A Patch Rectenna With an Integrated Impedance Matching Network and a Harmonic Recycling Filter

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***Abstract*—A new compact patch rectenna is presented in this letter. It consists of a rectangular patch antenna, a Schottky diode, and a harmonic filter with impedance matching to improve the rectifying efficiency. The filter is realized by a series short-ended one-eighth-wavelength microstrip transmission line, which also balances the capacitive impedance of the diode. The impedances of the diode and patch antenna are matched well by tuning the patch antenna and short-ended transmission line. A meander line is used to build a dc output path. For validation, a rectenna working at 2.45 GHz is designed, manufactured, and measured. A maximum rectifying efficiency of 82.2% is realized when the dc load is 400 Ω at an input power of 22.5 dBm. The proposed patch rectenna has potential applications such as rectenna arrays in wireless power transmission.**

***Index Terms*—Impedance matching, meander line, patch rectenna, Schottky diode, wireless power transmission (WPT).**

I. Introduction

The rectenna is a key component for receiving and converting microwave power into dc power in a wireless power transmission (WPT) system. Rectennas are widely implemented in electronic devices such as wireless powered sensors [1], [2], and microwave powered drones [3]. Rectennas are usually required to handle high power density and achieve high rectifying efficiency in WPT systems.

Several types of rectennas have been presented in previous papers, such as monopole rectennas [4], dipole rectennas [5]–[7], and patch antennas [8], [9]. A high-order harmonic rejection technique [10] and low-loss substrates [11] have been presented to realize high rectifying efficiency. Naoki Shinohara's group designed a GaAs Schottky diode with low series resistance and high breakdown voltage to realize a microwave rectifier with record efficiency [12]. Kenji Itoh's group designed a folded dipole rectenna with a bridge GaAs diode and realized a high rectifying efficiency [13]. Our group has chosen to research patch rectennas, which are more widely used in WPT, with a new design method to realize a high rectifying efficiency. A conventional patch rectenna is usually fabricated with a patch antenna and a rectifier that are both matched to 50 Ω. However, insertion losses are introduced, and the radiation performance of the patch antenna may also be affected by the impedance matching structures and harmonic suppression filters.

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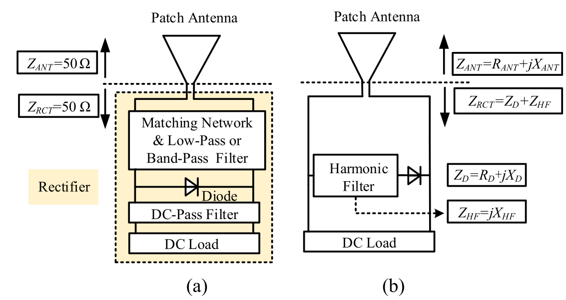

Fig. 1. (a) Conventional and (b) proposed rectenna configuration.

In this letter, we present a new patch rectenna that includes a Schottky diode with a series short-ended one-eighth-wavelength transmission line, a meander line as a dc output path, and a rectangular patch antenna to realize a simple design and high rectifying efficiency. A generic design process is presented that includes selecting the diode type and microwave power level. Then, as an example, a 2.45 GHz rectenna with a HSMS282 diode and a standard rectangular patch antenna is designed, fabricated, and measured. The diode and patch antenna are tuned to the same real part of impedance, which may not be 50 Ω. We remove unnecessary impedance matching networks, harmonic filters, and connecting lines with a characteristic impedance of 50 Ω between the patch antenna and rectifying diode. Meanwhile, dc pass filters are removed by applying the antenna's virtual ground. This facilitated design process achieves a 2.45 GHz rectenna with a compact size and high rectifying efficiency of 82.2%.

II. Principle and Design Method

A. Principle

The configuration of a conventional patch rectenna is shown in Fig. 1(a). The patch antenna has 50 Ω impedance. The input impedance of the rectifier is tuned to 50 Ω by a matching circuit, and there is a band- or low-pass filter to suppress the harmonics produced during rectifying. Extra insertion losses and circuit components will be introduced according to the matching network and harmonic suppression filter. These may also affect the radiation performance of the patch antenna.

We propose a design method to facilitate the matching networks and remove the filters between the patch antenna and

TABLE I
SPICE PARAMETERS OF AN HSM282 DIODE

B_v	C_j	I_s	R_s	P_b
15 V	0.7 pF	0.022 µA	6 Ω	0.25 V

diode. The rectenna configuration is shown in Fig. 1(b). According to circuit theory, maximum microwave power can be obtained by conjugate-matching the impedances of the patch antenna and the rectifier. Thus, we tune the patch antenna and compensate the impedance of the diode to make the impedances of these two components have identical real parts and opposite imaginary parts.

In our design, a higher rectifying efficiency is achieved by making the impedance of the patch antenna satisfy

$$Z_{ANT} = R_{ANT} + jX_{ANT} = (Z_D + Z_{HF})^* \tag{1}$$

where R_{ANT} and X_{ANT} are the real and imaginary parts of the antenna impedance Z_{ANT}, and Z_{HF} is the impedance of the harmonic filter structure, which is achieved by a series short-ended one-eighth-wavelength transmission line with $\mathrm{Z_{HF}} = j\mathrm{X_{HF}}$. The diode impedance is $\mathrm{Z_D} = \mathrm{R_D} + j\mathrm{X_D}$.

The new patch rectenna has two advantages:

1) Rectenna miniaturization. We remove unnecessary impedance matching networks and filters between the patch antenna and diode, and remove dc pass filters.
2) High rectifying efficiency with harmonic recycling. We use a series harmonic filter, which is a short-ended one-eighth-wavelength transmission line, to suppress the second harmonic $2f_0$ produced during diode rectification and compensate the diode capacitance at f_0. The third harmonic $3f_0$ is suppressed by the patch antenna itself.

B. Rectifying Diode Impedance

The Schottky diode is an essential part of a rectenna and converts microwave to dc power. It has lower series resistance, diode capacitance, and forward voltage than other diodes. The impedance of a Schottky diode is

$$Z_D = \frac{\pi R_s}{\cos\theta_{on}\left(\frac{\theta_{on}}{\cos\theta_{on}} - \sin\theta_{on}\right) + j\omega R_s C_j\left(\frac{\pi-\theta_{on}}{\cos\theta_{on}} + \sin\theta_{on}\right)} \tag{2}$$

where Rs, θ_{on}, and C_{j} are the series resistance, turn-on angle, and junction capacitance, respectively. The SPICE parameters of an HSM282 (Avago Tech.) are shown in Table I.

The impedance of an HSMS282 is 91-j125 Ω, which is obtained from (2) and verified by simulating the advanced design system (ADS) for an input power P_{IN}, dc load R_{L}, and frequency f_0 of 21 dBm, 450 Ω, and 2.45 GHz, respectively. Its impedance becomes 29-j97 Ω at $2f_0$ and 16-j58 Ω at $3f_0$ under the same conditions.

C. Patch Antenna Design

The impedance of a rectangular patch antenna is tunable when the feeding point is shifting on the broad-side edge. The real part of the patch antenna impedance should be the same as that of the rectifying diode. The imaginary parts of the diode impedance and antenna impedance are compensated by the short-ended one-eighth-wavelength transmission line.

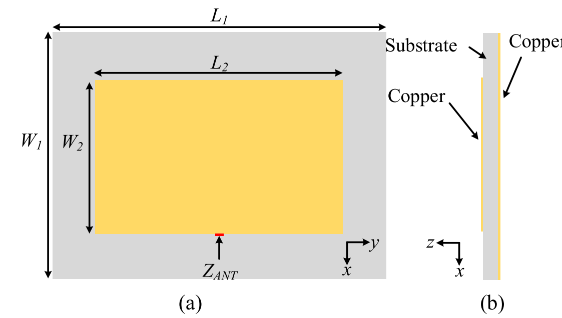

Fig. 2. Patch antenna configuration. (a) xoy-plane. (b) xoz-plane.

TABLE II
PATCH ANTENNA PARAMETERS

L_1	W_1	L_2	W_2
80 mm	61 mm	60 mm	37 mm

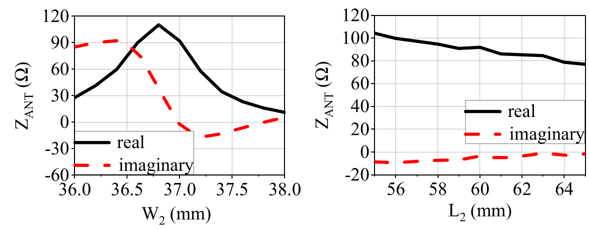

Fig. 3. Input impedance of the patch rectenna with respect to (a) W_2 and (b) L_2.

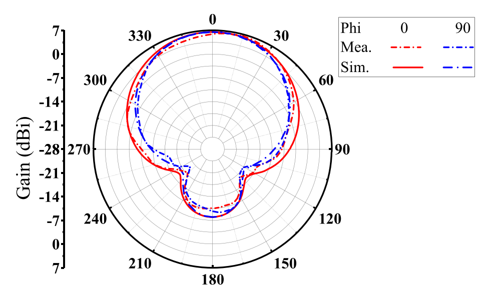

Fig. 4. Measured and simulated radiation patterns of the antenna for phi = 0° (xoz-plane) and phi = 90° (yoz-plane).

The rectangular patch antenna is shown in Fig. 2. It is printed on an F4BM substrate, which has a relative dielectric constant of 2.65, a thickness of 1 mm, and a loss tangent of 0.005. Table II gives the parameters of the patch antenna.

The input impedance Z_{ANT} of the patch antenna is plotted in Fig. 3(a) and (b) as a function of W_2 and L_2, respectively. The real part of the patch antenna's input impedance decreases with increasing L_2, while the imaginary part remains almost unchanged. After optimization, the real part of the patch antenna impedance is tuned to $\mathrm{R_{ANT}} = 91\,\Omega$, i.e., almost the same as that of the rectifying diode. The imaginary part of the antenna impedance is only $\mathrm{X_{ANT}} = -3\,\Omega$ at 2.45 GHz. Thus, the antenna impedance satisfies our requirements. Antenna impedances of 39+j48 Ω and 34+j82 Ω are obtained at 4.9 and 7.35 GHz, respectively.

To measure the patch antenna, a 50 Ω coaxial cable was fed to it. Its radiation patterns are shown in Fig. 4. The antenna is polarized along the x-direction with a maximum gain of 6.5 dBi, which agrees well with the simulation.

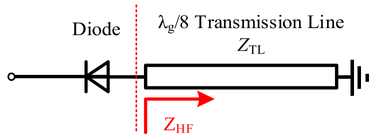

Fig. 5. Topology of a diode with a series short-ended one-eighth-wavelength transmission line (λ_g is the wavelength in the corresponding substrate).

TABLE III
RETURN LOSS AT HARMONICS

f	Z_D (Ω)	Z_{HF} (Ω)	Z_{RCT} (Ω)	Z_{ANT} (Ω)	Return loss from diode to antenna (dB)
$2f_0$	29-j97	∞	∞	39+j48	0
$3f_0$	16-j58	-j134	16-j192	34+j82	0.7

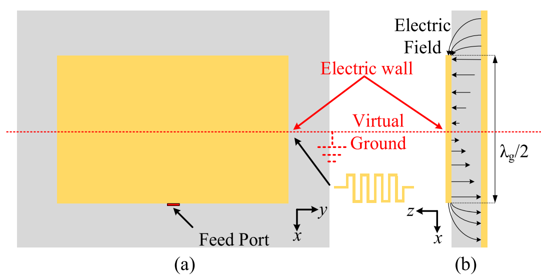

Fig. 6. (a) Topology and (b) electric field distribution of the patch antenna.

TABLE IV
PATCH RECTENNA PARAMETERS

L_1	W_1	L_2	W_2	L_3	L4	d
80 mm	61 mm	60 mm	37 mm	5.5 mm	5.5 mm	0.4 mm
W_3	L_5	L_6	L_7	W_5	W_6	
0.3 mm	1.0 mm	0.8 mm	2.4 mm	0.2 mm	0.4 mm	

D. Harmonic Filter

Fig. 5 shows the configuration of a diode with a series short-ended one-eighth-wavelength transmission line. According to transmission line theory, the input impedance of the short-ended one-eighth-wavelength transmission line is

$$Z_{\mathrm{HF}} = jZ_{\mathrm{TL}} \tan\left(\frac{\pi}{4}\frac{f}{f_0}\right) = \begin{cases} 0, & f = 0 \\ jZ_{\mathrm{TL}}, & f = f_0 \\ \infty, & f = 2f_0 \\ -jZ_{TL} & f = 3f_0 \\ \cdots & \cdots \end{cases} \quad (3)$$

where Z_{TL} is the characteristic impedance of the short-ended one-eighth-wavelength transmission line, and f_0 is the fundamental frequency. This presents inductive impedance at f_0, infinite impedance at $2f_0$, and capacitive impedance at $3f_0$. We set

$$\operatorname{Im}\{Z_D + Z_{HF}\}|_{f=f_0} = 0 \quad (4)$$

to facilitate the impedance matching at f_0. This *leads to* $Z_{TL} = |X_{ANT}+X_D|$.

The rectifying diode can be considered as a source at $2f_0$ and $3f_0$, while the antenna is a load. Table III shows the diode impedance Z_D, antenna impedance Z_{ANT}, harmonic filter impedance Z_{HF}, return loss, $Z_{RCT} = Z_D+Z_{HF}$. We see that most of the harmonic power is reflected back to the diode for harmonic recycling.

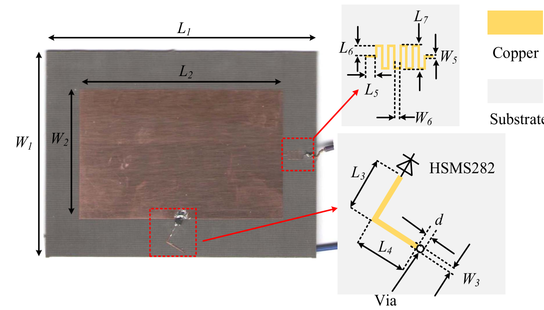

Fig. 7. Fabricated rectangular patch rectenna.

TABLE V
COMPARISON WITH RECENTLY REPORTED PATCH RECTENNAS

Ref. (year)	Frequency (GHz)	Input Power (dBm)	Maximum rectifying efficiency (%)	Rectenna Size* (λ_0×λ_0)	PCB Layers	Independent Matching Networks or dc-pass Filters
[8] (2020)	5.8	9	68	1.66×0.46	1	yes
[21] (2018)	2.45	0	36	0.61×0.61	2	yes
[22] (2018)	2.45	22.5	83.7	0.57×0.57	2	yes
[23] (2018)	2.4	16.49	47.7	0.32× 0.22	1	yes
[24] (2018)	2.45	12	70	0.73×0.73	1	yes
This work (2021)	**2.45**	**22.5**	**82.2**	**0.65×0.49**	**1**	**No**

*λ_0 is the wavelength in free space.

We apply the short-ended one-eighth-wavelength transmission line in the rectenna to suppress the second and third harmonics while compensating the imaginary part of the rectifying diode's impedance at the fundamental frequency [14]–[20]. The diode impedance is transformed by conjugate-matching it to the patch antenna impedance.

E. Dc Path Design

We facilitate the dc-pass filter to connect the meander line to the center of the narrow side of the patch antenna in our design. The patch antenna functions as a parallel plate capacitor and forms an LC low-pass filter in the dc path.

The topology of a patch antenna with a feeding port is shown in Fig. 6(a) and the TM_{10} electric field distribution in Fig. 6(b). According to antenna theory, the TM_{10} distribution is generated when the feeding port is at the center of the wide side. A virtual ground is formed as the dashed line shows in Fig. 6. The output dc-pass filter may be removed when we use the virtual ground as the dc output position owing to its uniqueness. Then, we use a simple meander line connection to the middle of the narrow side and replace the dc-pass filter in the conventional design. This design also reduces the disturbance from the dc path to the patch antenna.

F. Rectenna Design

The detailed process for designing the proposed rectenna is as follows.

1) Choose a Schottky diode with impedance $Z_D = R_D$-jX_D obtained from (2) at input power P_{IN} and frequency f_0.

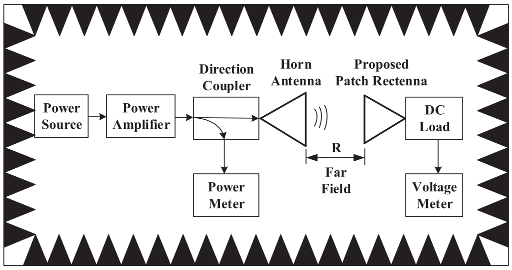

Fig. 8. Measuring environment.

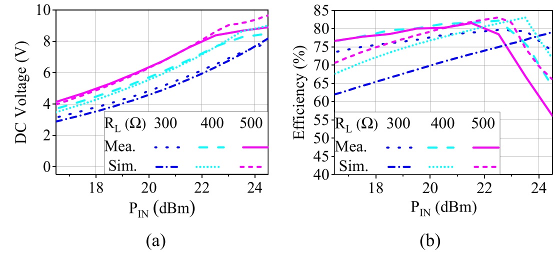

Fig. 9. Measured (a) output voltage and (b) rectifying efficiency of the proposed rectenna.

2) Simulate the antenna impedance Z_{ANT} at the edge center of the broad side. Slightly tune the width or length of the patch antenna to realize $\mathrm{Re}\{Z_{\mathrm{ANT}}\} = \mathrm{R_D}$.
3) Design a short-ended one-eighth-wavelength microstrip transmission line and connect it in series to the diode. Design the characteristic impedance of the transmission line such that $Z_{TL} = \mathrm{Im}\{Z_{\mathrm{ANT}}+Z_{\mathrm{D}}\}$.
4) Connect a meander line to the virtual ground of the patch antenna and form a dc path. The dc load R_{L} is estimated from $B_\nu/4P_{\mathrm{IN}}$, where B_ν is the diode breakdown voltage.
5) Optimize the rectifying efficiency of the rectenna in the ADS. Slightly tune the patch antenna dimensions L_2 and W_2, and the characteristic impedance Z_{TL} of the short-ended one-eighth-wavelength microstrip transmission line.

As an example, we have optimized one rectenna at 2.45 GHz. The impedance of the rectifying diode is 91-j125 Ω, and the patch antenna impedance is 91-j3 Ω. The characteristic impedance Z_{TL} of the short-ended one-eighth-wavelength transmission line is 134 Ω, which provides an inductive impedance of j134 Ω. The antenna and rectifying diode with the short-ended one-eighth-wavelength transmission line match well.

III. Results and Discussion

The proposed patch rectenna was fabricated as designed, as shown in Fig. 7. Its parameters are listed in Table IV. It has the same size as a conventional patch antenna. An HSMS282 rectifying diode with a series short-ended one-eighth-wavelength transmission line is directly connected to the patch antenna. A meander line with high characteristic impedance is connected to the nonradiation side of the patch antenna to provide a dc path. Microwave power does not couple into the dc load owing to the virtual ground, which is equivalent to an excellent dc-pass filter.

Fig. 8 shows the measuring system of the proposed rectenna. The measurement was performed in an anechoic room. We used an E8267C power source from Agilent Technologies to generate microwaves, and a WSPA-2000-6000-50 amplifier from Wattsine Electronic Technology to enhance the power. An AV2433 power meter from China Electronics Technology Group Corporation was used to detect the output power of the amplifier through a 20 dB direction coupler. A standard horn antenna with a gain of 13 dBi at 2.45 GHz was used to transmit the microwave power. The patch rectenna was set at the far-field of the horn antenna. Then, a standard resistance box and a voltage meter were used to obtain dc power.

The rectifying efficiency of the proposed patch rectenna is

$$\eta = \frac{P_{\mathrm{dc}}}{P_{IN}} \times 100\% = \frac{V_0^2}{R_L}\frac{1}{P_{IN}} \times 100\% \tag{5}$$

where P_{dc} is the output dc power, V_0 is the output dc voltage, R_{L} is the dc load, and P_{IN} is the microwave power input from the receiving antenna to the rectifying diode. P_{IN} is obtained from

$$P_{IN} = P_r = \frac{G_t G_r \lambda^2}{(4\pi R)^2} P_t \tag{6}$$

where G_{t} and G_{r} are the gains of the transmitting horn antenna and receiving patch antenna, respectively, P_{t} is the power transmitted by the horn antenna, P_{r} is the power received by the patch rectenna, and R is the distance between the horn and patch antennas.

Fig. 9(a) shows the output dc voltage with respect to dc load and input power. The output voltage increases with the input power P_{IN}. Fig. 9(b) shows the measured and simulated efficiencies with respect to input power and dc load. The maximum rectifying efficiency reaches 82.2% when the dc load is 400 Ω and the received power is 22.5 dBm. There are some deviations between the simulated and measured results. There are two possible reasons. The first is that in the simulation, the output power of the patch antenna is the source of the rectifier. Meanwhile, the patch antenna is a dc capacitor in our proposed method. Conventional harmonic simulation cannot be performed directly. We use equivalent circuits instead, which may introduce some errors. The second reason is that the diode, as an active component, has parameter variations in fabrication. The built-in voltage and junction capacitance may be different from those of the simulation model. This can introduce additional errors.

Table V shows a comparison between the proposed rectenna and previous patch rectennas. The proposed design achieves high rectifying efficiency, low profile, compact size, and easy design. Low fabrication cost is achieved because there is only one layer with a smaller size.

IV. Conclusion

We have presented a compact patch rectenna without independent matching networks or dc-pass filters. A simple short-ended one-eighth-wavelength transmission line is used to enhance the rectifying efficiency while compensating the imaginary part of the rectifying diode impedance. A meander line is connected as a dc path to the virtual ground of the patch antenna. The proposed design reduces the size of the rectenna by facilitating impedance-matching networks and filters, and improves the rectifying efficiency by suppressing the harmonics. A maximum rectifying efficiency of 82.2% is obtained at a received power of 22.5 dBm at 2.45 GHz.

The proposed design is suitable for patch rectennas and can be applied to rectenna arrays of WPT systems.

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