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RESEARCH PAPER

2.45-GHz wideband harmonic rejection rectenna for wireless power transfer

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In this paper, a 2.45-GHz wideband harmonic rejection rectenna for wireless power transfer is proposed. The rectenna comprises a microstrip-fed circular ring slot antenna (CRSA) and a series-parallel rectifier (SPR). A compact micro strip resonant cell is inserted into the CRSA so that the harmonic suppression over a wide bandwidth (3–8 GHz) can be obtained. The radio-frequency (RF)–DC conversion efficiency of the SPR is improved effectively by loading a proper compensating inductance, especially under the low input power levels. Furthermore, the proposed rectenna can easily achieve large-scale rectenna arrays using its simple structure. The adopted rectenna fabricated on a low cost Taconic RF-35 substrate has been measured. By up to 3rd-order harmonic rejection, the efficiency of the rectenna can achieve 70.2% with the optimum load resistance 1 kΩ. Good agreement among the calculated, simulated, and measured rectenna is observed.

Keywords: Antennas and propagation for wireless systems, Applications and standards (mobile, wireless, networks)

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I. INTRODUCTION

Nowadays wireless power transmission (WPT), which is one of the most promising research hotspots, is used in many modern applications such as microwave powered aircraft [1], radio-frequency identification [2], radio-frequency (RF) energy harvesting [3], and also widely developed in the portable electronic devices to realize the intellectualization of domestic life [4]. In WPT systems, the rectenna is the key component [5]. Many different antenna structures are proposed to improve the efficiency of the whole system. Sun [6] takes advantage of an enhanced rectenna with differential feeding to realize a better gain. However, the coaxial feeding is a non-planar design. In [7, 8], the rectennas with a kind of special slot are used to boost the efficiency over a wide band, but the slots are the three-dimensional (3-D) structures that are not suitable for the integration. Various types of rectenna arrays that provide an excellent RF–DC conversion efficiency have been reported in [9, 10], while matching to the diode is difficult and the size of the array is a little large.

High-directivity laser or weak-degenerativity electromagnetic wave is usually preferred for WPT. The 2.45 GHz microwave is widely applied in medical or industrial areas because of its low-attenuation and good-transmitting performance, which makes 2.45 GHz one of the best choices as transmitting energy spectrum.

In this paper, a novel 2.45 GHz rectenna unit is proposed, which is easy to set of array. It consists of two parts: one is the receiving antenna with a compact micro strip resonant cell (CMRC), whose harmonic suppression over a wide bandwidth between 3 and 8 GHz can be achieved; the other is the rectifier loaded with an inductance to enhance the RF–DC efficiency. Design and features of the proposed rectennas are described. Finally, a method of realizing large-scale rectenna arrays is depicted.

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II. RECTENNA DESIGN

The proposed rectenna printed on a Taconic RF-35 substrate with a relative permittivity of 3.5 and loss tangent of 0.0018 is presented in Fig. 1. The receiving antenna is a microstrip-fed circular ring slot antenna (CSRA) with a CMRC, which would realize wideband harmonic rejection. According to the equation as follows [11], the inner radius r_1 and outer radius r_2 can be calculated, respectively:

$$f_0 \approx \frac{c}{\pi(r_1 + r_2)} \times \left(\frac{\varepsilon_r + 1}{2\varepsilon_r}\right)^{1/2}, \tag{1}$$

where c, ε_r, $\pi(r_1 + r_2)$ is the speed light in free space, relative permittivity of the substrate, and mean circumference of the annular-ring-slot antenna, respectively.

The core mechanism of harmonic rejection is the microstrip-fed CMRC as shown in Fig. 2, which has been reviewed in [12], In order to investigate the property of CMRC, we only adjust c_1 with other parameters fixed in order to simplify the design.

As shown in Fig. 3, changing c_1 could affect the bandpass response of the CMRC. Figure 4 shows the simulated results and the corresponding measured results. The measured bandwidth of less than 3-dB insertion loss and better than 10-dB

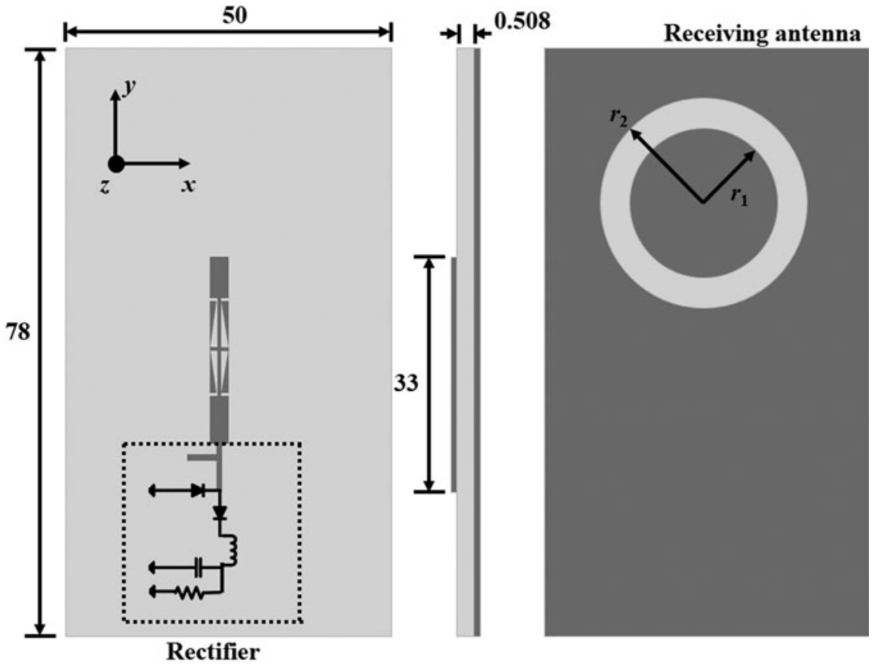

Fig. 1. The proposed rectenna with harmonic suppression ($r_1 = 10$, $r_2 = 13.8$. Unit: mm).

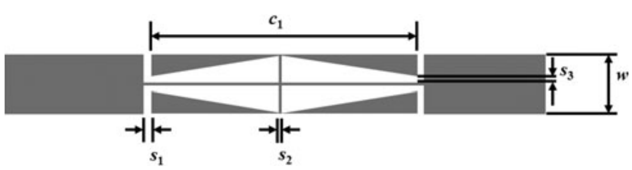

Fig. 2. The designed CMRC ($s_1 = 0.1$, $s_2 = 0.2$, $s_3 = 0.2$, $w = 1.13$. Unit: mm).

return loss is approximately 1.5 GHz when $c_1 = 13.6$ mm. The insertion loss and reflection coefficient are 0.68 and -18 dB, respectively. The return loss in 2nd- and 3rd-order harmonic are 0.56 and 0.69 dB, respectively.

Then the proposed receiving antenna is simulated on high-frequency structure simulator (HFSS), and the simulation result is demonstrated in Fig. 5. Here, a fundamental mode of the antenna is excited at exactly 2.45 GHz. Inset in the Fig. 5 shows the radiation pattern with or without the CMRC under the fundamental mode, which denotes that the CMRC does not have much effect on the radiation pattern. From the Fig. 5, a good reflection coefficient approximately -25 dB is achieved, while the harmonic waves, at the same time, are suppressed that the return loss at 2nd- and 3rd-order harmonic were 0.4 and 0.7 dB, respectively. Notably, the return loss is less than 1 dB over 3–8 GHz.

To visualize the harmonic suppression of the proposed antenna, the current distributions in the antenna are plotted in Fig. 6. It is clearly seen that the CMRC has blocked the signal at the 2nd- and 3rd-order harmonic, while only the fundamental frequency goes through successfully.

We have already reported a series-parallel rectifier with an inductance [13], which can develop the RF–DC efficiency notably as shown in Fig. 7. The series-parallel rectifier loads a proper inductance to compensate the capacitance of the

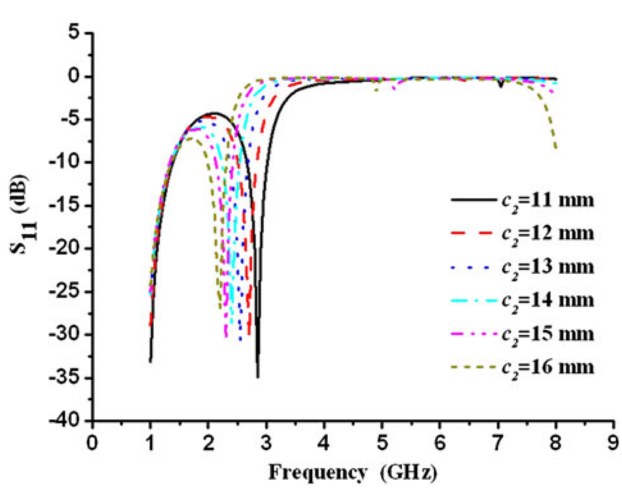

Fig. 3. The effects of c_1 on S_{11} (Unit: mm).

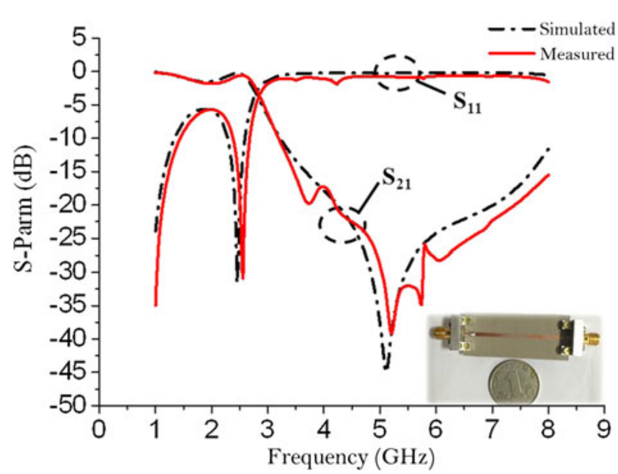

Fig. 4. The simulated and measured *S*-parameter of CMRC ($c_1 = 13.6$. Unit: mm).

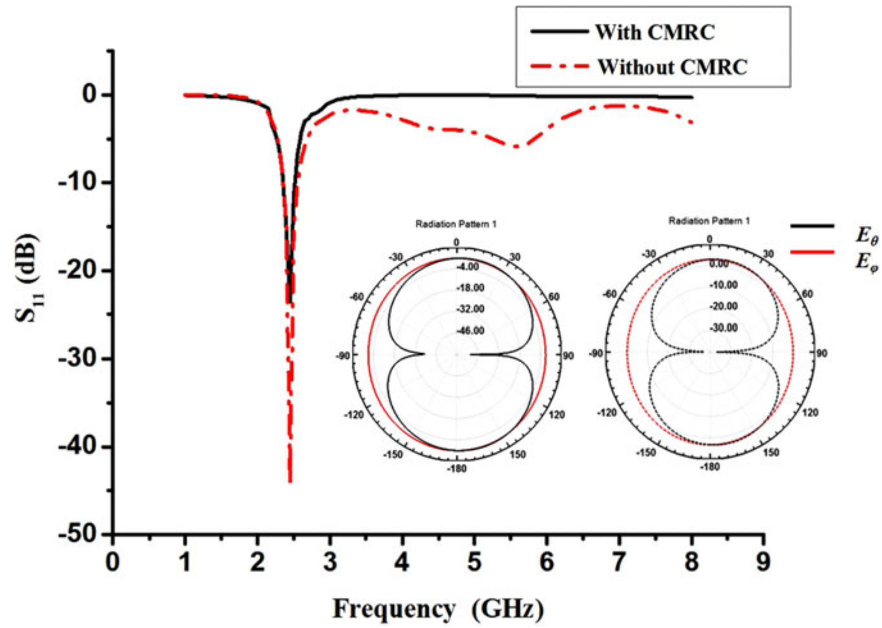

Fig. 5. The simulated radiation pattern and S_{11} of the proposed receiving antenna.

diodes so that the loop of the RF can be matched quite well, and it directly connects with the receiving antenna.

III. EXPERIMENTAL RESULT

To validate the concept proposed above, a rectenna operating at 2.45 GHz is fabricated on a 0.5 mm Taconic RF-35 substrate (shown in Fig. 8). The size of the rectenna is 78 × 50 mm^2 and the diodes are HSMS-8202.

Using Agilent E8267D as signal source and standard horn antenna (about 5 dBi gain at 2.45 GHz) as transmitting antenna, we calculated the efficiency of the rectenna by measuring the output DC voltage, as shown in Fig. 9. A power amplifier with a maximum gain of 20 dBi is used so that the available transmit power is large enough, and a standard horn antenna A_1 was used as transmitting antenna. Firstly, the received RF power was measured by a spectrum analyzer (Agilent N9030A) at a distance of 15 cm (far-field condition) from the transmitting horn antenna, and the receiving antenna is the designed microstrip-fed CSRA A_2. Then the

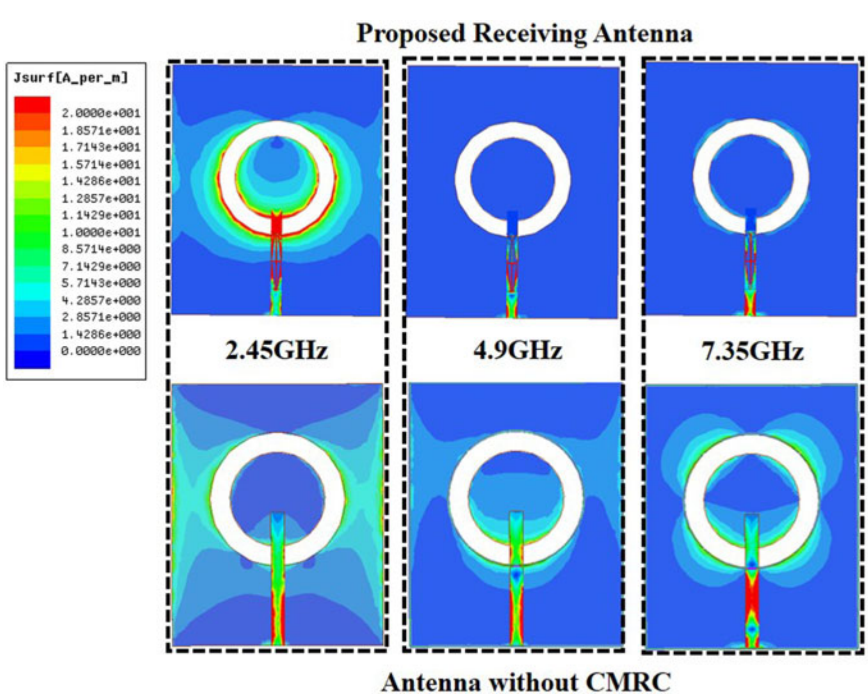

Fig. 6. Simulated current distribution diagrams of the proposed antenna and slot antenna without CMRC at 2.45, 4.9, and 7.35 GHz.

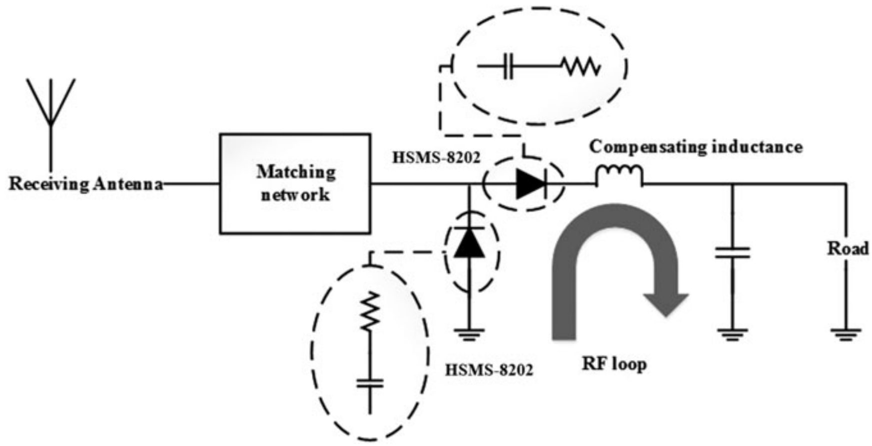

Fig. 7. The series-parallel rectifier with an inductance loaded.

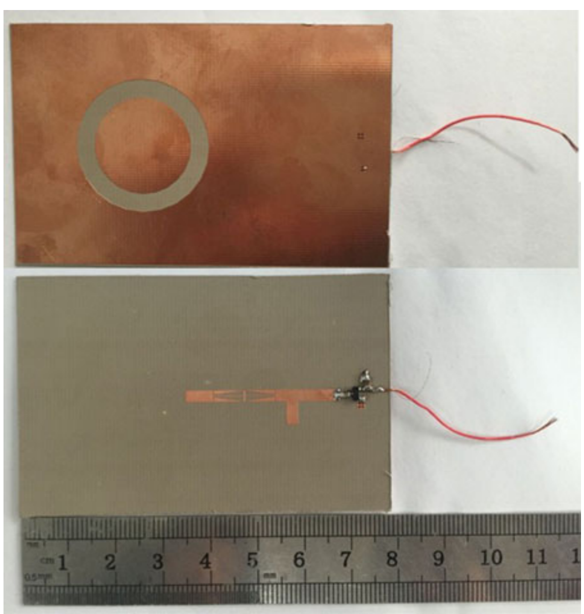

Fig. 8. Photograph of the fabricated antenna.

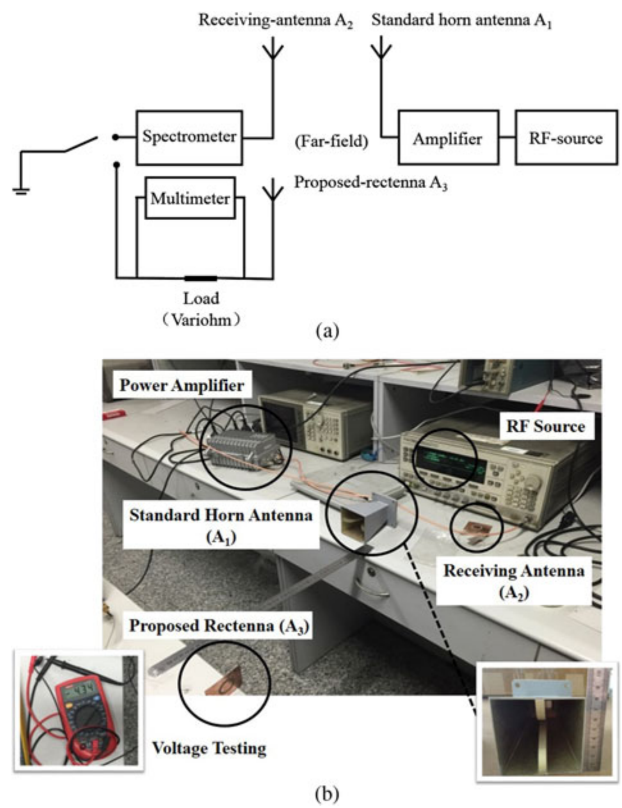

Fig. 9. The measuring experiment. (a) Experimental scheme (b) Experimental photograph.

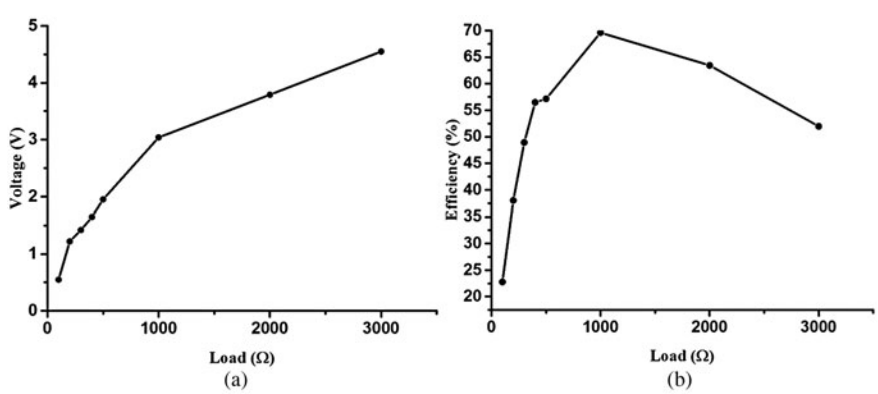

Fig. 10. Measured results. (a) Output voltage versus load resistance (b). Conversion efficiency versus load resistance ($P_R = 10$ dBm).

Table 1. Comparisons of the fabricated rectenna with the reported ones.

References	Frequency (GHz)	Input power (dBm)	Circuit size (mm²)	Efficiency (%)	Load (kΩ)
[7]	1.8–2.5	−10	70 × 70	55	15
[8]	2.45	22	100 × 100	82.3	1
[14]	2.45	25	60 × 60	51.5	30
[15]	2.45	–	60 × 60	78	1
[16]	0.5	−20	500 × 500	45	10
This work	2.45	10	78 × 50	70.2	1

prototype CRSA was replaced by the rectenna A_3 at the same location. The RF–DC conversion efficiency is defined as:

$$\eta(\%) = \frac{V_{DC}^2}{R_L P_R} \times 100\%, \tag{2}$$

where V_{DC} is the output DC voltage of the rectenna, R_L is the load resistance and the P_R is the RF power received and measured by the designed microstrip-fed CSRA A_2. When the received power is about 10 dBm, the measured results are depicted in Fig. 10. It figures out that the output voltage increases as the load resistance increases while the maximum value of conversion efficiency could achieve up to 70.2% when the optimum load is 1 kΩ. Good agreement is obtained. Moreover, in Table 1, the performance of the proposed rectenna is summarized and compared with the existing reports.

Table 1 illustrates the comparisons between the proposed rectenna and the previously reported ones. Compared with the works, the proposed design has the merits of compact size and relatively high efficiency.

IV. LARGE-SCALE RECTENNA ARRAY

When the transmitting RF energy is weak, antenna arrays as the receiving antenna is preferred. The high-gain antenna

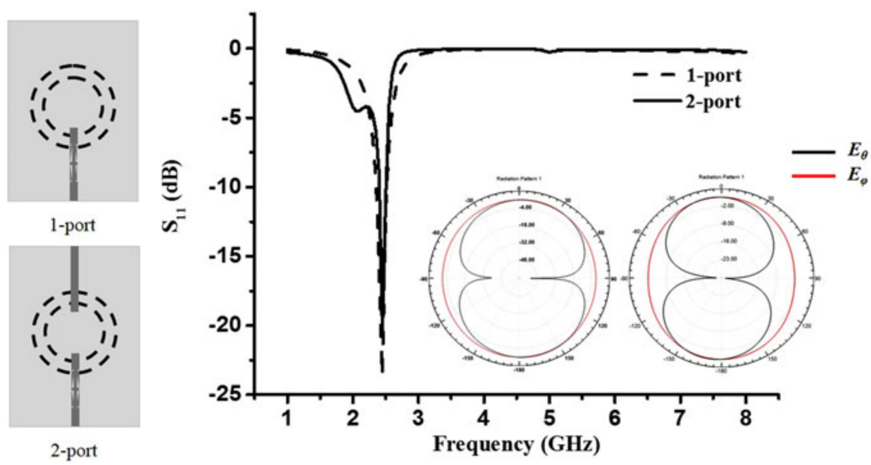

Fig. 11. The simulated S_{11} and radiation pattern of the two antennas.

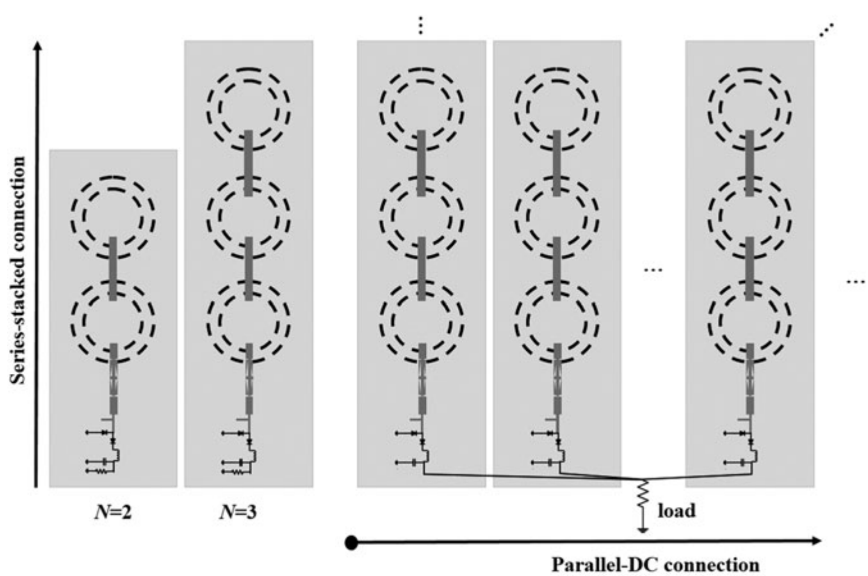

Fig. 12. The large-scale rectenna array. (a) Series-stacked rectenna array ($N = 2, 3, \ldots$). (b) Parallel-DC connection rectenna array.

arrays could induce high voltage applying to the diodes. Figure 11 shows the simulated reflection coefficient and antenna directivity, respectively. Inset in Fig. 11 demonstrates the radiation patterns of the two antennas almost identical.

In this paper, it is very convenient to stack the proposed rectenna as a large-scale rectenna array, as shown in Fig. 12(a). There is only one rectifier combined with the array, which may limit the performance of the diode because the input voltage of the diode must be lower than the breakdown voltage. Hence, the DC accumulation is a good method to achieve a high-voltage rectenna. Figure 12(b) shows the proposed rectenna array by connecting output DC lines with the ground planes in parallel. Furthermore, it is also possible to improve the performance by increasing the slot ring antenna units in series.

V. CONCLUSION

A 2.45-GHz wideband harmonic rejection rectenna for WPT is proposed. The rectenna comprises a microstrip-fed CRSA and a SPR. A CMRC is inverted into the CRSA so that the harmonic suppression over a wide bandwidth (3–8 GHz) can be achieved. The RF–DC conversion efficiency of the SPR improves greatly, especially under the low input power levels by loading a proper compensating inductance. The adopted rectenna built on a low cost Taconic RF-35 substrate is measured. By up to 3rd-order harmonic rejection, the efficiency of the rectenna could achieve 70.2% with optimum load resistance 1 kΩ. Furthermore, the proposed rectenna can easily achieve the large-scale rectenna arrays by connecting output DC lines with the ground planes in parallel or increasing the slot ring antenna units in series. The relevant work is being carried out. There would be a simulation and verification on the concept of large-scale rectenna array in the future. The DC voltage is large enough for mobile phone charging so that an experimental is under way.

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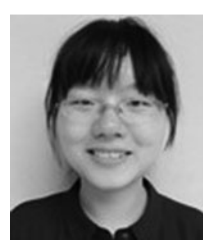

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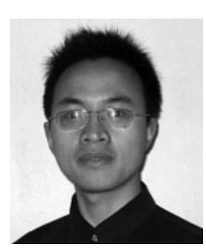

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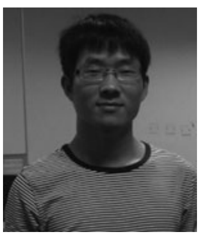

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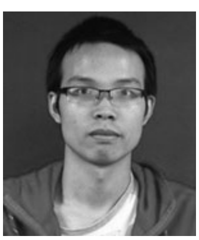

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