Compact Patch Rectennas Without Impedance Matching Network for Wireless Power Transmission

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***Abstract*— In microwave wireless power receivers, impedance matching networks can maximize power transmission from RF to dc. However, they require circuit components and physical space to implement. To circumvent the problem, we present two compact patch rectennas that do not require matching networks. They comprise a patch antenna and rectifying Schottky diodes which are mounted on the ground plane and connected to the patch antenna through metallic vias. The positions of the vias are chosen in such a way that the input impedance of the antenna and that of the rectifying units are conjugately matched. The two rectenna types are all fabricated and tested: one with one rectifying unit and the other with double rectifying units, respectively. Measurements show that the rectenna with the single rectifying unit has the peak RF-dc conversion efficiency of 77% at 2.45 GHz and the dynamic power range (>60%) is 10 dB. The rectenna with the double rectifying units has the peak conversion efficiency of 74.14% at 2.45 GHz and the dynamic power range (>60%) is 10 dB. Both rectennas are good candidates for integrated microwave wireless power receivers due to the removal of the impedance matching networks and the suppression of harmonic components.**

***Index Terms*— Compact design, impedance matching network, microwave power transmission, rectenna, rectification, Schottky diode, wireless power transfer (WPT).**

I. Introduction

IMPEDANCE matching networks are essential for maximizing power transmission from a source to a load in the active circuit systems. They have been widely employed in amplifiers, filters, and antennas [1]–[4]. Various matching networks have been proposed [5]–[8], including capacitive impedance matching networks [9]. The design of impedance matching networks may not be just electrical: it also needs to consider circuit complexity and physical space that mount the matching networks.

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Ever since Nikola Tesla successfully demonstrated the concept of wireless power transfer (WPT) [10] in the 19th century, WPT technology has attracted the attention of researchers [11]–[15]. Attempts have been made to improve WPT system efficiency, including the RF-to-dc conversion efficiency [16]–[20]. Research has also been conducted to make a WPT receiver more compact; it has led to the development of the rectenna that integrates a receiving antenna with an RF-to-dc rectifier.

A conventional rectenna is shown in [21] and [23]. It is generally made of five parts: a receiving antenna, an impedance matching network, a Schottky diode, a low-pass filter, and a dc load. It brings or transforms the impedance of the rectifier (or the diode) to the conjugate of the input impedance of the antenna to achieve maximum power transmission from the antenna to the diode. It is critical for the efficient performance of a WPT rectenna receiver. Therefore, a suitable impedance matching network is required and is essential in the designs of the conventional rectennas.

One way to design the matching network is first to develop or select an antenna that has an input impedance of 50 Ω. Then the matching network is developed to bring or transform the input impedance of the rectifier to the 50 Ω (realizing the conjugate match), as shown in Fig. 1(a). Another more general way is to drop the 50 Ω requirement but design the matching network that brings or transforms the rectifier's (or diode's) input impedance to the conjugate of the antenna input impedance [see Fig. 1(b)]. For example, in [24], a broadband antenna impedance is tuned successfully via symmetrical arms, and a pair of radial stubs are inserted to provide a complex conjugate match to the impedance of a rectifier. The proposed rectenna realizes a maximum measured conversion efficiency of 75% at 0.95 GHz. In [25], a dual-band rectenna uses a rectangular patch to adjust the antenna impedance and realize conjugate matching between the antenna and the rectifying diode, achieving the highest measured efficiency of 70% at 2.45 GHz. These methods adjust the antenna input impedance by adding extra structures to enable the conjugate matching of the antenna impedance to the Schottky diode impedance.

In all the above cases, the matching network or extra structures ask for a circuit area for mounting the matching network components, which is not conducive to compact rectenna design but increases the design complexity. In addition, the matching network may lead to unwanted insertion losses.

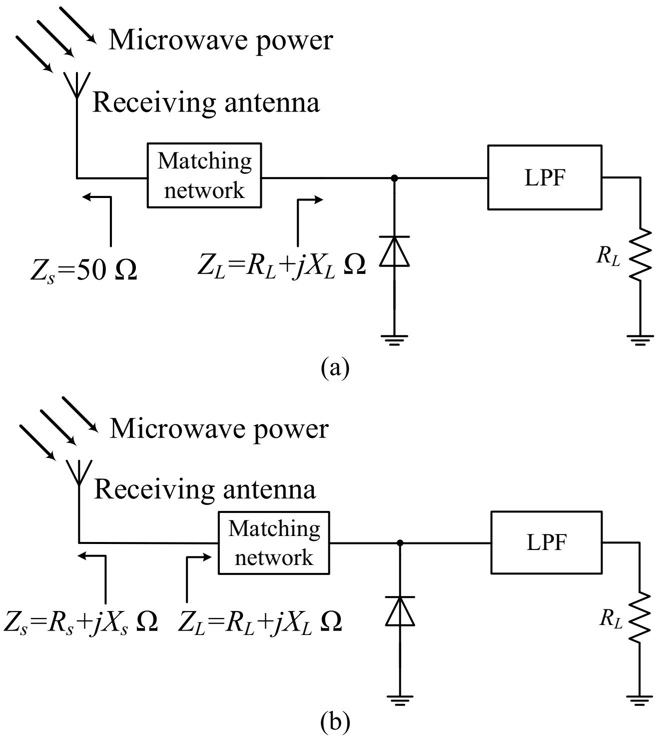


Fig. 1. Conventional rectenna with the impedance matching network. Impedance matching to (a) 50 and (b) $R_s + jX_s$.

Therefore, simplification or even elimination of the impedance matching networks is much desired in a compact rectenna design.

In this article, we present the method that does not require the matching network but can realize the conjugate impedance match directly between the rectifier and the antenna (in our case, the microstrip patch antenna). The method involves simulation of the antenna and identification of a suitable position in the antenna structure for direct mounting of the diode. The position is found in such a way that antenna impedance is conjugately matched with the diode impedance. The proposed method has a high rectification efficiency while being simple and adding no extra circuit complexity. In addition, we propose a dual rectifying unit rectenna (DRUR) that increases the received power handling capability.

The article is organized in the following manner. Section II will introduce the direct impedance conjugate matching without the network for a rectenna structure. Section III will present the analysis and experiments of a single rectifying unit rectenna (SRUR). Section IV will introduce the proposed DRUR along with the experimental verification and the measurement results. Finally, Section V concludes this article.

II. Impedance Conjugate Matching Without the Matching Network in the Rectenna Structure

With reference to Fig. 1(b), it is easy to see that the maximum transmitted power P_L is achieved when the source (or antenna) impedance $Z_s = R_s + jX_s$ is conjugately matched to the load impedance $Z_L = R_L + jX_L$. In other words, when

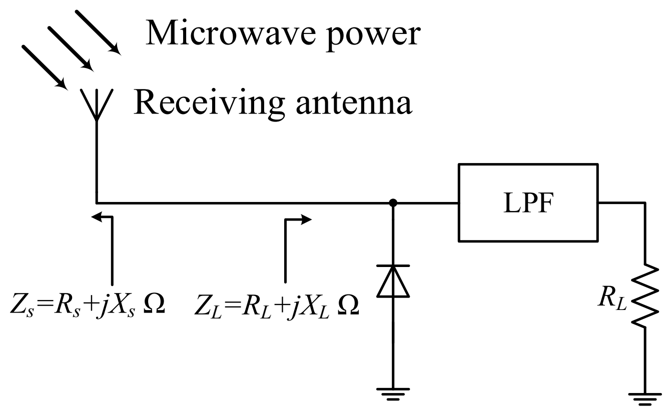


Fig. 2. Rectenna without the impedance matching network.

$R_s = R_L$ and $X_L = -X_s$

$$P_L = P_{L,\mathrm{MAX}} = \frac{1}{2}\frac{|V_s|^2 R_L}{(R_s + R_L)^2 + (X_s + X_L)^2}. \tag{1}$$

Similar to the design idea for the active integrated antennas [26], in a rectenna design, we construct the rectenna in such a way that its input impedance is the conjugate of that of the rectifier input impedance. Thus, we eliminate the need for a matching circuit, as shown in Fig. 2. The circuit configuration of Fig. 2 without the impedance matching network has three advantages.

1) It uses no extra components and associated physical space to achieve maximum power transfer.
2) It eliminates the potential insertion loss caused by the matching network.
3) It makes the planar circuit integration easy (as shown in this article with the microstrip antenna).

III. Microstrip Patch Rectenna of a Single Rectifying Unit

In this section, we present the development of the rectenna with a single rectifying unit. The antenna is the microstrip patch antenna.

A. Patch Antenna

The microstrip patch antennas have been well studied [27], [28]. They are of low profile, small size, lightweight, simple structure, low cost, and easy for integration. A rectangular microstrip patch antenna is used as the receiving antenna in this work (see Fig. 3). The dot is the feed point that is connected to the rectifying diode. The model of the patch antenna is shown in Fig. 4. The dimensions of the patch, side length L, with W, and feed location y can be calculated with (2)–(4), respectively

$$L = \frac{c}{2f\sqrt{\varepsilon_{\mathrm{re}}}} - 2\Delta l \tag{2}$$

$$W = \frac{c}{2f}\left(\frac{\varepsilon_{\mathrm{re}} + 1}{2}\right)^{-\frac{1}{2}} \tag{3}$$

$$y = \frac{L}{2}\left(1 - \frac{1}{\sqrt{\varepsilon_{\mathrm{re}}}}\right) \tag{4}$$

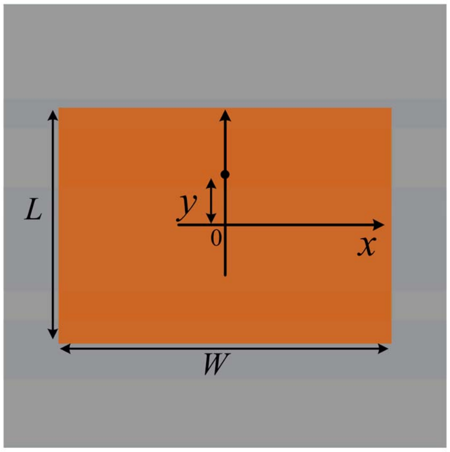


Fig. 3. Rectangular patch antenna.

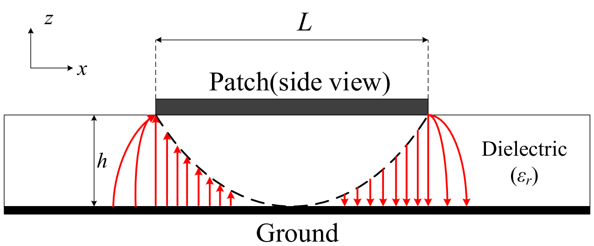


Fig. 4. Model of the patch antenna.

TABLE I
DIMENSIONS OF RECTANGULAR PATCH ANTENNA (UNITS: mm)

Dimension	L	W	y
Theoretical value	38.3	49.5	7.88
Optimized value	37.3	52.64	8.1

where f is the operating frequency of the patch antenna (which is 2.45 GHz in our case), ε_{re} is the equivalent dielectric constant, and Δl is the equivalent radiation gap width.

We fabricated the patch: an F4B-2 double-sided copper-clad board with the relative permittivity of 2.65, the loss angle tangent of 0.005, the thickness of 1 mm, and the copper cladding thickness of 18 μm. The theoretically calculated L, W, y, and their corresponding simulation-optimized values are shown in Table I. The patch antenna was designed on a 70 $\times$ 70 mm^2 printed circuit board with the input impedance of the patch chosen to be 50 Ω.

The 2.45 GHz patch antenna was tested. Fig. 5 shows the simulated and measured $|S_{11}|$. The results show that the measured $|S_{11}|$ reaches -17 dB, which represents a good impedance match to meet the antenna design requirements, and the antenna can thus be used effectively in 2.45 GHz wireless power transmission systems. Fig. 6 shows the measured and simulated 2-D patterns over the E- and H-plane of the rectangular antenna at 2.45 GHz. From the figure, we know that the gain of the patch is 6.33 dB. The E- and H-plane of the antenna obtained from the simulations show good general agreement with the measured results. The simulated 3-D pattern with directivities is also shown in Fig. 6

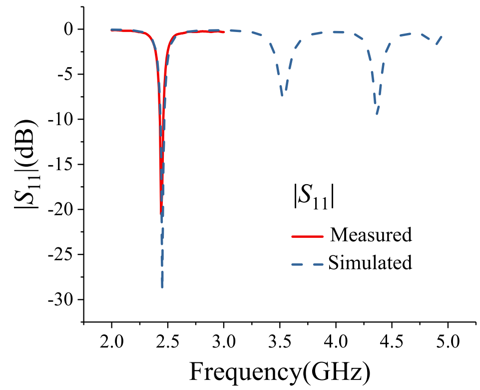


Fig. 5. Simulated and measured $|S_{11}|$ of the rectangular antenna versus frequency.

We can use commercial electromagnetic software to determine the impedance position. In other words, the impedance value at any position on the patch antenna can be simulated using the HFSS software. Because the patch is symmetrical about (0, 0) (the center of the rectangular patch), only the impedance at ($x > 0$, $y > 0$) is computed. Table II shows antenna impedance distribution ($x > 0$, $y > 0$). From the table, we can see that the real part of the impedance increases as the y increases when x is fixed. The real and imaginary parts both remain essentially constant when y is fixed. From the center of the patch to its edge, the real part of the impedance varies from 0 to 80 Ω and the imaginary impedance varies between 0 and 60 Ω. The closer to the edge of the antenna, the larger real and imaginary parts of the impedance. These results form the basis of the next step in impedance conjugate matching design using a Schottky diode.

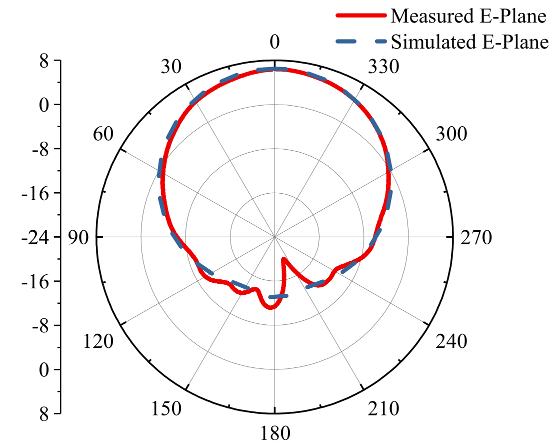
B. Schottky Diode

When rectenna design is carried out, Schottky diode with low junction capacitance and resistance, high cut-off frequency, and short reverse recovery time is considered. Therefore, the HSMS-286 series Schottky diode (Avago Technologies) is selected here because of its low cost and it is surface-mounted.

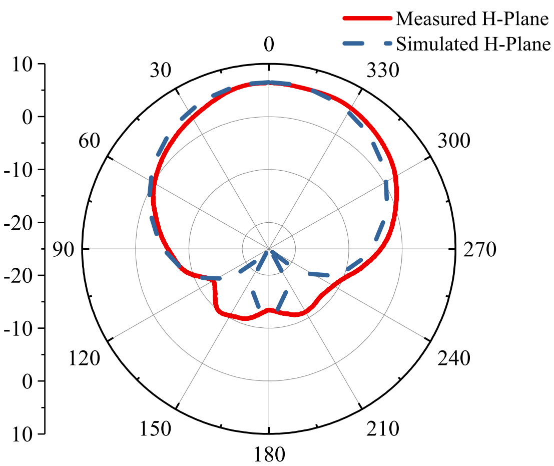
The input impedance of the HSMS-286F diode at an input power of 14 dBm and with a load of 150 Ω can be calculated using the Advanced Design System (ADS) software with its harmonic balance, and large-signal S-parameter controls to be Z_d = 90.04 – j63.16 Ω. This impedance is approximately conjugate of the impedance at the patch antenna feed point of (11, 14), $Z_{\text{ant}} = 71.17 + \text{j}50.62\ \Omega$, which is at $\{x = 11$ mm, $y = 14$ mm$\}$, where settings of coordinate axes are shown in Fig. 3. The voltage reflection coefficient for power wave is defined as [29]

$$\Gamma = S_{11} = \frac{Z_d - Z_{ant}^*}{Z_d + Z_{ant}}. \quad (5)$$

Here, $|S_{11}|$ is equal to -17.07 dB when the calculated diode impedance Z_d is 90.04–j63.16 Ω, and the simulated patch antenna impedance is 71.17 + j50.62 Ω, as shown in Fig. 7. It represents a good impedance match between the diode and



(a)



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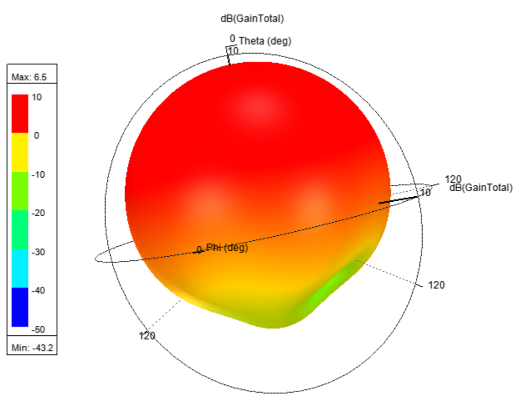


(c)

Fig. 6. Simulated radiation patterns at 2.45 GHz. (a) Pattern over the E-plane. (b) Pattern over the H-plane. (c) Three-dimensional pattern.

the antenna at 2.45 GHz, and the Schottky diode's impedance meets our design requirements.

C. Integration of the Diode With the Patch to Form the SRUR

Now, the HSMS-286F diode is mounted at the patch feed point (11, 14) on the ground plane of the patch (see Fig. 8).

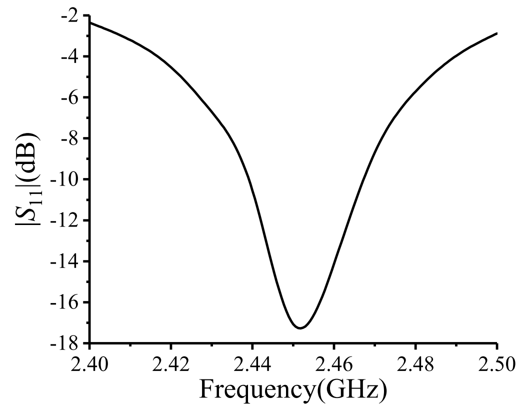
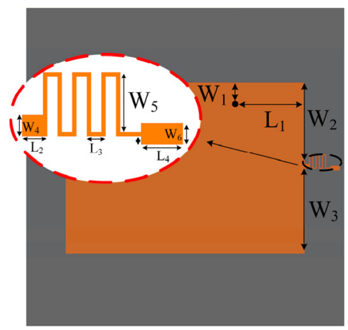
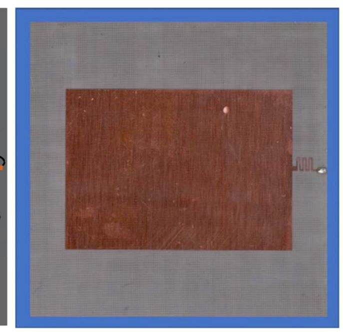


Fig. 7. Simulated $|S_{11}|$ between the antenna and the HSMS-286F versus frequency. The diode impedance 90.04–j63.16 Ω is obtained at 2.45 GHz with an input power of 14 dBm and a dc load of 150 Ω.



(a)



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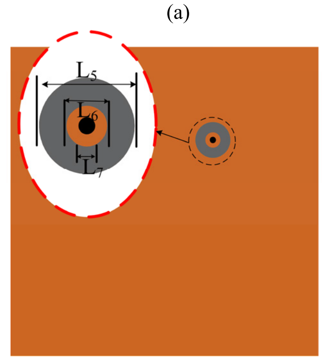

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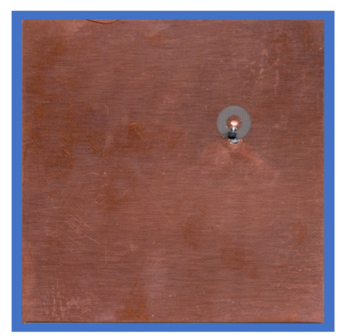

(d)

Fig. 8. (a) and (b) are the top views of the SRUR design and prototype, respectively. (c) and (d) are the bottom views of the SRUR design and prototype, respectively.

A via is used to connect the diode to the radiation patch. The dc output is obtained by having a high impedance line which also serves as an RF choke reflecting the harmonics generated by the diode back to the circuit and thus improving the rectenna's rectification efficiency. In addition, the patch also serves as a low-pass capacitor, saving one more element. The dimensions of the proposed SRUR are shown in Table III.

The simulated radiation patterns and the gains of the antennas are shown in Fig. 9. They are nearly the same as those of Fig. 6. It means that drilling of the metalized via-hole and insertion of the diode has almost no effect on the performance of the rectangular patch antenna.

The hardware measurement was conducted to test the efficiency of the proposed rectenna; the setup is shown in Fig. 10. Because the diode is integrated into the antenna, $|S_{11}|$ of the

TABLE II
IMPEDANCE DISTRIBUTION FOR 2.45 GHz PATCH ANTENNA

y=14.0mm	70.48+j52.41	70.43+j51.8	73.96+j49.55	**71.17+j50.62**	72.46+j48.02
y=12.0mm	66.25+j40.44	63.54+j41.61	68.48+j36.94	62.4+j41.34	69.55+j36.74
y=8.0mm	42.17+j12.32	41.5+j14.92	41.68+j14.98	42.36+j12.46	42.72+j11.69
y=4.0mm	11.2+j7.8	0.18+j9.6	11.3+j6.34	0.19+j6.98	12 +j3.15
y=0.0mm	0.07+j10.73	0.1+j11.06	0.06+j8.98	0.07+j7.37	0.13+j7.2
Impedance (units: Ω)	x=0.0 mm	x=4.0 mm	x=8.0 mm	x=11.0 mm	x=16.0 mm

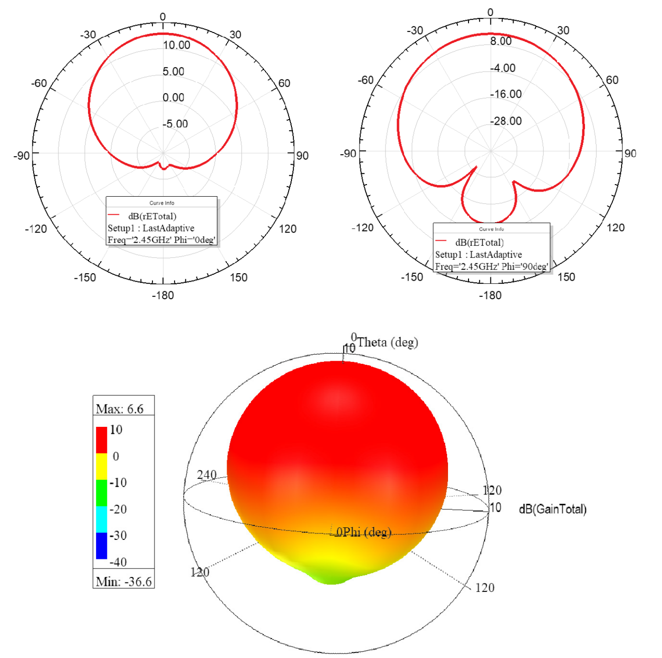

Fig. 9. Simulated three-dimensional radiation patterns and the patterns on the E- and H-plane for the proposed SRUR at 2.45 GHz.

TABLE III
DIMENSIONS OF PROPOSED SRUR (UNITS: mm)

L_1	L_2	L_3	L_4	L_5	L_6	L_7
15.32	1.00	0.50	2.00	8.00	3.40	1.40
W_1	W_2	W_3	W_4	W_5	W_6	
4.65	17.75	18.55	1.00	3.00	1.00	

rectenna cannot be measured directly. Instead, we used an Agilent signal generator (model E8267C) and connected it to a standard gain horn antenna (model HD-22SGAH10N) manufactured from Xi'an Hengda Microwave Technology Development Co. The horn radiated onto the rectenna and was placed at a distance of 1.1 m from the rectenna. A dc load R_L was connected to the diode, and the voltage V_{dc} at the load was measured with a multimeter. The rectified dc power is obtained using the equation $P_{\mathrm{out}} = V_{\mathrm{dc}} \times V_{\mathrm{dc}}/\ R_L$.

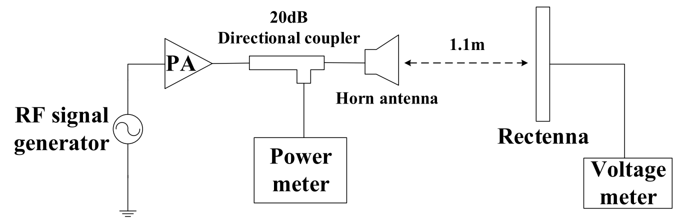

Fig. 10. Topology of the measurement system.

The power available to the transmitting horn antenna is measured using a power meter; the RF power received by the patch rectenna can then be estimated using the Friis transmission equation

$$P_r = P_t + G_t + G_r + 20\log_{10}\frac{\lambda}{4\pi r} \tag{6}$$

where P_r is the received power in dBm, P_t is the power obtained from the power meter in dBm, G_t and G_r are the gains of the horn and the rectenna in dB, respectively, λ is the wavelength, and r is the distance between the horn and the rectenna ($r = 1.1$ m in our case).

The conversion efficiency is then

$$\eta = \frac{P_{\mathrm{out}}}{P_r} \times 100\%. \tag{7}$$

The measurements were conducted at 2.45 GHz with $R_L =$ 50, 100, 150, and 200 Ω, respectively, and the received power P_r varied from 8 to 18 dBm (by changing the power of the Agilent signal generator). The measured efficiencies versus the received power P_r for the proposed SRUR are shown in Fig. 11. The measured efficiencies versus the dc load R_L are plotted in Fig. 12 at the different received powers P_r of 14, 15, 16, 17, and 18 dBm, respectively.

Fig. 11 shows that as the received power P_r increases, the conversion efficiency increase first, reaches the peak, and then drops. In other words, there is an optimum P_r where the highest efficiency is achieved. This is due to the nonlinear characteristics of the diode: at the low power levels, the diode works in a linear region, and at a relatively high power region, it works at a nonlinear averaged region. The rectifying efficiency is greater than 60% from 8 to 18 dBm when the dc load is 100 Ω. Likewise, Fig. 12 presents a very similar variation between the efficiency and the dc load R_L. There is an optimum load with which the efficiency reaches its peak. In our case, the optimum load is 110 Ω with a peak efficiency of 77%.

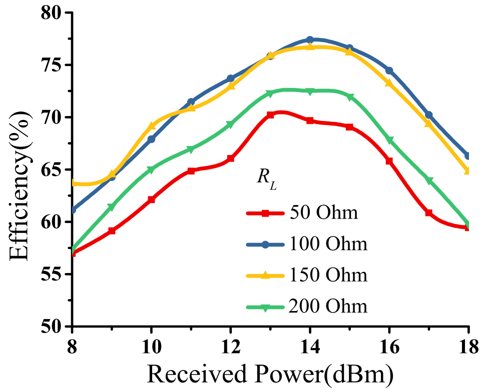

Fig. 11. Measured RF-dc conversion efficiency η of the proposed SRUR versus received power P_r.

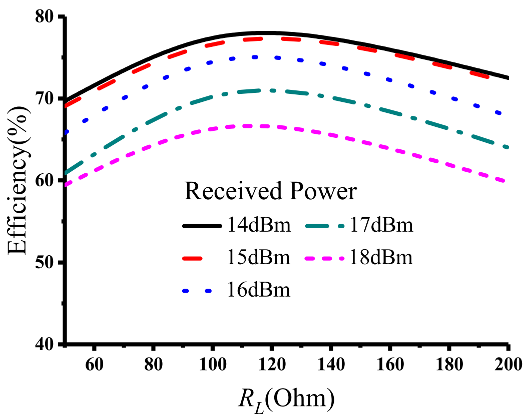

Fig. 12. Measured efficiency η of the proposed SRUR versus the dc load R_L.

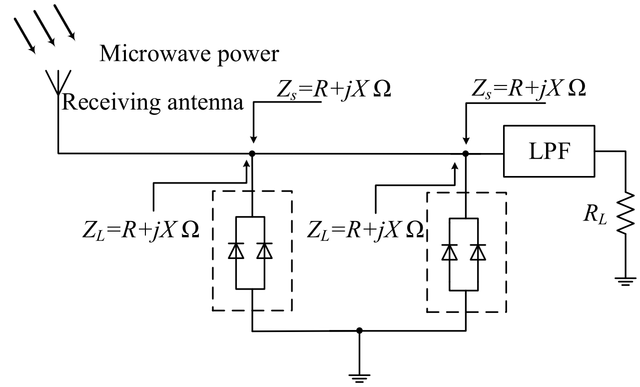

Fig. 13. Schematic of dual-rectifying unit rectenna.

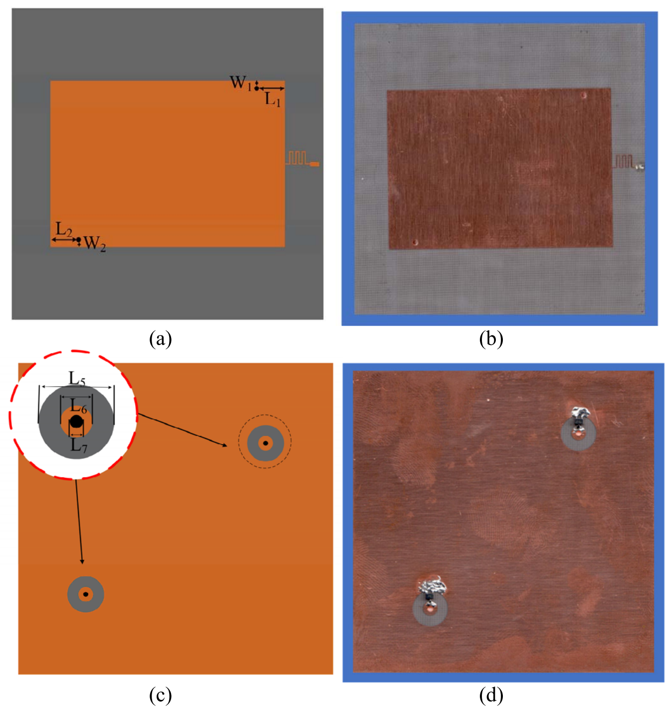

Fig. 14. (a) and (b) are the top views of the DRUR design and prototype, respectively. (c) and (d) are the bottom views of the DRUR design and prototype, respectively.

IV. Double Rectifying Unit Rectenna

In the conventional rectennas, to enable high power handling capability, a three-port power divider is often used to connect the patch antenna to the two rectifying units. As a result, microwave power received by the receiving antenna will pass through the power divider and flow to the two rectifying circuits for rectification.

To avoid additional space and insertion losses associated with the power dividers, we adopt the rectenna design method from Section III. We employ four identical diodes and connect them to the patch antenna through two metalized via-holes at the two positions that present the conjugate impedance of the antenna impedance. The schematic of DRUR is shown in Fig. 13. Two positions are symmetric about the center. The patch antenna can effectively distribute its power to two rectifying units and thus double the power handling capacity without power dividers while maintaining the high rectified antenna RF-to-dc conversion efficiency.

In our case, the two metalized via-hole positions are at $\{x = 20\text{ mm}, y = 17\text{ mm}\}$ and $\{x = -20\text{ mm}, y = -17\text{ mm}\}$ (referred to Fig. 3), respectively. The two Schottky diodes are connected in parallel and form a pair. Each pair is soldered and connect to the patch through each hole (see Fig. 14). The simulated impedance of the parallel-connected-diode pair is approximated to be 64.37–j41.33 Ω at an input power of 17 dBm for a dc load of 100 Ω. The final dimensions of the double rectifying unit rectenna are shown in Table IV.

TABLE IV
DIMENSIONS OF PROPOSED DRUR (UNITS: mm)

L_1	L_2	W_1	W_2
6.32	6.32	1.65	1.65
L_5	L_6	L_7	
8.00	3.40	1.40	

Simulations were conducted with HFSS and the simulated $|S_{11}|$ of is −11.46 dB, $|S_{22}|$ is −11.57 dB, and $|S_{21}|$ is

TABLE V
COMPARISON WITH RECENTLY REPORTED RECTENNAS

Reference	Frequency (GHz)	Use of impedance matching networks	Maximum conversion efficiency (%)	Input power level (dBm)	Dimensions (mm^2)
[21]	2.4, 5.8	Yes	63	12.3	$1.32\lambda_g \times 0.75\lambda_g$
[22]	0.925, 0.182, 2.17	Yes	40	N.A.	$1.45\lambda_g \times 1.27\lambda_g$
[23]	2.45	Yes	72.5	13	$2\lambda_g \times 2\lambda_g$
[24]	0.9–1.1, 1.8–2.5	No	75	20	$1.6\lambda_g \times 1.6\lambda_g$
[25]	2.45, 5.8	No	70	16.814	$0.8\lambda_g \times 0.43\lambda_g$
[30]	2–3.1	Yes	70	5	$0.6\lambda_g \times 0.86\lambda_g$
This work	**2.45**	**No**	**77**	**14**	$\mathbf{0.93\lambda_g \times 0.93\lambda_g}$

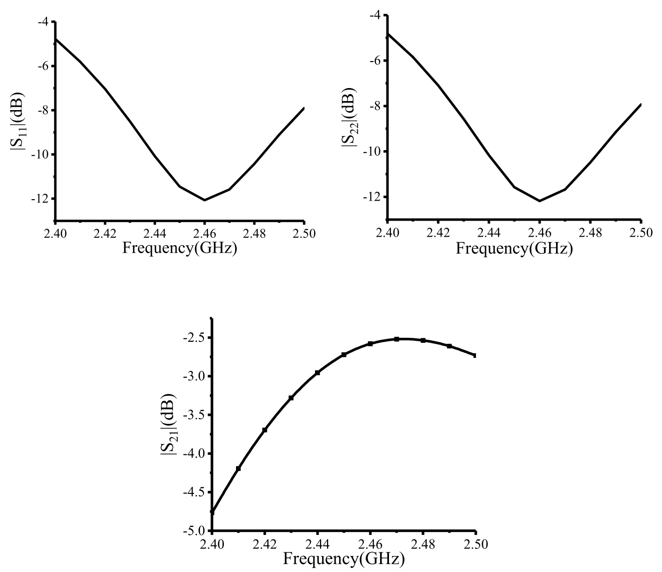

Fig. 15. Simulated S-parameters of the proposed DRUR when the impedance of parallel-diode pair is set as 64.37–j41.33 Ω at an input power of 17 dBm for a dc load of 100 Ω.

-2.72 dB, which meet our design requirements for the proposed DRUR, as shown in Fig. 15. Note that the relatively high mutual coupling $|S_{21}|$ does not affect the performance since it already considered when the position of antenna impedance is located. The rectenna output was also designed with a high impedance line as the RF choke to reflect back the high harmonics to the diode and improve the rectification efficiency of the rectenna in a manner similar to the above-mentioned SRUR design.

Fig. 16 shows the radiation patterns of the rectenna when the feed ports are set to have an impedance of 64.37–j41.33 Ω. They are nearly the same as the patterns when the impedance is 50 Ω. This means that the rectifying units have almost no effect on the antenna performance.

The efficiency measurement setup for the DRUR is the same as that for the SRUR, except the SRUR has been replaced with the proposed DRUR. Again, the frequency is 2.45 GHz, and the dc load was $R_L = 50$, 100, 150, and 200 Ω, respectively. Fig. 17 shows the measured DRUR efficiency versus the received power, and Fig. 18 presents the measured rectenna efficiency versus the dc load. Similar to the SRUR, the DRUR presents the optimum rectenna efficiency when the received

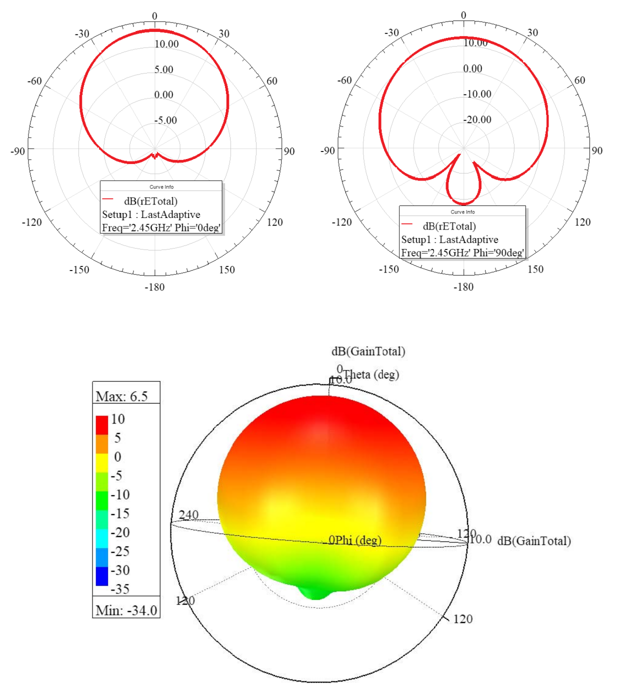

Fig. 16. Simulated three-dimensional patterns and the two-dimensional patterns on the E- and H-plane of the proposed DRUR at 2.45 GHz.

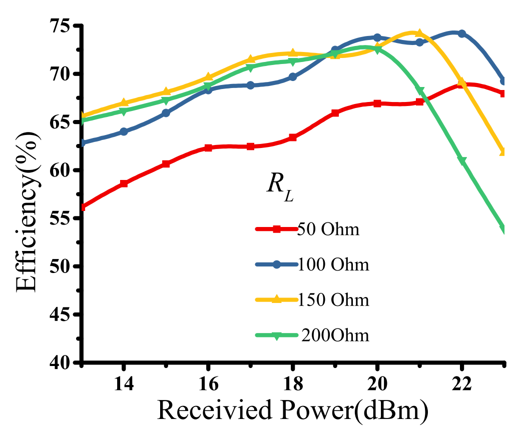

Fig. 17. Measured conversion efficiency η of the proposed DRUR versus received power P_r.

power or load changes. For example, the maximum efficiency of 74.14% is obtained at $R_L = 100\Omega$ when the received power of the proposed DRUR is 22 dBm.

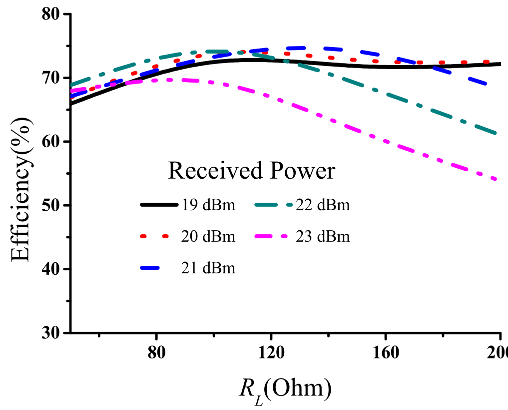

Fig. 18. Measured conversion efficiency η of the proposed DRUR versus dc load R_L.

The proposed rectenna is also compared with the existing rectennas [21]–[25], [30]: Table V presents the comparison results (where λ_g is the wavelength at 2.45 GHz). As seen, our proposed design presents better RF-dc conversion efficiency and less circuit complexity (without output matching networks required).

V. Conclusion

We have presented new patch rectenna structures that do not require impedance matching networks at 2.45 GHz for high conversion efficiency. The patch antenna is directly connected to the rectifying diode through a metallic via at the position where the antenna input impedance and the rectifier's input impedance are conjugated matched. Two types of rectenna have been developed and fabricated: one with a single rectifying unit and the other one with double rectifying units. The proposed rectennas show very good performances at different transmitted power levels. The measured conversion efficiency of the SRUR can reach a maximum of 77% at a received power of 14 dBm. The dynamic input power range of the single rectifying unit for a conversion efficiency greater than 60% reaches 10 dB over the received power from 8 to 18 dBm. The double rectifying unit rectenna's measured efficiency can reach a maximum of 74.14% at a received power of 22 dBm. The dynamic input power range of the double rectifying units for a conversion rate larger than 60% can reach 10 dB over the received power range from 13 to 23 dBm.

In comparison with the existing rectennas, the proposed rectennas show overall better performances. It means that the proposed rectennas can be used for wireless power transmission applications. In addition, the design of the proposed rectennas is easy to follow, and they can be optimized for different uses.

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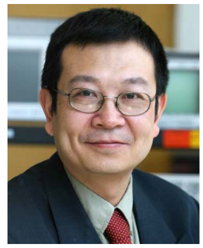

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