Codesign of a Schottky Diode's and Loop Antenna's Impedances for Dual-Band Wireless Power Transmission

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***Abstract*—In this letter, we proposed a simple design method of rectenna for dual-band wireless power transmission (WPT). This method introduces a codesign of a Schottky's diode and antenna's impedance at 2.45 and 5.8 GHz, which are conjugate matching, respectively. One example shows the design. The rectifying diode presents capacitive impedance, and inductive impedance can be given by a loop antenna through optimization. A Schottky diode is directly connected into the dual-band antenna. An uncomplicated structure is achieved without additional matching network and filtering. For validation, a rectenna working at 2.45 and 5.8 GHz was designed, fabricated, and tested. The measurement results show that a maximum conversion efficiency of 70% with a load resistance of 400 Ω was realized at 2.45 GHz. At 5.8 GHz, the peak efficiency is 61.5% with a load resistance of 200 Ω. This rectenna can be used to charge electronic devices, such as wireless sensors.**

***Index Terms*—Codesign, conjugation matching, dual band, high efficiency, rectenna, wireless power transmission (WPT).**

I. Introduction

RECENTLY, wireless power transmission (WPT) has attracted special attention since it is potential to charge the electronic devices that gain power hard through wires [1], such as wearable medical sensors, wireless sensors, and so on. In order to output more dc power, high efficiency and high power are required in a WPT system.

Rectenna (rectifier + antenna) can receive radio frequency (RF) power and convert it to dc power [2]–[6]. Thus, the RF-dc conversion efficiency of a rectenna is closely related to the performance of a WPT system. Some research teams have given several methods to improve the performance of rectenna, such as dipole antennas [7],[8], loop antennas [9]–[11], dual-frequency antennas [12]–[14], fractal antennas [15], bent triangular antennas [16], and so on. However, most of those rectennas focus on the energy harvester (EH) that requires the RF power density is low. When the input power is high, the RF-dc conversion efficiency of those designs becomes low, since the efficiency depends on the power level owing to nonlinear characteristics of rectifying diodes.

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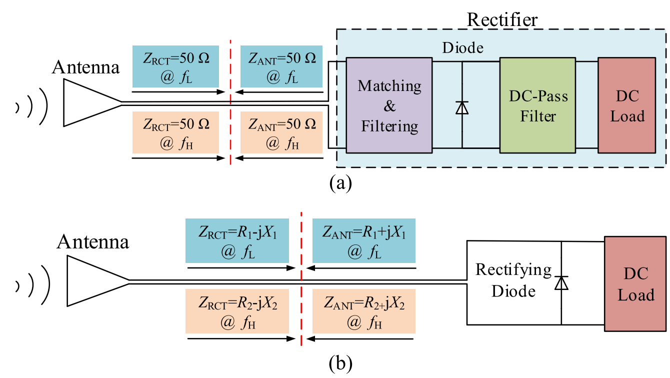


Fig. 1. Circuit configuration of the (a) conversional and (b) proposed dual-band rectenna.

In this letter, a simple dual-band rectenna based on codesign of a Schottky diode's and a loop antenna's impedances to achieve high efficiency for WPT is presented. This method has been published in [17] and [18] for single-frequency application. The design method for the dual-band WPT is discussed in this letter. A rectenna operating at 2.45 and 5.8 GHz is fabricated with an HSMS286 diode directly connecting into the loop antenna. The impedances of the diode and antenna are conjugate matching at the fundamental frequency to enhance the power conversion efficiency. Neither microstrip line with 50 Ω characteristic impedance nor matching circuit network is employed between the antenna and rectifying diode. The proposed rectenna is simple without matching circuit stubs and filter. RF-dc conversion efficiency of 70% at 2.45 GHz and 61.5% at 5.8 GHz is realized.

II. Principle and Design Method

A. Principle

A conversional dual-band rectenna schematic is shown in Fig. 1(a), in which a matching and filtering networks and a dc-pass filter are introduced to transfer the impedance of the rectifier to 50 Ω, then realize impedance matching between the antenna and rectifier at dual band. Usually, the matching and filtering networks will introduce insertion loss and increase the circuit size, which causes decrease in the RF-dc conversion efficiency and difficulty in system miniaturization. What is worse, in order to eliminate the possible effect of the rectifier circuit on antenna,

TABLE I
SPICE PARAMETERS OF AN HSMS286 DIODE

B_V	C_{j0}	I_S	R_S	V_{bi}
7 V	0.18 pF	0.005 μA	6 Ω	0.28 V

a long transmission line may be inserted in front of the matching network. This will further affect rectenna's performance.

Different from the traditional dual-band rectenna, we proposed another topology for conjugate matching between the antenna and rectifying diode at dual band, which removes the matching and filtering networks and dc-pass filter, as shown in Fig. 1(b). When the working frequency, input power, and dc load are determined, the input impedance of a Schottky diode can be given by $Z_{\mathrm{RCT}} = \mathrm{R} - j\mathrm{X}$. According to the transmission line theory, when the impedances of load and source are conjugate matching, the load can gain the maximum input power. Thus, in order to get more rectifying RF power, the impedance of the antenna can be optimized to achieve $Z_{\mathrm{ANT}} = \mathrm{R} + j\mathrm{X}$.

The conjugate matching structure owns the following advantages.

1) Maximizing the rectifying RF power. A small reflection coefficient will be realized thanks to conjugate matching between the antenna and rectifying diode.
2) Removing matching network and filters can realize reduction in insertion loss and circuit physics size.
3) Simplifying rectenna structure. A Schottky diode is directly connected into the antenna, which is small, easy processing, and integration.

Thus, it is a simple structure compared with the conventional dual-band rectenna. It is an alternative method to achieve impedance matching between the antenna and rectifying diode for the high RF-dc conversion efficiency at dual band.

B. Diode Impedance

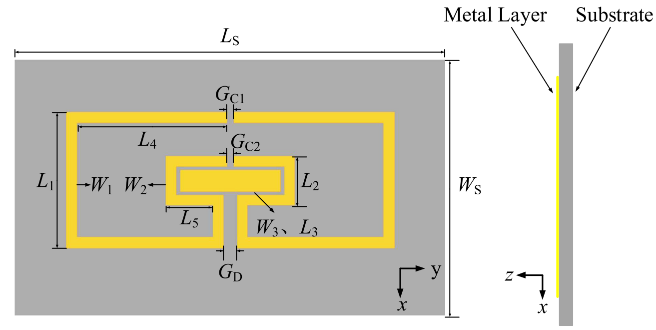
The rectifying diode plays a crucial role in a WPT system, which can convert RF power to dc power. Since the implementation of WPT, Schottky diodes have been widely employed in the rectifier circuit owing to their excellent performance in forward voltage, series resistance, and diode capacitance. An HSMS286 diode from Avago Technologies was applied in this design considering the operating frequency and input power level. Table I lists the main SPICE parameters of the HSMS286 diode.

According to the nonlinear diode model from Chang [7], the input impedance of the Schottky diode is

$$Z_D = \frac{\pi R_s}{\cos\theta_{on}\left(\frac{\theta_{on}}{\cos\theta_{on}} - \sin\theta_{on}\right) + j\omega R_s C_j\left(\frac{\pi-\theta_{on}}{\cos\theta_{on}} + \sin\theta_{on}\right)} \tag{1}$$

where R_s is the series resistance of the diode, θ_{on} is the turn-ON angle of the diode, and C_j is the junction capacitance of the diode. When the input power is 17 dBm and dc load is 400 Ω, from Table I and (1), the impedance of the HSMS286 at operating frequency of 2.45 GHz is 280 − j110 Ω. When the input power is 17 dBm and dc load is 200 Ω at 5.8 GHz, the impedance of the HSMS286 at fundamental frequency is 75 − j49 Ω.

Thus, the impedance of HSMS286 meets the design requirement that need to be capacitive impedance.



(a) (b)

Fig. 2. Configuration of the proposed antenna. (a) Top view. (b) Side view.

TABLE II
PARAMETERS OF THE LOOP ANTENNA

L_S	W_S	W_1	W_2	W_3	G_{C1}	G_{C2}
60	33	1.5	1.4	3	1	1
G_D	L_1	L_2	L_3	L_4	L_5	
2	19	6.8	14	21	6.6	

Unit: mm.

C. Dual-Band Antenna Design

As the loop antenna has been successfully applied in WPT systems, a dual-band loop antenna was also employed in this design as a receiving antenna. Through the aforementioned analyses, the impedances of the antenna and rectifying diode are conjugate matching at 2.45 and 5.8 GHz, respectively, so the input impedance of the antenna is determined by the diode. After optimization, the antenna's input impedances of 280 + j110 Ω and 75 + j49 Ω are obtained at 2.45 and 5.8 GHz, respectively.

The proposed loop antenna is shown in Fig. 2. There is no ground in the antenna for reducing effects of the rectenna on the antenna of wireless sensors. Two loops are used to receive RF power at different frequencies. The big one is for low frequency (2.45 GHz), and the small one is for high frequency (5.8 GHz). Three gaps are introduced in the loop antenna to weld the capacitance (dc block) and rectifying diode, i.e., the top one and middle one marked as G_{C1} and G_{C2} for capacitances, and the bottom one marked as G_D for the diode. The rectangle patch in the center can provide well tuning of the antenna's impedance by varying the parameters W_3 and L_3. The substrate of F4B is applied in this design with a thickness of 1 mm, a relative dielectric constant of 2.65, and loss tangent of 0.002. The parameters of the antenna are listed in Table II.

Fig. 3 shows how the antenna's impedance changes according to the parameter W_3 of the rectangle patch at different frequency. The final parameter W_3 of 3 mm is chosen to realize conjugate matching between the antenna and rectifying diode.

The fabricated loop antenna with a balun is shown in Fig. 4. In order to measure the proposed dual-band loop antenna, two

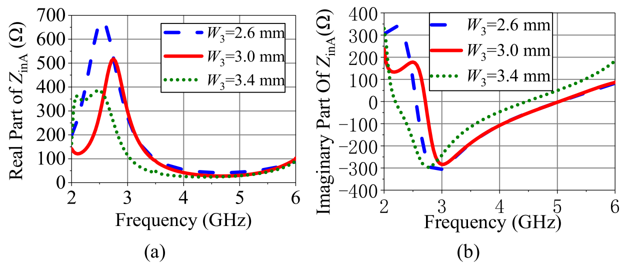


Fig. 3. Simulated (a) real and (b) imaginary part of the proposed antenna's impedance.

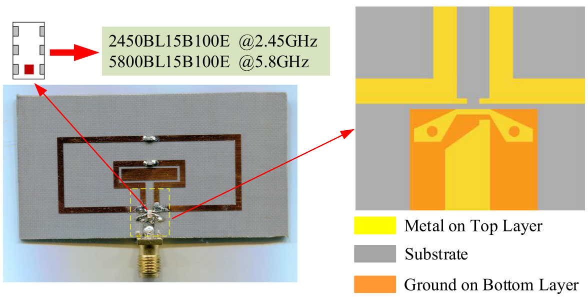


Fig. 4. Fabricated antenna with a balun.

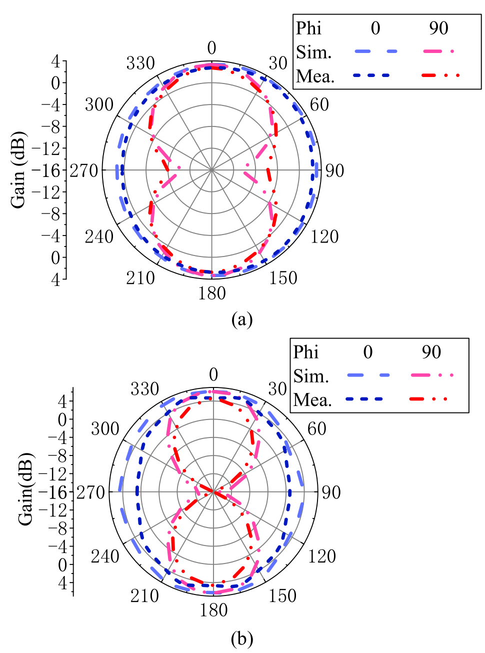


Fig. 5. Measured and simulated radiation patterns of the antenna in $\phi = 0°$ (*xoz* plane) and $\phi = 90°$ (*yoz* plane) at (a) 2.45 and (b) 5.8 GHz.

baluns 2450BL15B100 and 5800BL15B100 are employed to fed the antenna, respectively. They are both from Johanson Technology and operate at 2.45 and 5.8 GHz, respectively. Their package information and performance are given in [19] and [20].

Fig. 5 shows the simulated and measured gain at $\phi = 0°$ and $\phi = 90°$ of the proposed antenna taking reflection coefficient into consideration, which present a good agreement. The proposed antenna is polarized along the *y*-direction and has a maximum antenna gain of 3.2 and 5.4 dBi at 2.45 and 5.8 GHz, respectively.

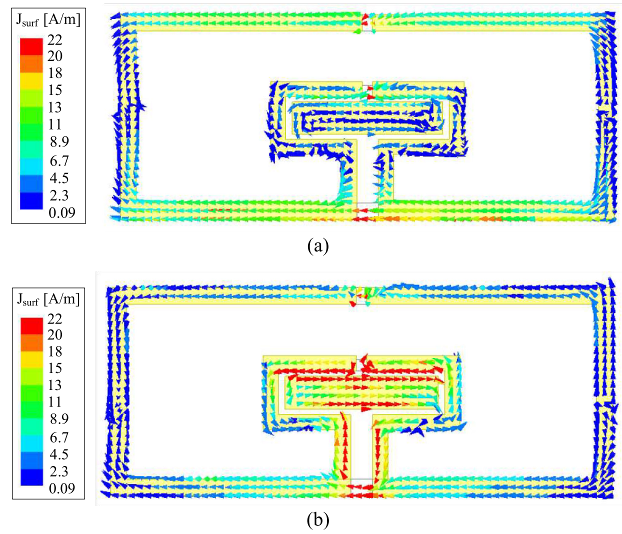


Fig. 6. Currents distribution on the proposed antenna at (a) 2.45 and (b) 5.8 GHz.

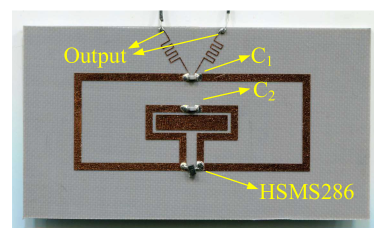


Fig. 7. Fabricated dual-band rectenna.

Fig. 6 depicts the currents distribution on the proposed loop antenna at 2.45 and 5.8 GHz. It is clear that the currents are mainly distributed in the outer ring at 2.45 GHz, which are symmetrical on the upper and lower parts. While at 5.8 GHz, the currents are mainly distributed in the inner ring. Thus, this antenna has good dual-band performance. The currents are stronger at the capacitor. However, it has no great effects on the current direction.

III. Experiment Results

Fig. 7 shows the fabricated rectenna. Two capacitances of 22 pF as dc block are inserted in the loop antenna, whose reactances are small at operating frequency of 2.45 and 5.8 GHz. A Schottky diode HSMS286 is directly connected into the loop antenna. Two meander lines are used to output dc power, and they are not parallel to each other so as to avoid RF coupling in measurements.

The measurement system of the proposed rectenna is shown in Fig. 8. An anechoic chamber provides the testing place. A signal generator is used to produce low RF power, which is amplified thousands of times after passing through the power amplifier. A direction coupler and a power meter are employed to monitor the output power of the power amplifier, and an attenuator of 20 dB is applied to protect the power meter from high RF power. Then, a standard horn antenna is connected to the output port of the direction coupler for transmitting the RF power. The under

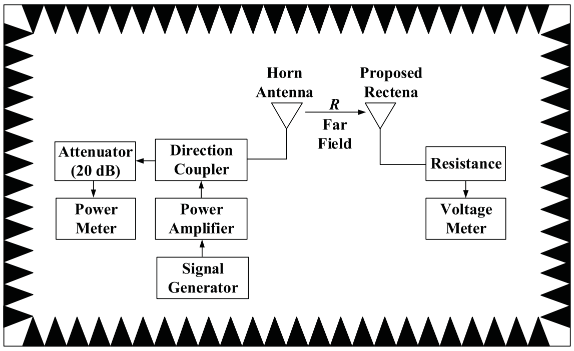
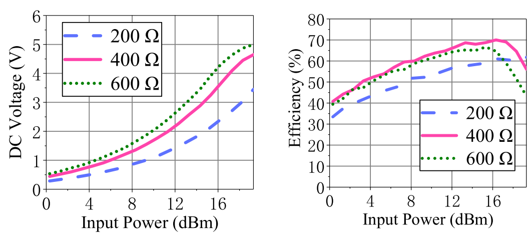


Fig. 8 Rectena measurement system.



(a) (b)

Fig. 9. Measured (a) dc voltage and (b) efficiency of the proposed rectenna as a function of the input power at 2.45 GHz.

test rectenna is placed in the far field of the transmitting antenna. Finally, a standard resistance box and a voltage meter are used to absorb dc power and to measure the dc voltage, respectively.

The proposed rectenna conversion efficiency can be given as

$$\eta = \frac{P_{\mathrm{dc}}}{P_r} \times 100\% = \frac{V_0^2}{R_L}\frac{1}{P_r} \times 100\% \tag{2}$$

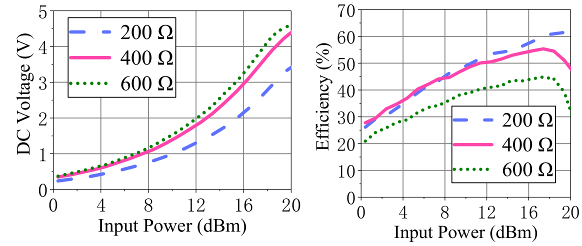
where P_{dc} is the output dc power, P_r is the received RF power by the antenna, V_0 is the dc voltage detected by the voltage meter, and R_L is the resistance as dc load. From the Friis transmission equation, P_r is given by

$$P_r = \frac{G_t G_r \lambda^2}{(4\pi R)^2} P_t \tag{3}$$

where G_t is the transmitting horn antenna gain, G_r is the receiving antenna gain, λ is the wavelength of input signal, P_t is the transmitting power from horn antenna, and R is the distance between the transmitting antenna and receiving antenna.

The rectenna operating at 2.45 and 5.8 GHz has been measured at $R_L = 200$, 400, and 600 Ω, respectively. The output dc voltage as a function of the input power is shown in Figs. 9(a) and 10(a). At the same input power, the dc voltage increases with the dc load. Then, the dc voltage will stabilize due to the power capacity and reverse breakdown voltage of the rectifying diode.

The measured efficiency of the rectenna versus input power is plotted in Figs. 9(b) and 10(b). It is clear that the efficiency of the rectenna increases with the dc load and decreases after reaching the optimum load of 400 Ω at 2.45 GHz. The maximum efficiency of 70% is realized. At 5.8 GHz, the optimum load changes to 200 Ω with a peak efficiency of 61.5%.



(a) (b)

Fig. 10. Measured (a) dc voltage and (b) efficiency of the proposed rectenna as a function of the input power at 5.8 GHz.

TABLE III
COMPARISON TO RECENTLY REPORTED RECTENNAS

Ref.	Freq. (GHz)	Max. η(%)	Input Power (dBm)	Circuit Size	Design Complexity
[11]	2.45 /5.8	65 /46	23 /23	$0.52\lambda_g \times 0.48\lambda_g$ $1.23\lambda_g \times 1.15\lambda_g$	Easy
[12]	5.2 /5.8	65.2 /64.8	16 /15	$2.17\lambda_g \times 1.08\lambda_g$ $2.42\lambda_g \times 1.21\lambda_g$	Medium
[13]	0.915 /2.45	40.7 /56.2	- /-	$0.32\lambda_g \times 0.29\lambda_g$ $0.86\lambda_g \times 0.78\lambda_g$	Medium
[14]	0.915 /2.45	37 /30	-9 /-9	$0.34\lambda_g \times 0.34\lambda_g$ $0.9\lambda_g \times 0.9\lambda_g$	Medium
[16]	0.98 /1.8	60 /17	7.2 /7.4	$0.64\lambda_g \times 0.56\lambda_g$ $1.54\lambda_g \times 1.4\lambda_g$	Medium
This work	**2.45 /5.8**	**70 /61.5**	**16.8 /19**	$\mathbf{0.8\lambda_g \times 0.43\lambda_g}$ $\mathbf{1.88\lambda_g \times 1.06\lambda_g}$	**Easy**

The proposed rectenna is compared with some prior works as shown in Table III. Different from the design methods given by [11]–[14] and [16], our design presents advantages on the RF-dc conversion efficiency, and design complexity by a rectifying diode directly connected into antenna, resulting in an uncomplicated structure. Most of the relevant works focus on the RF energy harvester, our design shows competitive overall power capacity and design concept compared with these low-power designs.

IV. CONCLUSION

A compact dual-band rectenna is designed, fabricated, and measured in this letter. The matching and filtering networks between antenna and rectifier in the conversional rectenna have been removed by the simple design method, which leads a compact structure. Codesign of a Schottky diode's and a loop antenna's impedances is introduced to achieve them conjugate matching at operating frequency of 2.45 and 5.8 GHz, resulting in a high RF-dc conversion efficiency. A maximum efficiency of 70% has been realized with the input power of 16.9 dBm (corresponding power density 1.3 mW/cm^2) at 2.45 GHz and at 5.8 GHz, the peak efficiency is 61.5% at 19 dBm.

The proposed rectenna design is suitable for antenna whose impedance is easy to tune. If the antenna's impedance is difficult to adjust, the condition of conjugate matching cannot be satisfied. The proposed rectenna design may be applied to the WPT system in the future.

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