Wideband Isosceles Trapezoid Dipole Array for Electromagnetic Energy Harvesting

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Abstract. In this paper, a novel energy harvesting dipole array based on two printed asymmetric off-center fed isosceles trapezoid dipoles is proposed. The dipole array not only has extremely high energy conversion efficiency, but also has wideband characteristics due to the isosceles trapezoidal electromagnetic structure. In order to verify the feasibility of design, the dipole cell and array are numerical simulated with ANSYS HFSS successively. For the alternating current (ac) conversion, the bandwidth with over 80% efficiency of cell reaches approximately 1 GHz, while the bandwidth with over 90% efficiency also approaches 0.6 GHz. Besides, when cells are expanded to an array, the array’s performance can be further improved. The experimental results are in line with expectations.

Introduction

In recent years, Wireless Power Transfer (WPT) technology has been greatly developed and widely applied into various fields [1] [2]. In this technology, rectennas are extremely important factor affecting the effectiveness of the WPT system. But improving the performance of rectennas has always been a challenging task.

WPT system includes Radio Frequency (RF) transmitters, RF receivers and the freespace between them [3]. The loss in freespace is inevitable [4]. Therefore, most of the optimization designs aim at improving the performance of rectennas or energy harvesting systems in the receiving end. While they are committed to maximizing the conversion efficiency [5], an equally important but constantly neglected consideration is bandwidth. Most designs with high efficiency are only for a specific frequency point, and their efficiency decline with frequency obviously under ideal numerical simulation conditions, and this trend is more apparent in actual measurement and application.

In this paper, a printed asymmetric off-center fed isosceles trapezoid dipoles structure is proposed to achieve wideband characteristics. It can maintain superior energy conversion efficiency in a continuous and wide band of frequency. During the conversion of the radiation to alternating current power (RF-ac), resistors are placed across metallic elements’ gaps. Within the range from 3.3 GHz to 4.3 GHz, its efficiency exceeds 80%, while maintaining more than 90% efficiency over a continuous frequency range from 3.5 GHz to 4.1 GHz. For the direct current (dc) conversion, the resistors are replaced with Schottky diodes. The simulation results show that the array’s performance can be furtherly improved when it is expanded to an array with minor parameter changes. The bandwidth with over 80% efficiency reaches approximately 1.1 GHz, while the bandwidth with over 90% efficiency also approaches 0.7 GHz. Therefore, the structure of asymmetric off-center fed isosceles trapezoid dipole is extremely valuable for energy harvesting devices to increase bandwidth.
Principle and Analysis

Classical dipole antenna which consists of two symmetrical center-fed straight wires has been widely used because of its simple structure and superior performance [6]. However, in some special applications such as energy harvesting, its deficiencies are gradually exposed. In many circumstances, its input impedance is too low and inconvenient to match the load [12].

Compared to traditional dipole antenna, off-center fed dipole provides increase of the input impedance with respect to the center-feed impedance, by means of finding the proper feed location along a dipole or monopole [7]. In addition, it’s easier to reach requirements during circuit matching. Most importantly, this kind of feed form can greatly expand the bandwidth of the proposed energy harvesting surface. Brown-Woodward (bow-tie) antenna is the planarization of Biconical antenna, which has relatively stable characteristic impedance and wide frequency band [8]. Inspired by its structure, isosceles trapezoidal is designed to replace the common rectangle in energy harvesting surface [9]. Due to the utilization of the off-center feed and isosceles trapezoid dipoles, the conversion bandwidth can be extended greatly.

It is worth mentioning that the loss in space cannot be changed [4]. Therefore, the RF-ac efficiency referred in this paper is the efficiency of the energy harvesting device to transfer the total power reaching the dipole array to available power at the feed (i.e., where a resistive load or Schottky diode is placed to connect metallic elements, referred to as the load in Figure. 1 (a) (b)). Its expression is

\[
\eta_{RF-ac} = \frac{P_{out}}{P_{in}}.
\]

(1)

Where \( P_{in} \) is the total power arriving the energy harvesting surface, and it can be obtained by calling Calculator function in ANSYS HFSS to make the appropriate calculation of Poynting vector. Here \( P_{out} \) is the time-average ac power collected by collectors, and it can be calculated by the following formula

\[
P_{out} = \sum_{i=1}^{m} \frac{U_i^2}{R_i}.
\]

(2)

Where \( U_i \) is the voltage across \( i \)-th load (i.e., resistor or Schottky diode), which can be obtained by calling Calculator function to make the appropriate calculation of electric field vector (E) vector, and \( R_i \) is its resistance. Besides, \( m \) is the total number of loads.

Design and Simulation

First of all, a suitable dielectric material must be chosen to serve as the dielectric superstrate. Like other energy harvesting, it’s expected to retain strong charge storage ability with a low dielectric loss. The above involves two important parameters \( \varepsilon_r \) and \( \tan\delta \). \( \varepsilon_r \) is defined as the amount of electrostatic energy stored in a unit volume in the unit electric field, therefore a larger relative permittivity is expected. The physical significance of \( \tan\delta \) represents energy loss ratio to energy storage in the dielectric in one cycle, so the value of the tangent loss angle should be small. Combine the above, Rogers TMM-10i (i.e., \( \varepsilon_r = 9.8 \), \( \tan\delta = 0.002 \)) is an eligible material.

A Floquet port is used in the process of numerical simulation to provide a plane wave propagating in the -z direction. (i.e., it is found that the dielectric layer must be placed in the direction of the incoming wave to affect the surface impedance seen by the incoming waves [9]), and periodic boundaries are applied to simulating a planar infinite array.

In order to prove the feasibility of the design, a RF-ac unit energy harvesting surface (unit cell) is first simulated. The layout of the RF-ac unit cell is shown in Figure. 1 (a) (b), where \( H_1 = 6.35 \text{ mm}, W_1 = 18.90 \text{ mm}, L_1 = 38.00 \text{ mm}, M_1 = 15.00 \text{ mm}, Q_1 = 6.70 \text{ mm}, a_1 = 2.90 \text{ mm}, b_1 = 2.00 \text{ mm}, c_1 = \)}
1.71 mm, \( d_1 = 0.40 \) mm, \( e_1 = 5.00 \) mm, \( f_1 = 14.70 \) mm, \( g_1 = 4.52 \) mm. It can be seen that two metallic isosceles trapezoids of different sizes (with a public side length \( e_1 \)) are connected by a 50\( \Omega \) load to constitute a dipole [9], and two identical dipoles form an asymmetric structure due to the difference in orientation. The entire unit cell is covered by Rogers TMM-10i material whose thickness is \( H_1 \).

The curve shows that RF-ac conversion efficiency exceeds 80% in the frequency range of 3.28 GHz to 4.29 GHz, while maintaining more than 90% efficiency over a continuous frequency range from 3.52 GHz to 4.14 GHz. Effective bandwidth reaches 1 GHz and 0.6 GHz respectively. It means that the unit cell still maintains superior ac conversion efficiency in a wider bandwidth.

As mentioned before, the off-center fed structure can achieve high input impedance. Besides, we can also change the value of the above parameter \( M_1 \) and \( C_1 \) to alter the input impedance of the dipoles. Due to the above, impedance matching can be implemented for different loads or diodes comfortably. As a result, additional matching network won’t be demanded, which make it possible to minimize the overall structure size.

For dc conversion, the resistors which connect two metallic isosceles trapezoids will be replaced with Schottky diodes [12]. Due to the nonlinear characteristics of the diode, its impedance characteristics will change with fluctuations in input power and operating frequency. In order to achieve impedance matching after replacing loads, the parameters of the entire unit cell should be slightly adjusted. Here HSMS-2860 Schottky diodes are chosen. Its input impedance and related data can be consulted in its datasheet. In the simulation, the default value of the input impedance \( Z_{\text{IN}} \) is 184-j45\( \Omega \) [9] [13]. Moreover, in order to accomplish the dc channeling, a connector is added to connect the dipoles on each column [9].

Improved model and RF-ac efficiency are shown in Figure. 2. It can be seen in Figure. 2 (a) (b) that, the shape of the dipole has been altered, but still an asymmetric isosceles trapezoidal off-center fed structure. The parameters have been changed slightly, where \( H_2 = 6.8 \) mm, \( W_2 = 11.5 \) mm, \( L_2 = 37.8 \) mm, \( M_2 = 12.0 \) mm, \( Q_2 = 6.1 \) mm, \( a_2 = 7.0 \) mm, \( b_2 = 1.7 \) mm, \( c_2 = 0.5 \) mm, \( d_2 = 2.5 \) mm, \( e_2 = 0.4 \) mm, \( f_2 = 8.0 \) mm, \( g_2 = 4.0 \) mm.

Figure 1. (a) and (b) are the model and parameters of original RF-ac unit cell respectively, which are terminated by 50\( \Omega \) resistive loads. (c) shows the RF-ac conversion efficiency when the unit cell is simulated by a Floquet port.

Figure 2. (a) and (b) are the model and parameters of original RF-ac unit cell respectively, which are terminated by Schottky diodes. (c) shows the RF-ac conversion efficiency when the unit cell is simulated by a Floquet port.
The curve shows that the effective frequency range is not the same, but the bandwidth with over 80% and 90% efficiency also reaches 1 GHz (3.7~4.7 GHz) and 0.6 GHz (3.9~4.5 GHz) respectively. This shows that the entire circuit has achieved an excellent matching to Schottky diodes.

Finally, a 2×2 finite array is simulated to observe its performance. Array model and its efficiency are shown in Figure 3, where W = 23.0 mm, H = 6.8 mm and L = 75.6 mm. In this case, Floquet port is replaced by the incident wave excitation to carry out the array simulation, but the plane wave is still traveling in the -z direction. Interestingly, it is found that with slight change to the parameter a₂, the RF-ac efficiency for the finite array is basically unchanged, but high-efficiency bandwidth is wider.

Because of minor change in parameter a₂, the entire 2×2 array shows better performance. Its RF-ac efficiency exceeds 80% over a continuous frequency range from 3.09 GHz to 4.15 GHz (nearly 1.1 GHz), while the bandwidth with over 90% efficiency ranges from 3.21 GHz to 3.92 GHz (nearly 0.7 GHz). The result shows that when the unit cells are combined into an array, Bandwidth is further improved.

In order to show the superiority of this design, we compare it with other rectennas, and Table 1. shows the comparison results. The results show that while inheriting Other designs’ advantages, this design has realized wideband characteristics which means more practical.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Frequency</th>
<th>Structure</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>[9]</td>
<td>3.4 GHz</td>
<td>Rectangular dipole array</td>
<td>High efficiency, Narrow band</td>
</tr>
<tr>
<td>[10]</td>
<td>2.4 GHz</td>
<td>parallel association</td>
<td>High efficiency, Narrow band</td>
</tr>
<tr>
<td>[11]</td>
<td>2 GHz, 3 GHz, 3.5 GHz</td>
<td>Multilayer structure</td>
<td>High efficiency, Triple band</td>
</tr>
<tr>
<td>This work</td>
<td>Range from 3.09 GHz to 4.15 GHz (Variable)</td>
<td>Isosceles trapezoid dipole array</td>
<td>High efficiency, Wideband, flexible</td>
</tr>
</tbody>
</table>

**Summary**

In this paper, an energy harvesting dipole array based on two printed asymmetric off-center fed isosceles trapezoid dipoles has been proposed. The simulation results show that unit cells of the structure can maintain superior energy efficiency in a wide frequency range. In summary, the proposed energy harvesting dipole array with the capability of wider bandwidth and high efficiency is very promising for wireless communication applications and energy harvesting devices. We will
simulate the efficiency of RF-dc and fabricate the model to measure actual performance in the future work.

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References