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Novel Design of 2.45-GHz Rectenna Element and Array for Wireless Power Transmission

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ABSTRACT A novel design of 2.45-GHz rectifying antenna (rectenna), which is composed of antenna element, two-element series-fed array, and four-element cascaded array, has been proposed in this paper. The array designs are introduced in order to adapt various power density is used in the array, especially in near-field of the transmitting antenna, in this case, the power density in the center and far away from center differs greatly. The compact low-profile air supported microstrip antenna is introduced as receiving antenna element in order to reduce substrate loss. The rectifying circuit has been designed and optimized using ADS software. The diode in the rectifying circuit is installed in series and the capacitance is replaced by microstrip line as dc pass filter. A maximum RF to dc conversion efficiency of the rectifying circuit can reach 80% when the input power is 21 dBm and 3500-Ω resistive load is connected to the circuit end through experiment. The rectenna exhibits a maximum efficiency of 77.2% and an output dc voltage of 18.5 V. The proposed rectenna element and the array can be easily expanded to a large scale integrated rectenna arrays, it will be practically attractive for wireless power transmission system design.

INDEX TERMS Wireless power transmission, rectenna, rectifying circuit, antenna array.

I. INTRODUCTION

Nowadays, the space solar power transmission (SPT) and microwave wireless power transmission (WPT) using the rectenna has a great interest [1]–[3]. The rectenna is an essential device to convert RF energy into useful electricity [4], [5]. Conventional rectennas are generally composed of a microwave antenna to receive microwave power and a rectifying circuit. An input low-pass filter to suppress unwanted higher harmonics, diodes, an output dc pass filter and a resistive load constitute the rectifying circuit. In recent past, many kinds of rectifying circuits have been introduced, the RF-DC conversion efficiency in these papers can reach 60%-80% when proper power density is met [6]–[9]. Various receiving antennas used in rectennas have been reported such as dipole antennas [10], patch antennas [11]–[16] and differential rectennas [17], [18]. However, these publications only design the antenna element and each element is connected with a rectifying circuit, which will reduce efficiency in the large rectenna array because there is power density difference in the center and far away from center. Therefore, it is necessary to design antenna array composed of more elements in order to capture enough power to meet optimal input power.

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In this paper, for the purpose of reducing substrate loss, the air supported low profile microstrip antenna is proposed. The height of the antenna is only 5mm, at the designed frequency 2.45GHz, the relative bandwidth of the designed antenna element is 4.1% for $S_{11} < -10$dB, which can prevent from debugging if resonant point is slightly deviated from 2.45GHz. Because the RF-DC conversion efficiency generally depends on the RF power density owing to nonlinear characteristics of diodes, RF-DC conversion efficiency reduces when RF power density deviates from the proper value. To solve this problem, two-element series-fed array and four-element cascaded array have been designed. The arraying method can be easily extend to large scale integrated rectenna arrays. The diode in the rectifying circuit is installed in series, which tends to have a higher efficiency [19]. In order to suppress additional parasitic effect, the microstrip line is used as output DC pass filter instead of conventional capacitance. Through the experimental results, the maximum RF to DC conversion efficiency of the rectifying circuit and the rectenna can reach 80% and 77.2% respectively.

The designed antenna and arrays are simulated by HFSS software and the rectifying circuit is analyzed by ADS software. The antenna configuration and basic behavior are described in detail in the section II. The detailed design process of rectifying circuit is shown in section III. The measured results of rectenna are demonstrated in section IV. Finally, some conclusions are drawn in section V.

II. RECEIVING ANTENNA DESIGN

A. RECEIVING ANTENNA ELEMENT DESIGN

The low profile air supported microstrip antenna is selected as the antenna element for the purpose of reducing substrate loss. Fig.1 (a) and (b) show the structure of four-element receiving antenna, the size of the radiating patch is 55mm×55mm×1mm, the ground size is 200mm×200mm×1mm, the height between the radiating patch and the ground is 3mm, the overall size of the four

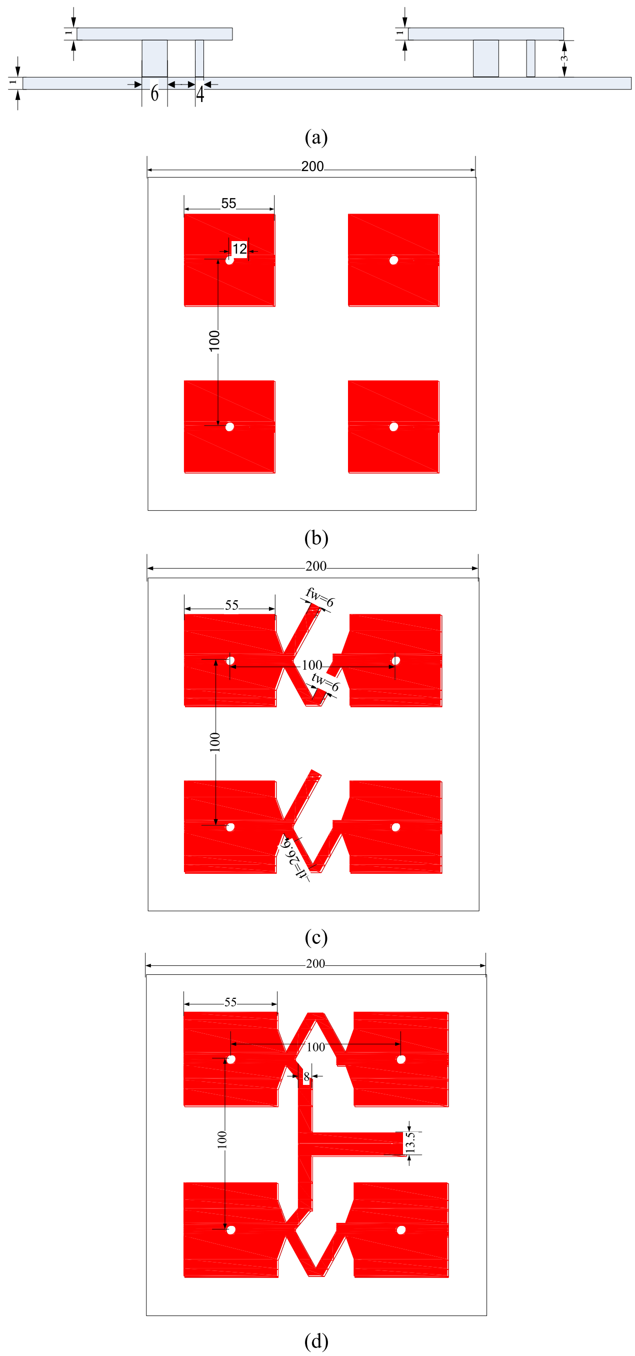

FIGURE 1. The configuration of the antenna. (a) Side view of antenna element. (b) Front view of antenna element. (c) Front view of two-element series-fed array. (d) Front view of four-element cascaded array.

B. TWO-ELEMENT SERIES-FED ARRAY DESIGN

In most recent rectenna developments, researchers focus on the study of antenna element design. However, if the input power density decreases, it is necessary to develop an antenna array to capture enough power in order to meet optimal input power. As can be seen in Fig.1 (c), two-element series-fed antenna array has been designed first. In order to reduce transmission loss, the series-fed structure has been introduced in the antenna design making transmission line as short as possible. Two opponent feeding points at different elements introduce 180° phase differences, a $\lambda/2$ long transmission line is added for the purpose of making two elements radiate with same phase.

Compared to usual Wilkinson power divider, the structure of series-fed network is much simpler. The width of the transmission line have been tuned to make two elements radiate with same amplitude. The width of feeding line have been optimized to minimize the input reflection coefficient. Fig.5 shows the variety of simulated S_{11} by tuning feeding line width (fw) from 4 to 8mm. As indicated in the figure, when fw is 6mm, the simulated S_{11} is better than other values of fw. Fig.6 presents the variety of the operating frequency affected by the transmission line width (tw). Obviously, when the value of tw increases, the operating frequency moves to higher frequency, and vice versa. The affection of beam point by different values of transmission line length (tl) has been presented in Fig.7. As can be seen in the figure, the beam point deviates from normal when the value of tl varies, because the phases of different elements are not consistent. Fig.2 (b) shows the photo of the two-element series-fed array. Fig.3 (b) gives the simulated and measured S_{11} for two-element series-fed array, the relative impedance bandwidth of the antenna is 3.7% for $S_{11} < -10$dB at designed frequency 2.45GHz. Fig.4 (b) presents the E-plane and H-plane radiation patterns of the antenna array at 2.45GHz. The beam width is narrower than that of the antenna element.

C. FOUR-ELEMENT CASCADED ARRAY DESIGN

Furthermore, four-element antenna array also has been designed if the received power by two-element array is still lower than optimum input power. The four-element cascaded array is composed of two two-element series-fed arrays and a T-junction power divider, which can be seen in Fig.1 (d) and Fig.2 (c). The width of T-junction power divider is optimized to match to 50Ω input resistance. Fig.3 (c) presents the simulated and measured S_{11}, the measured -10dB bandwidth is 4% at 2.45GHz. The E-plane and H-plane radiation patterns are shown in Fig.4 (c). The arraying method can be easily extend to more elements antenna array design.

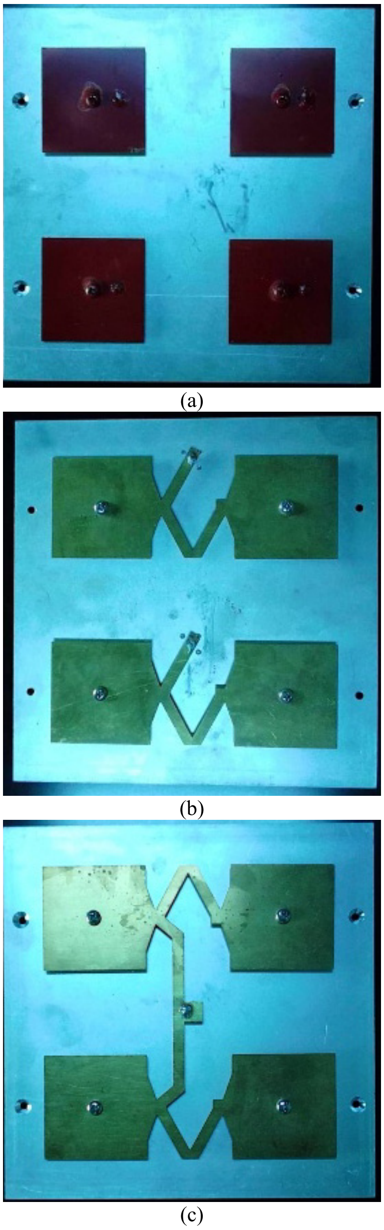

FIGURE 2. The photo of designed antenna. (a) The photo of antenna element. (b) The photo of two-element series-fed array. (c) The photo of four-element cascaded array element receiving antenna is 200mm×200mm×5mm. The designed antenna introduces air substrate, which can reduce substrate loss and enlarge the impedance bandwidth, so that preventing from debugging if resonant point is slightly deviated from 2.45GHz. The photo of the fabricated antenna can be seen in Fig.2 (a). Fig.3 (a) shows the simulated and measured S_{11} for designed antenna element. Seen from the figure, the relative impedance bandwidth of the antenna is 4.1% for $S_{11} < -10$dB at center frequency 2.45GHz. Fig.4 (a) presents the simulated and measured E- and H-plane patterns at 2.45 GHz. Good agreement can be obtained from comparison between the simulated and measured results.

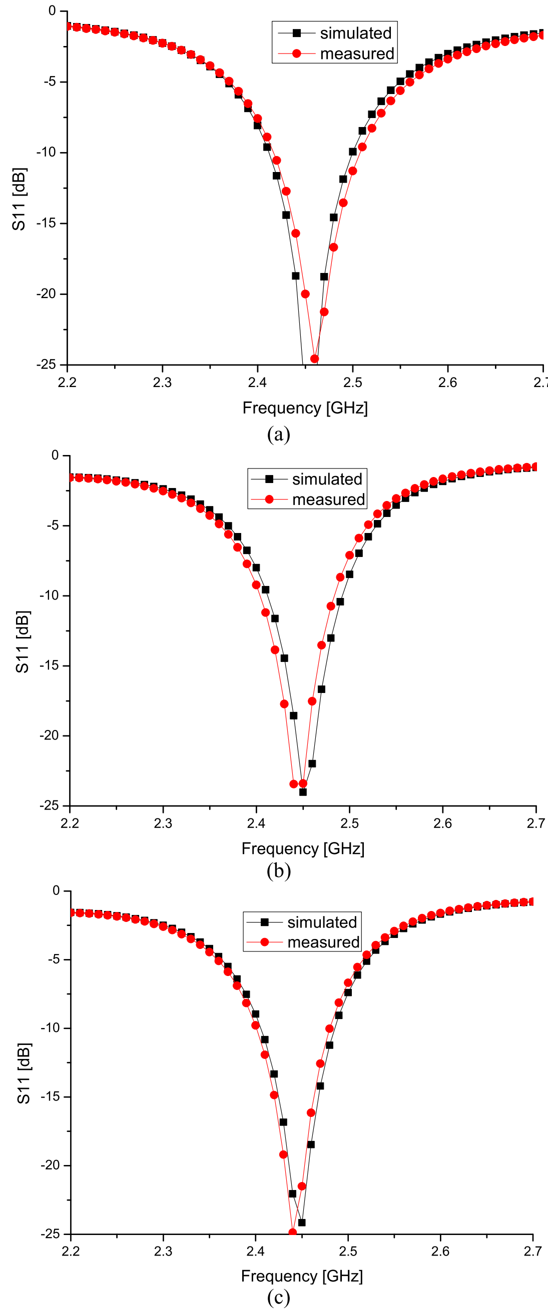

FIGURE 3. Simulated and measured S_{11} for designed antenna. (a) Simulated and measured S_{11} for antenna element. (b) Simulated and measured S_{11} for two-element series-fed array. (c) Simulated and measured S_{11} for four-element cascaded array.

III. RECTIFYING CIRCUIT DESIGN

The traditional rectifying circuit usually contains low-pass filter, diode, matching circuit, a DC pass filter and a resistive load connected to the end of the circuit. The HSMS-282c diode has been used for the rectifying circuit design in series form, which tends to have a higher efficiency [14]. The main parameters of the diode are $R_S = 6\Omega$, $C_{J0} = 0.7$pF, and $V_{BR} = 15$V. The parameters of the rectifying circuit are optimized by ADS software. Fig.8 shows the schematic of designed rectifying circuit. The rectifying circuit is printed on ARLON AD255A substrate with $\varepsilon_r = 2.55$ and 1mm thickness. The values of parameters marked in Fig.8 are listed in Table 1. The low-pass filter located behind the antenna has been designed first, the role of it is that allowing the input power at 2.45 GHz to pass to the detector diode, where a

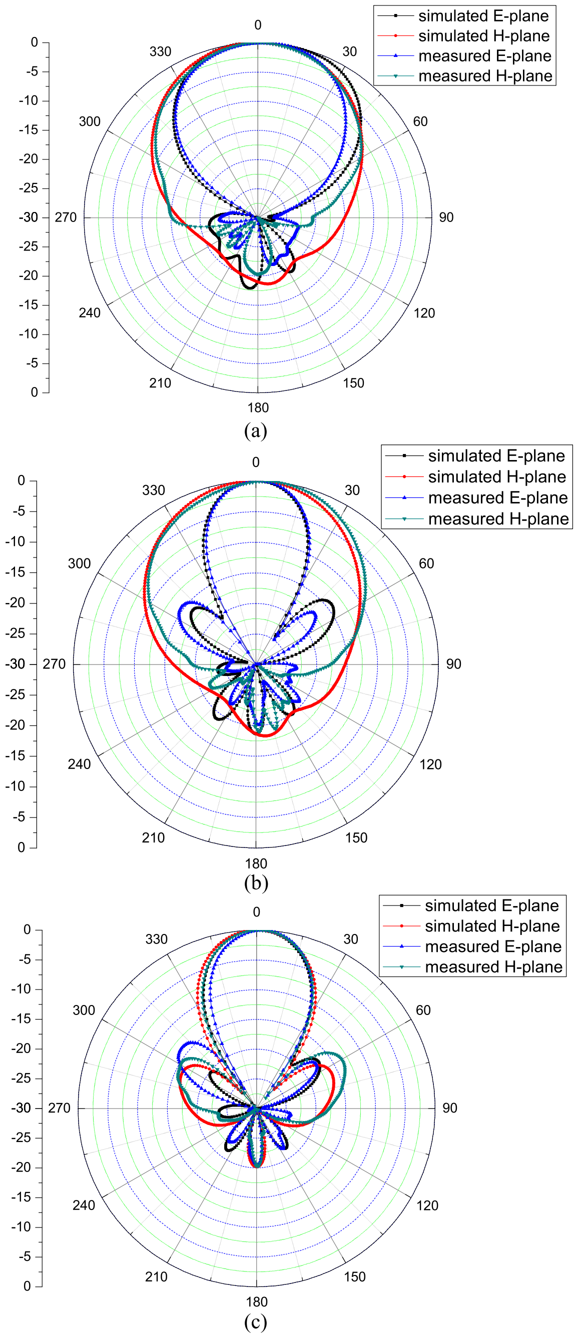

FIGURE 4. The simulated and measured radiation pattern for designed antenna. (a) Simulated and measured radiation pattern for antenna element. (b) Simulated and measured radiation pattern for two-element series-fed array. (c) Simulated and measured radiation pattern for four-element cascaded array.

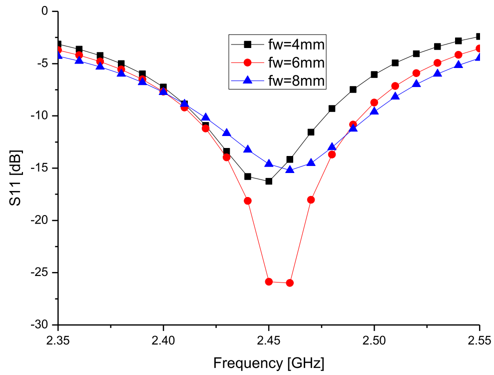

FIGURE 5. The variety of simulated S_{11} by tuning fw.

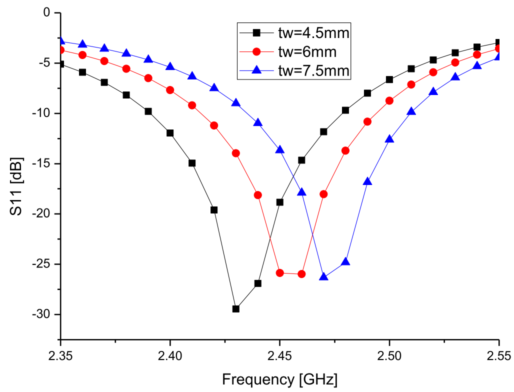

FIGURE 6. The variety of operating frequency affected by tw.

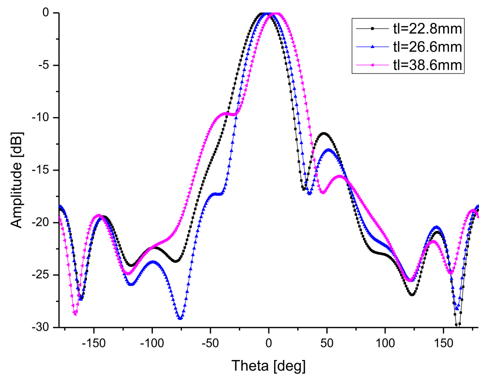

FIGURE 7. The affection of beam point by different values of transmission line length (tl).

large portion of the RF power is converted to dc power and block the high order harmonic such as second harmonic at 4.9 GHz from flowing from the diode to the antenna. In this design, a three-section T-shape microstrip transformer acts as low input low-pass filter, and one of the microstrip line is grounded by via-holes to provide a dc-patch in the circuit. The matching circuit is realized by the $\lambda/4$ microstrip line which transforms the impedance seen from the diode into 50Ω. For the purpose of suppressing additional parasitic effect, a simple stepped-impedance microstrip line low-pass filter acts as DC pass filter instead of conventional capacitance. An optimal resistive load is connected at the end of the circuit. Fig.9 shows the photograph of the fabricated rectifying circuit.

The conversion efficiency of the rectifying circuit (η_r) is defined as

$$\eta_r = \frac{V_{DC}^2}{P_{in}R_L} \times 100\% \tag{1}$$

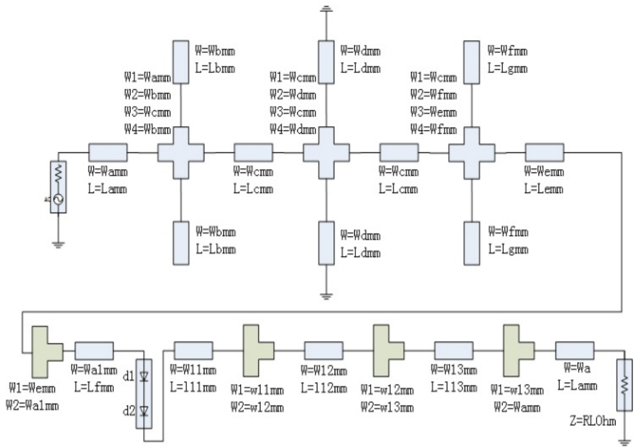

FIGURE 8. The schematic of designed rectifying circuit.

TABLE 1. The values of parameters marked in Fig.8.

Parameter	Value	Parameter	Value
Wa	2.8mm	*Le*	30.0mm
Wa1	0.7mm	*Lf*	15.1mm
Wb	4.7mm	*Lg*	4.9mm
Wf	1.32mm	*W11*	1.1mm
Wc	5.0mm	*w12*	9.9mm
Wd	1.0mm	*w13*	0.5mm
We	11.7mm	*l11*	5.3mm
La	6mm	*l12*	21.3mm
Lb	5mm	*l13*	19.2mm
Lc	5.1mm	*RL*	3500Ω
Ld	9.1mm		

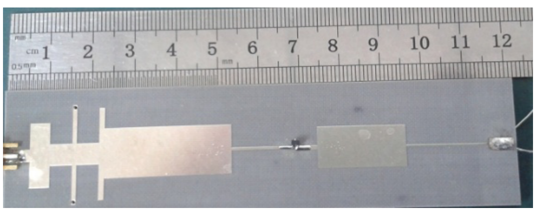

FIGURE 9. The photograph of the fabricated rectifying circuit.

where, V_{DC} is the measured DC voltage at the load resistance, P_{in} in the denominator is the diode's input power, R_L is the load resistance. Fig.10 shows the measured RF-DC conversion efficiency with different load and input power at 2.45GHz. The measured results illustrate that the maximum conversion efficiency of the designed rectifying circuit can reach 80% on the condition of 3500Ω load, 21dBm input power at 2.45GHz operating frequency. Fig.11 shows the output voltage curves corresponding to input power with different R_L, as can be seen in the figure, the output voltage is 18.8V when $R_L = 3500\Omega$ load and $P_{in} = 21$dBm.

IV. RECTENNA MEASUREMENT

The rectifying circuit and the receiving antenna were connected by an SMA connector with 50Ω characteristic impedance. The designed rectenna has been measured in an anechoic chamber which can be shown in Fig.12. The conversion efficiency (η) of the rectenna is illustrated as:

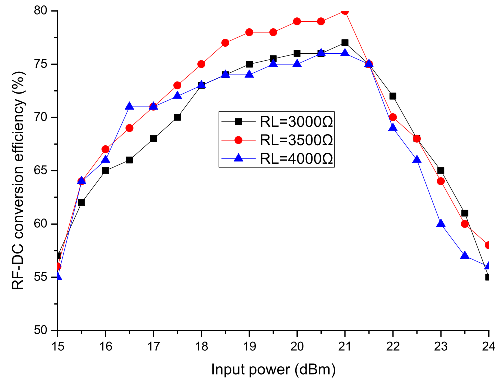

FIGURE 10. The measured RF-DC conversion efficiency with different load and input power.

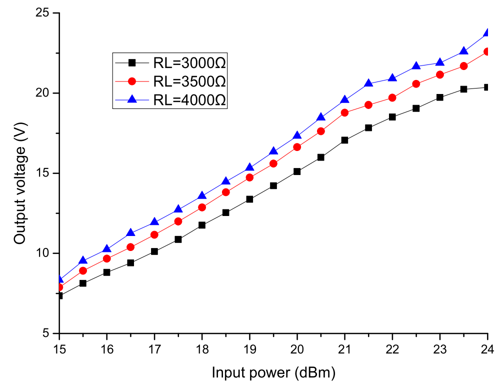

FIGURE 11. The output voltage curves corresponding to input power with different R_L.

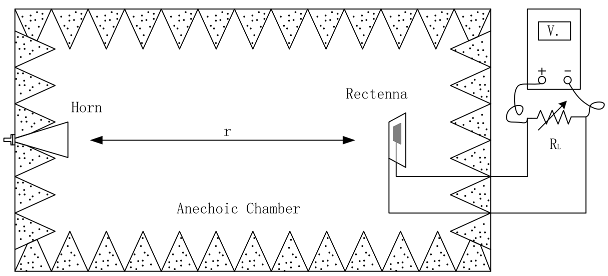

FIGURE 12. The rectenna efficiency measured system.

$$\eta = \frac{P_{dc}}{P_{rectenna}} \times 100\% \tag{2}$$

where P_{dc} is the DC power measured at the load resistance (R_L) and can be expressed as:

$$P_{dc} = \frac{V_{dc}^2}{R_L} \tag{3}$$

where $P_{rectenna}$ is the received RF power of the rectenna and can be calculated as follows:

$$P_{rectenna} = P_{pd} \times A_{er} = P_{pd} \times G_{rec} \times \frac{\lambda^2}{4\pi} \tag{4}$$

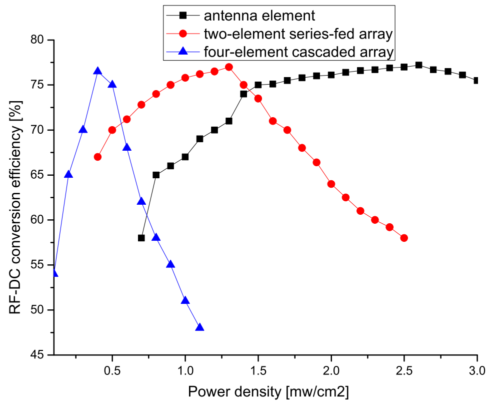

FIGURE 13. **The conversion efficiency of three kinds of rectennas versus different power densities.**

where P_{pd}, A_{er}, G_{rec} and λ are the RF power density, the effective area of the rectenna, the gain of the rectenna and wavelength at the design frequency respectively. The power density P_{pd} is given by

$$P_{pd} = \frac{P_t G_t}{4\pi r^2} \tag{5}$$

where P_t is the transmitting power, G_t is the horn antenna gain, and r is the distance between the horn antenna and the rectenna.

A 30dB gain power amplifier has been connected between a RF signal source and a BJ-22 standard horn antenna with 17dBi gain. The measured gains of the antenna element, two-element series-fed array and four-element cascaded array are 8.8dBi, 11.5dBi and 13.4dBi respectively. The distance between the transmitting horn antenna and the rectenna is selected as 1m which satisfies the far-field condition at 2.45 GHz. According to equation (4) and equation (5), $P_{rectenna}$ can be obtained. Fig.13 presents the conversion efficiency characteristics of three kinds of rectennas versus different power densities when 3500Ω resistive load is connected to the circuit. It is found that the maximum conversion efficiency can reach nearly 77.2% under different power densities. From Tab.2, the proposed design has high efficiency and low substrate loss, so it is suitable for forming array because it can reduce loss of massive transmission lines in large rectenna array, and different antenna elements can adapt various power density to improve efficiency. The output voltage with different power densities at 2.45 GHz operation frequency are illustrated in Fig.14. 18.5V DC voltage can be obtained under the power densities where the conversion efficiency reach the maximum.

TABLE 2. **Comparison of the proposed rectenna with related work.**

Reference	Efficiency	Substrate loss	Suitable for array or not
[12]	68%	big	no
[13]	69.4%	big	no
[14]	66.2%	big	no
[15]	83.7%	big	no
[16]	71.2%	big	no
Proposed work	77.2%	small	yes

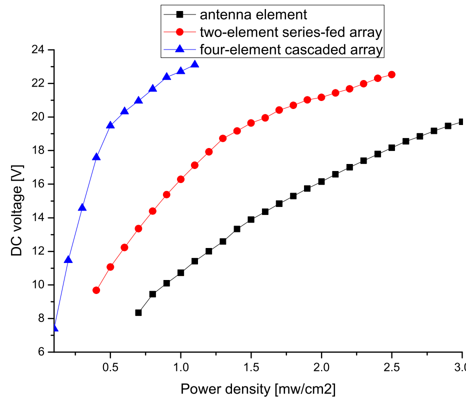

FIGURE 14. **The output voltage with different power densities.**

V. CONCLUSION

This paper introduces a novel design of 2.45GHz rectenna element and its array, which can adapt various power density if used in the rectenna array. Through the carefully design, the maximum RF to DC conversion efficiency of rectifying circuit with diode installed in series can reach 80% by experiment, in the case that input power is 21dBm and 3500Ω resistive load is connected to the circuit end. The rectenna exhibits a maximum efficiency of 77.2% and an output dc voltage of 18.5V. It will be practically attractive for expanding the method to large scale integrated rectenna arrays design in wireless power transmission system application.

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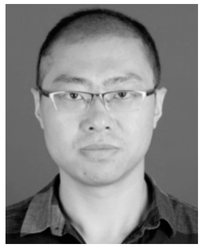

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