A Miniature Antenna for 2.45 GHz RFID Tag

Yanzhong Yu
College of Physics & Information Engineering, Quanzhou Normal University, Quanzhou, China
yuyanzhong059368@gmail.com

Zhongyi Huang, Caiqiang Zheng, and Yongxing Wu
College of Physics & Information Engineering, Quanzhou Normal University, Quanzhou, China
Email: {25598257, 820562362, and 271175781}@qq.com

Abstract—On the basic of fractal theory and folded technique, a miniature antenna for 2.45 GHz radio frequency identification (RFID) tag applications is designed and analyzed in the present paper. In order to realize the miniaturization of tag antenna, a Hilbert fractal structure is used. Impedance matching between antenna and IC chip is of great importance for improving tag performances. A folded technique is employed to achieve impedance matching flexibly. The value of input impedance of tag antenna can be varied readily only by tuning the high of folded line. The dimensions for the designed tag antenna at 2.45GHz are 23.32mm×7.66mm, and its return loss, bandwidth, and gain are analyzed by HFSS. The detection distance is estimated by Friis transfer theory. Analysis results demonstrate that the tag antenna designed in this paper may satisfy the requirements of RFID tag applications.

Index Terms—RFID (Radio Frequency Identification), HFA (Hilbert fractal antenna), folded technique, impedance matching

I. INTRODUCTION

Recently, radio frequency identification (RFID) has become a rapidly developing technology [1-5], which uses radio waves to transfer data, for the purposes of automatically identifying and tracking tags attached to objects. Much attention has been paid to RFID field. Now it finds many important applications in various industries, such as service trades, logistics management, and public transport system and etc.

In RFID systems data are exchanged between a local reader and a remote transponder (also known as tag) which is composed of a RFID IC chip and an antenna connected to the IC chip at the feeding point of the tag antenna [6]. The antenna plays an important role in transferring data, and therefore its design perhaps becomes a most challenging task for RFID system [2]. With the constant widening applications of RFID, the requirements of antenna design become more rigorous. Nowadays antenna miniaturization becomes one of the research focuses, owing to the limitation of size of RFID card. In the present paper, Hilbert fractal theory and technique are employed to achieve the goal of reduction dimension of tag antenna. Additionally, in order to improve antenna efficiency, the impedance matching between tag antennas and IC chip must be considered [1]. It is known that the input impedance of IC chip varies from manufacturer to manufacturer. Generally speaking, the tag antenna is requested to directly match to IC chip. This is to say, the input impedance of tag antenna can be adjusted flexibly to realize impedance matching. To solve this problem, a folded technique is applied in our work. Simulations indicate that the value of input impedance of tag antenna can be changed readily by tuning the high of folded line. The size for the designed tag antenna are 23.32mm in width and 7.66mm in height when it operating frequency at 2.45GHz. The relevant performances of tag antenna are analyzed by electromagnetism simulation software HFSS. The results show that tag antenna designed in the paper can meet the requirements of practical applications.

The rest of the present paper is organized as follows. The design and analysis of tag antenna are given in Section II, including Fractal theory and Hilbert structure, Hilbert fractal antenna (HFA), design HFA for RFID applications, folded HFA, Optimization of folded HFA, estimation of read range. A brief conclusion is drawn in the last Section III.

II. ANTENNA DESIGN AND ANALYSIS

A. Fractal Theory and Hilbert Structure

The fractal theory was coined out by Mandelbrot in 1975. After that many types of fractal shapes have been proposed and found their applications in various fields, such as Hilbert [7, 8], Sierpinski [9, 10], Tree [11, 12] and Minkowski [13, 14]. Fractals are typically self-similar patterns, and may be exactly the same at every scale, or, nearly the same at different scales, as illustrated in Fig 1.
The Hilbert curve that was proposed by Hilbert in 1891 is a famous fractal shape. The geometries were generated in iterative patterns. Provided that outer dimension of $h$ and order of fractal iteration $n$, the length of each line segment $d$ is given by \[ d = h / (2^n - 1) \] (1) And the total length of Hilbert curve can be calculated by \[ l = (2^n - 1) \times d \] (2)

Fig. 2 shows the Hilbert curve with order 0–3, in which $h$ and $d$ are the width and fractal segment length, respectively. It can be seen clearly from Fig. 2 that with the increase of order $n$, the total length of Hilbert fractal curve also increases. Hilbert fractal curve therefore has a property of space filling.

Fractal structure has been combined with electromagnetic theory to design a new type of antenna, i.e., fractal antenna, which uses a fractal, self-similar design to maximize the length, or increase the perimeter (on inside sections or the outer structure), of material that can receive or transmit electromagnetic radiation within a given total surface area or volume. Nowadays, a fractal technique is employed to minimize the size of antenna. And lots of fractal structures are utilized to design antennas for compact size [15, 16]. Combined the idea of Hilbert fractal structure and dipole antenna, one dimension Hilbert fractal antenna (HFA) is designed, as depicted in Fig. 3. The length of half-wave dipole antenna is $L = 30\text{mm}$ and the height of Hilbert fractal is $h = L/3$. These antennas are analyzed by Using HFSS. Their results are illustrated in Fig. 4 and performances are summarized in Table 1. From Fig. 4 and Table 1, the conclusions can be made as follows. (1) The HFA has a characteristic of multiple resonant frequencies, when compared with the dipole antenna. It can be seen from Fig. 4 (a) that the zero-order HFA has two harmonic frequency points, that is, one locates at 1.44GHz and the other at 3.81GHz. Similarly, the first order HFA also has two resonant points, i.e., 1.31GHz and 3.18GHz (see Fig. 4 (c)). (2) The value of resonant frequency of HFA tends to decline with increase of its order. Compared Fig. 4 (a) with Fig. 4 (c), one can find that the first resonant frequency point drops from 1.44GHz to 1.31GHz, and the second one decreases from 3.81GHz to 3.18GHz. This means that the sizes of antenna may be reduced effectively by fractal approach. (3) By observing Table 1 and Figs. 4 (b) and (d) carefully, we find that the gain and efficiency of HFA drops when its order increases. This illustrates that the multiple frequencies of HFA obtain at the price of gain and efficiency.

<table>
<thead>
<tr>
<th>Antenna type</th>
<th>Resonant Frequency (GHz)</th>
<th>$S_{11}$ (dB)</th>
<th>Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-wave dipole</td>
<td>2.45</td>
<td>-42.3</td>
<td>2.17</td>
</tr>
<tr>
<td>Zero order HFA</td>
<td>1.44</td>
<td>-8.75</td>
<td>2.25</td>
</tr>
<tr>
<td></td>
<td>3.81</td>
<td>-15.58</td>
<td>2.02</td>
</tr>
<tr>
<td>First order HFA</td>
<td>1.31</td>
<td>-11.63</td>
<td>1.22</td>
</tr>
<tr>
<td></td>
<td>3.18</td>
<td>-14.12</td>
<td>1.01</td>
</tr>
</tbody>
</table>
Fig. 4. Simulation results of one dimension HFA with zero order (a), (b) and one order (c), (d).
C. Design HFA for RFID Applications

According to the analysis of HFA above, we design a HFA for RFID tag applications, as shown in Fig. 5. Its height, width, line width and distance from fractal structure to feeding point are represented by \( h, d, w \) and \( a \), respectively. We suppose the antenna operating frequency of \( f = 2.45 \text{GHz} \). The substrate material FR-4, with relative dielectric constant \( \varepsilon_r = 4.4 \) and dielectric loss tangent \( \tan \alpha = 0.002 \), is selected, and its thickness is 1mm. The area of radiation zone is \( h \times 2L = 9 \text{mm} \times 26 \text{mm} \), and \( a = 4 \text{mm} \). The performances of designed antenna are analyzed by HFSS. Figs. 6 and 7 illustrate the return loss \( S_{11} \) and input impedance, respectively. It can be observed from Fig. 6 that the harmonic frequency of the designed antenna locates at 2.45GHz, and the bandwidth is 370MHz when return loss \( S_{11} \leq -10 \text{dB} \). We find that the input impedance almost remains constant as the frequency varies from 2.0GHz to 2.8GHz. It indicates that the antenna has a wide impedance bandwidth. At the resonant frequency of \( f = 2.45 \text{GHz} \), the input impedance is \( Z_{in} = (53.5 + 145.4 j) \Omega \). The input impedance of the tag antenna must be the conjugate of impedance of the chip to transfer maximum power. Nowadays, the chips made from different factories have different input impedances. That requires the input impedance of tag antenna can be varied flexibly to conjugate match the impedance of chip.
D. Folded HFA

To reach this purpose of impedance matching flexibly, the configuration of the tag antenna shown in Fig. 5 is improved. The straight line between the fractal and feeding point is innovated to folded line, as illustrated in Fig. 8. The relevant parameters are same as Fig. 5, besides \( w_1 = 0.5\text{mm} \), \( m = 4\text{mm} \), and \( a_0 = 1\text{mm} \). The return loss of the folded HFA is depicted in Fig. 9. When compared with Fig. 6, one can find that the value of resonant frequency of the folded HFA is not 2.45GHz, but shifts to 2.151GHz. This is because the current phases in folded line are reversed and present capacitive reactance and inductive reactance simultaneously. Therefore, they effectively cancel each other out. As a result the harmonic frequency drops.

In order to require the optimal dimensions of the folded HFA, we now examine the influences of fractal height \( h \), folded line width \( s \) and its height \( m \) on the performances of the folded HFA. First, supposed that other parameters remain unchanged, only the value of fractal height \( h \) varies from 1mm to 7mm. The effect of fractal height \( h \) on the resonant frequency is examined, as shown in Fig. 10. It can be seen from Fig. 10 that the larger the fractal height \( h \) is, the lower the harmonic frequency is. One can also find that when \( h = 7\text{mm} \), then \( f_0 = 2.66\text{GHz} \); and when \( h = 8\text{mm} \), then \( f_0 = 2.37\text{GHz} \). Consequently, one can locate the desired resonant frequency of 2.45GHz, only by adjusting the fractal height \( h \) between 7mm and 8mm. At the same way, the input impedance as a function of the folded line width \( s \) is illustrated in Fig. 11. It is obvious that the input impedance of the folded HFA almost remains unchanged while line width \( s \) varies from 300um to 800um. Fig. 12 shows the influence of folded line height \( m \) on the input impedance. A conclusion can be drawn from Fig. 12 that the input impedance rises with increase of the height. The value of resistance varies from 30\( \Omega \) to 100\( \Omega \), and the reactance is in the range of 120\( \Omega \) to 400\( \Omega \). The input impedances of most chips locate at this range. Therefore, one can adjust readily the height of folded line to reach the conjugate match between chip and tag antenna.
E. Optimization of Folded HFA

By parameter sweep and optimization, we obtain the optimal sizes of the folded HFA, as listed in Table 2. The simulation results of the folded HFA after optimized are showed in Figs. 13-16, and the electrical performances are listed in Table 3. One can readily find from Table 2 that effective radiation area of the folded HFA is reduced to 23.32mm×7.66mm. It drops 23.66% when compared with the radiation area of 26mm×9mm before folded. The location of resonant frequency is just at 2.45GHz. At this resonant frequency point the return loss is $S_{11} = -31.92 \text{dB}$ and the input impedance is $Z_{in} = (34.55 + 115.8j) \Omega$, which can be a conjugate match to most chip. The bandwidth of 334MHz is obtained by $S_{11} \leq -10 \text{dB}$. And the total gain is 1.78dB.

In a word, it can be observed easily from Figs. 13-16 and Table 3 that the performance parameters of the folded HFA after optimized fully satisfy the requirements of RFID tag applications.

### Table 2. Optimal sizes of the Folded HFA

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>h</td>
<td>7.66</td>
</tr>
<tr>
<td>L</td>
<td>11.66</td>
</tr>
<tr>
<td>m</td>
<td>4</td>
</tr>
<tr>
<td>s</td>
<td>0.8</td>
</tr>
<tr>
<td>a</td>
<td>4</td>
</tr>
<tr>
<td>$a_1$</td>
<td>1</td>
</tr>
<tr>
<td>w</td>
<td>1</td>
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<tr>
<td>w_1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### Table 3. Electrical parameters after optimization

<table>
<thead>
<tr>
<th>Electrical Parameters</th>
<th>Value</th>
<th>$S_{11}$ (dB)</th>
<th>BW (MHz)</th>
<th>Gain (dB)</th>
<th>$Z_{in}$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>2.45</td>
<td>-31.92</td>
<td>334</td>
<td>1.78</td>
<td>34.55+115.8j</td>
</tr>
</tbody>
</table>

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Fig. 13. Return loss $S_{11}$ as a function of frequency for the folded HFA

Fig. 14. Input impedance as a function of frequency for the folded HFA

Fig. 15. 2D gain patterns at 2.45GHz for the folded HFA

Fig. 16. 3D gain patterns at 2.45GHz for the folded HFA
F. Estimation of Read Range

The read range is the most important tag performance feature. It represents the maximum distance at which RFID reader can detect the backscattered signal from the tag. Using Friis transfer theory the estimation value of read range can be computed by [1]

\[
R_{\text{max}} = \frac{\lambda}{4\pi} \sqrt{\frac{P_G G_r r}{P_h}}
\]  

(3)

where \(\lambda\) denotes the wavelength at resonant frequency, \(P_t\) is the power transmitted by the reader, the gains of the transmitting antenna and the receiving tag antenna are represented by \(G_t\) and \(G_r\) , respectively, \(P_h\) is the minimum threshold power for activating the RFID tag chip and \(r\) is the transmission coefficient. In our work, \(\lambda = 0.122m\) at \(f = 2.45GHz\) \(G_t = 1.78dB\) \(P_h = -14dBm\) = 0.0398mW \(G_r = 8dB\) , and \(r = 1\), the read range can be estimated by Eq. (3), yielding \(R_{\text{max}} = 4.74m\).

III. CONCLUSIONS

A folded HFA is designed and analyzed by HFSS. The input impedance of the folded HFA can be adjusted flexibly by tuning the height of folded line. The simulation results demonstrate that the folded HFA antenna has good performances and satisfy the requirements of RFID tag applications.

ACKNOWLEDGMENT

This work was supported by the key project of science and technology department of Fujian province (2012H0035), and the Key Project of Quanzhou City Science and Technology Program (No. 2011G14).

REFERENCES


Yanzhong Yu was born in Fujian, China, in 1972. He received the B. S. degree from Fujian Normal University, Fujian, China, in 1996; the M. E. degree from East China Normal University, Shanghai, China, in 2005; and the Ph. D. degree from State Key Lab of Millimeter Waves, Southeast University, Nanjing, China, in 2009. His current research activities are concerned with the design and analysis of antennas, including RFID antenna, GPS antenna, smart antenna, and so on.

Zhongyi Huang was born in China in 1989, and received the B. S. degree in Electronics Information Science and Technology, from College of Physics & Information Engineering, Quanzhou Normal University, Quanzhou, China, in 2013. His research interest is the design of RFID tag antennas.

Caiqiang Zheng was born in China in 1990, and received the B. S. degree in Electronics Information Science and Technology, from College of Physics & Information Engineering, Quanzhou Normal University, Quanzhou, China, in 2013. His research interest is the design and analysis of GPS antenna.

Yongxing Wu was born in China in 1991, and received the B. S. degree in Electronics Information Science and Technology, from College of Physics & Information Engineering, Quanzhou Normal University, Quanzhou, China, in 2013. His research interest is the design and analysis of mobile antenna.