testing. The measured results demonstrate that the antenna exhibits a good −10 dB-impedance bandwidth at 5.38–5.68 GHz and has the characteristics of miniaturization, quasi-isotropy, and high gain.

1. INTRODUCTION

The dielectric resonator used as an antenna was first proposed by long et al. in 1983 [1]. Dielectric resonator was first made of materials with high dielectric constant. When there is no metal shield around the dielectric resonator, the electromagnetic wave in the resonator will be bound inside, and a small part will be radiated into the surrounding space, which has a high Q value. When the dielectric resonator works at a low Q value, the electromagnetic wave can radiate a large amount from the surface of the dielectric resonator to form effective radiation. Similarly, using materials with relatively low dielectric constant makes it easier to radiate energy. In this way, the dielectric resonator can be used as an antenna to radiate energy outward.

With the development of modern communication and the increasing demand for indoor wireless services such as industrial wireless network, 5th generation mobile communication and wireless energy transmission, stable wireless connection in channel environment is becoming more and more important [2–6]. The ideal-isotropic antenna that can radiate electromagnetic field uniformly in all directions can be used as a simple and cheap solution [7]. However, in practice, it is impossible to realize this radiation mode [8]. Therefore, the almost isotropic radiation mode obtained by synthesizing the radiation of transverse magnetic field and transverse electric field has become the focus of attention [9].

In 2014, Pan's team first proposed quasi-isotropic DRA [10]. The antenna is a rectangular DRA fed by an eccentric coaxial probe. The antenna structure is composed of a coaxial probe, a rectangular dielectric resonator, and a small ground plane. The research shows that the dielectric resonator radiates like a magnetic dipole, while the small ground plane radiates like an electric dipole. By combining two complementary dipoles, a good quasi-isotropic radiation pattern is obtained.

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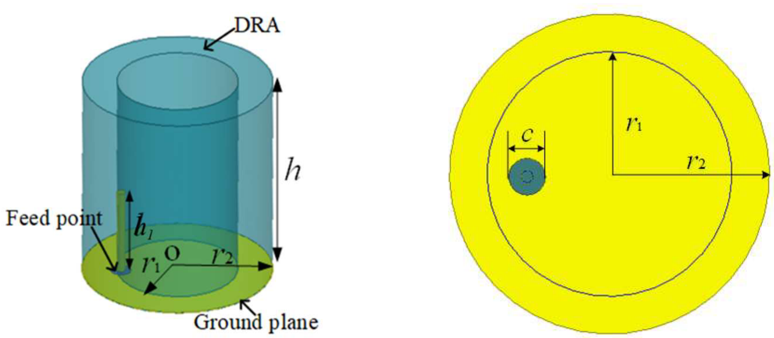
In 2019, Pan's team proposed another quasi-homosexual structure for the second time [11], which is a microstrip fed cylindrical DRA. The antenna is composed of a microstrip line, a cylindrical DRA, and circular small floor. We dig a large hole in the cylindrical dielectric resonator to excite $\text{hem}_{11\delta}$ mode and TM_{10} mode, which are orthogonal. Their radiation characteristics are equivalent to magnetic dipoles and electric dipoles. Because they are orthogonal to each other, quasi isotropy is formed.

In 2018, Masaharu proposed a broadband helical antenna operating at 500 MHz with quasi-isotropic radiation mode [12]. This paper introduces the design process of the antenna and the necessity of quasi-isotropic antenna in the capsule endoscope system, but the article does not explain the principle of realizing quasi-isotropy, nor does it give the gain deviation and 3D pattern. The antenna is 5 mm high and 10 mm in diameter. However, the antenna is placed at one end of the capsule, which does not form a conformal shape, wasting the hemispherical space of the capsule. Paper [13] proposes a dielectric resonator antenna system operating at 2.4 GHz in ISM band, with a relative bandwidth of 3.3% (2.36–2.44 GHz). It obtains three orthogonal currents through three orthogonal bending dipoles, so as to realize the quasi-isotropic antenna. The antenna can transmit effectively when the direction is changed, and the direction insensitive performance is realized. Using a reverse T-shaped matching branch line and curved line, better impedance matching and miniaturization are realized.

In this paper, we propose a quasi-isotropic antenna based on a hollow cylindrical dielectric resonator. By digging a large hole in the cylindrical dielectric resonator, the $\text{HEM}_{11\delta}$ mode and TM_{10} mode of the floor are excited. The two modes are orthogonal, and the radiation characteristics are equivalent to orthogonal magnetic dipoles and electric dipoles, so as to achieve quasi-isotropic radiation characteristics. Compared with the work of Pan's team and Lee, the antenna in this paper reserves space for other electronic equipment through the hole in the cylinder, which makes the antenna further miniaturized, and uses coaxial feed at the edge of the central hole, which achieves more accurate impedance matching. Compared with other antennas, it works in a higher frequency band (5.38–5.68 GHz) and has more bandwidth. It has the advantages of miniaturization, quasi-isotropy, and high gain characteristics.

2. ANTENNA DESIGN AND PARAMETRIC STUDIES

In order to realize quasi-isotropic radiation characteristics, a hollow cylindrical DRA is proposed based on the small floor cylindrical dielectric resonator. The antenna structure is shown in Figure 1. The distance from the center of the circle to the inner wall of the hollow cylinder $r_1 = 3.5$ mm, the distance to the outer wall $r_2 = 5.5$ mm, and the thickness is 2 mm. The length of the probe is $h_1 = 5.1$ mm. It is the same model as the feed probe of cylindrical dielectric resonator. The inner core radius is 0.25 mm, and C is the outer core diameter of coaxial probe. In order to avoid short circuit, its diameter can be set slightly larger than the outer core radius of coaxial probe. Figure 2 shows four hollow cylindrical radiation patterns with different r_2/h (the radius of the hollow cylindrical DRA is r_2, and the height is h), which are used to optimize the quasi-isotropic radiation performance. In order to facilitate the optimization, fix the r_2 value to 5.5 mm and change the height h to simulate the radiation patterns



(a) (b)

Figure 1. Geometry of compact hollow cylindrical DRA. (a) Schematic view. (b) bottom view.

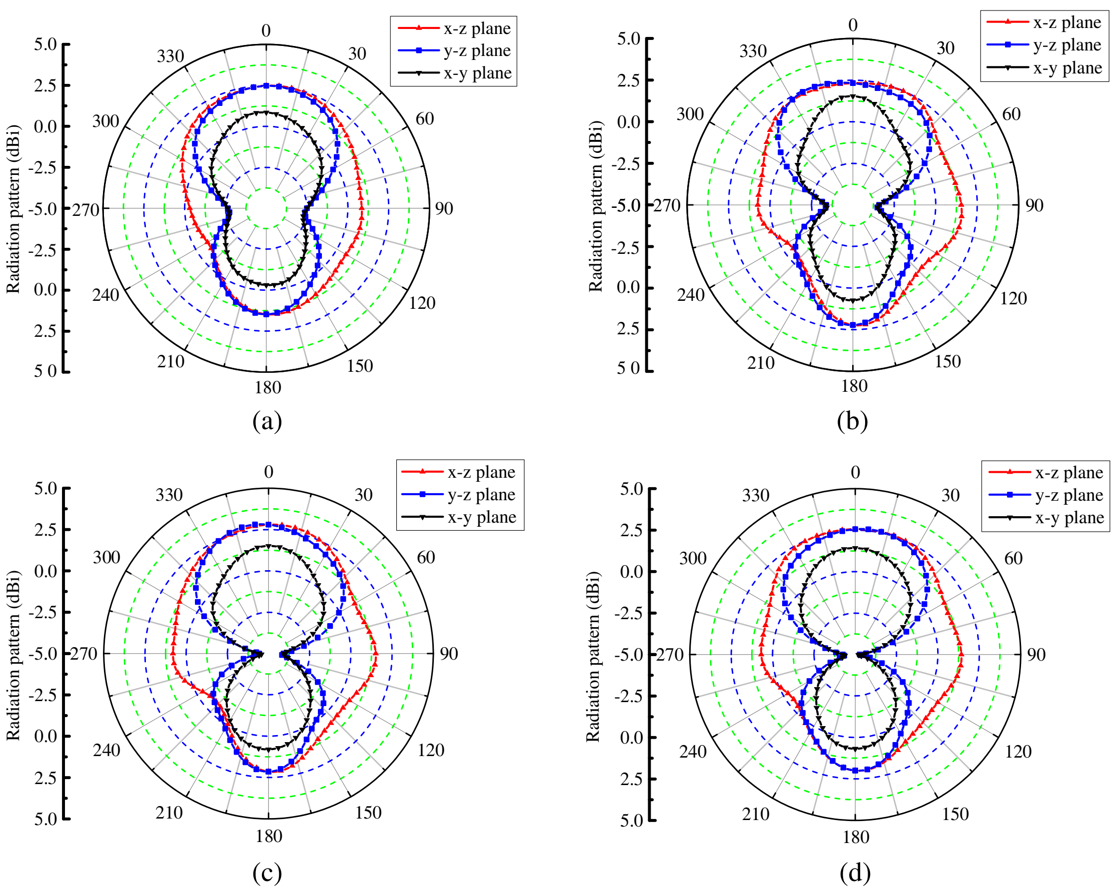


Figure 2. Radiation patterns of hollow cylindrical DRA. (a) $h = 9\,\text{mm}$, $r_2/h = 0.61$, $f = 5.97\,\text{GHz}$. (b) $h = 10\,\text{mm}$, $r_2/h = 0.55$, $f = 5.83\,\text{GHz}$. (c) $h = 11\,\text{mm}$, $r_2/h = 0.5$, $f = 5.73\,\text{GHz}$. (d) $h = 12\,\text{mm}$, $r_2/h = 0.45$, $f = 5.65\,\text{GHz}$.

at the center frequency corresponding to different heights. It can also be found from the relationship between H and center frequency f that the higher the h is, the lower the resonant frequency is. Finally, we choose the ratio around 0.55. The influence of the hole size is discussed on the working state of the dielectric resonator antenna. Figure 3 shows the S_{11} and radiation pattern at the excavation radius of 3.25 mm, 3.5 mm, and 3.75 mm. From the figure, we can see that the resonant frequency of the DRA shifts to the high frequency direction while the hole digging becomes larger. The radiation mode changes slightly, which indicates that the resonance mode does not change. This also explains the source of error between our test and simulation.

3. MEASURED RESULTS AND DISCUSSIONS

The manufacturing of the designed antenna prototype is shown in Figure 4(a), and its reflection coefficient is tested by Agilent e5071c RF network analyzer, as shown in Figure 4(b). Its radiation performance was measured in a microwave anechoic chamber.

The r_2/h ratio was selected to be about 0.55, and the final height was 10 mm, which was used for processing test. The metal ground is realized by a copper sheet in reality, so the thickness (h_g) of the copper sheet was simulated and analyzed. The results show that the thinner the copper sheet is, the better the performance of S_{11} is. However, due to the manufacturing process, a thick copper sheet was selected to be about 2 mm for processing test. The comparison between S_{11} test and simulation data is shown in Figure 5(a). The test data show that the resonant frequency of the antenna is 5.53 GHz, and the antenna has a good impedance bandwidth of -10 dB at 5.38–5.68 GHz (5.4%). The peak value

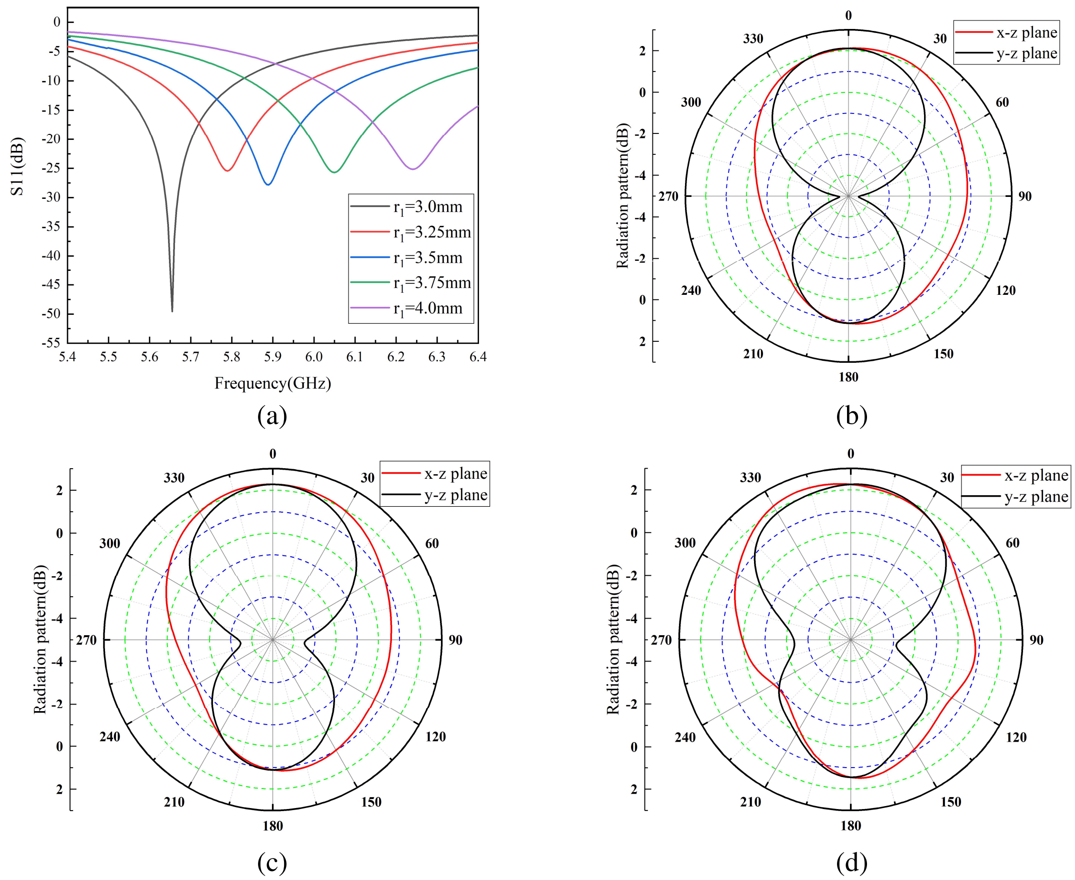


Figure 3. S_{11} and radiation patterns with different hole sizes. (a) S_{11} with opening size of 3.25 mm, 3.5 mm and 3.75 mm respectively. (b) Radiation pattern with opening size of 3.25 mm. (c) Radiation pattern with opening size of 3.5 mm. (d) Radiation pattern with opening size of 3.75 mm.

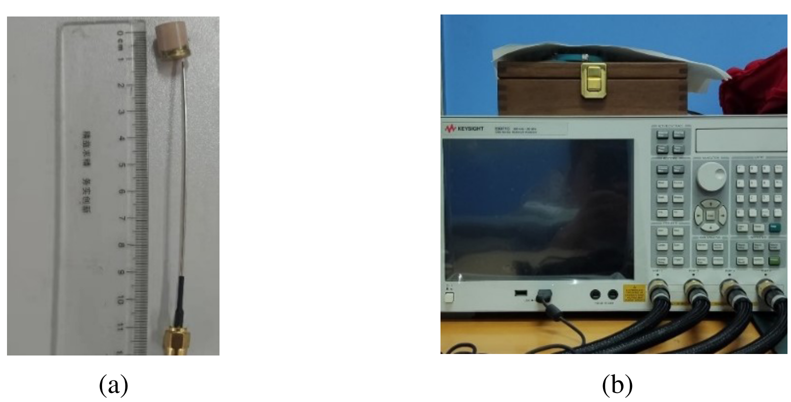
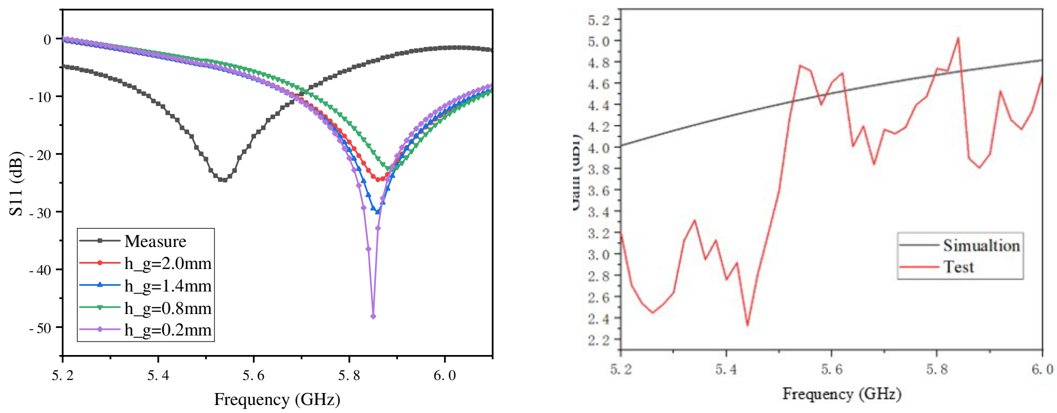


Figure 4. Processing and testing of antenna, (a) antenna object, (b) Agilent e5071c RF network analyzer, (c) simulation and test of antenna S_{11}.

is −24.5 dB. In the simulation results, the resonant frequency is 5.86 GHz; the impedance bandwidth is 5.69–6.06 GHz (6.3%); the peak value is −24.46 dB. In the test and simulation, the resonant frequency is shifted by 0.33 GHz and the bandwidth narrowed. Through analysis and simulation test, these errors are caused by the fact that the size of the hole in the machining process is not completely consistent with



(a) (b)

Figure 5. (a) Simulation and test of antenna S_{11}, (b) simulation and test of antenna gain.

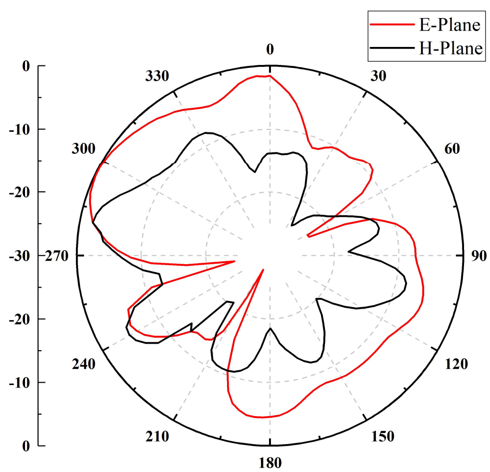


Figure 6. Test of radiation pattern at 5.8 GHz.

the simulation data. This is consistent with the simulation results of different sizes of holes. However, the peak value of S_{11} is basically consistent with that in the simulation, which shows that the antenna has good impedance characteristics. The simulation and test of antenna gain are shown in Figure 5(b). The gain of the antenna in the working bandwidth is basically more than 3.0 dBi, and the gain in 5.5–6.0 GHz is more than 3.8 dBi. Although the test data and simulation data have some errors at low frequency, the data errors of individual points are large. But at high frequencies, these errors may also come from fabrication and testing. The radiation pattern measured at 5.8 GHz is shown in Figure 6, which is about 30 degrees offset from the simulation result. These errors are produced in the process of manufacturing and testing the antenna.

In order to understand the resonant mode of DRA, we draw the electric field and current distribution of hollow cylindrical dielectric resonator. As can be seen from Figure 7(a), the electric field trend is a to B to C, which is the first half cycle, and the second half cycle, which is C to B to a. From Figure 7(b) X-Y plane, the electric field distribution is symmetrical about the x-z plane, forming a complete $\text{hem}_{11\delta}$. Compared with other dielectric resonators, the hollow cylindrical dielectric resonator achieves quasi-isotropic radiation characteristics. The radiation characteristics of the mode can be roughly equivalent to the radiation pattern of a magnetic dipole, and the direction is parallel to the x-z plane. The radiation pattern is in the shape of "O" along the x-z section and "8" along the X-Y section. The radiation current is equivalent to the "Y-8" tangent plane of the magnetic medium along

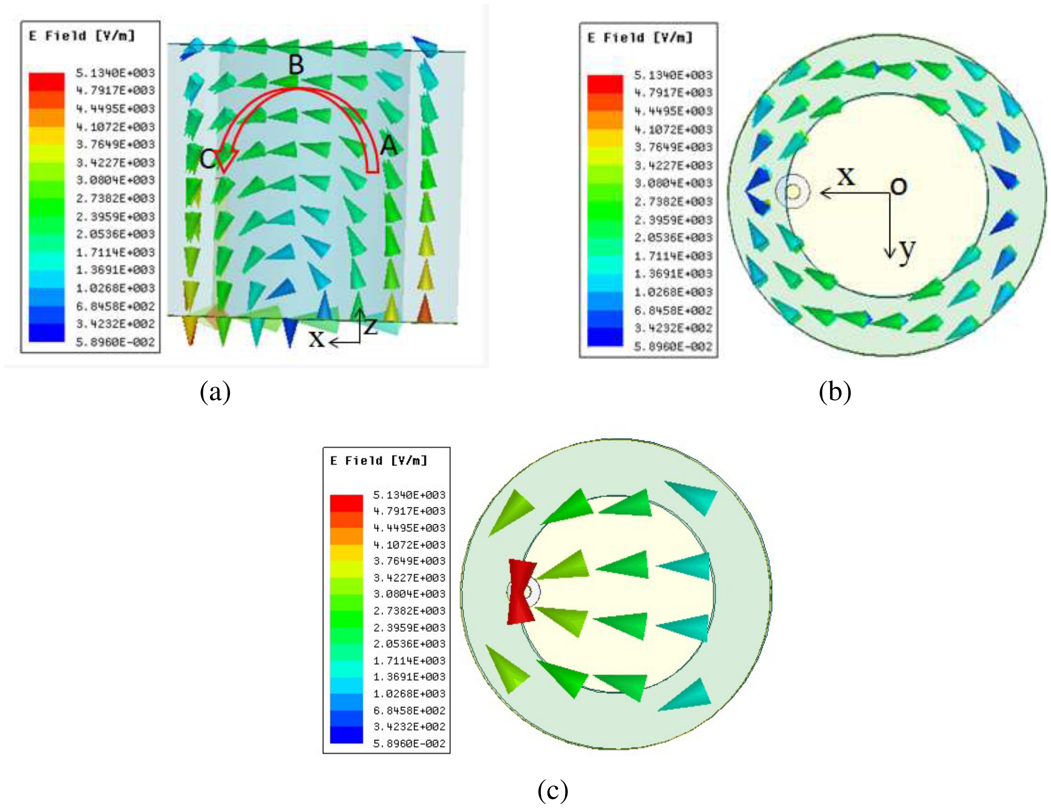


Figure 7. The electric field and surface current distribution. (a) The electric field distribution on plane x-z, (b) the electric field distribution on plane y-z, and (c) the surface current of metal ground on plane x-y.

the X-8 axis, and the radiation current flows along the "Y-8" tangent plane of the floor along the X-8 axis, which can form an equivalent characteristic of the "Y-8" tangent plane of the magnetic dipole.

4. CONCLUSION

In this paper, a quasi-isotropic dielectric resonator antenna is proposed, which excites $\mathrm{hem}_{11\delta}$ mode and the TM_{10} mode by digging a large hole in the cylinder, and the two modes are orthogonal, so as to realize the quasi-isotropic radiation characteristics. At the same time, the way of digging large holes leaves space for other electronic components for small capsule endoscope, Bluetooth headset, and other devices. The test results show that the antenna has good impedance characteristics in the working frequency band and has the advantages of miniaturization, quasi-isotropy, and high gain.

ACKNOWLEDGMENT

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