A Novel Class-C Rectifier With High Efficiency for Wireless Power Transmission

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***Abstract*— In this letter, a compact Class-C rectifier with high efficiency based on a novel structure was proposed for wireless power transmission (WPT). This structure is connected to the rectifying diode in parallel. It presents infinite impedance at the output port at the fundamental frequency for impedance matching and zero impedance at the high harmonic frequencies. An open-end 12th wavelength microstrip line and a short-end quarter wavelength microstrip line are applied in this design. For fabricated, a radio frequency (RF) rectifier operating at 2.45 GHz was designed and tested. The measurement results show that the maximum RF–dc conversion efficiency is 82.7% at 25 dBm. Moreover, the proposed rectifier is compact with the size of 0.35λ_g× 0.13λ_g.**

***Index Terms*— Class-C, compact, high efficiency, rectifier, wireless power transmission (WPT).**

I. Introduction

MICROWAVE wireless power transmission (WPT) technology has been successfully employed to charge electronic devices [1], such as sensors [2] and airplanes [3]. The rectifiers play an important role in WPT systems, which convert the radio frequency (RF) power into dc power [4]–[7]. Rectifiers with wide dynamic input power range have been studied as well [8]–[11].

Since the last century, recycling power technology has been used to enhance the RF–dc conversion efficiency in K. Chang group of A&M University [5] and microwave power transmission (MPT) research group of Kyoto University [12], [13]. A low-pass filter is inserted between the input port and the rectifying diode to reflect the harmonic signals in their works. Table I lists a comparison between performances of the prior work and the proposed rectifier. In [4], a novel band-stop structure is connected to the diode in series for rejecting the second harmonic power produced during rectifying. Finally, a simple rectifier circuit is achieved with the efficiency of 80.9%. In [14], a coupler is applied as a power recycling network, which is connected to the RF input port of two parallel subrectifiers. This design realizes better impedance matching and high conversion efficiency of 80%. In [15], a novel harmonic termination network is proposed in high-power microwave rectifier. A $\lambda/12$ and a $\lambda/8$ transmission lines are used in this design to realize peak efficiency of more than 80% at the input power of 31 dBm. Some rectifiers with obvious structure characteristics, such as Class-C, Class-E, Class-F, and Class-F^{-1} rectifiers, are reported in [16]–[18], respectively. Two short-end lines at $2f_0$ and $3f_0$ are used in [16] to show zero impedance at harmonics. Abdelhalem *et al.* [17] propose a Class-E rectifier with a wide range of input power and loading conditions. About ten surface mount devices (SMDs) are applied in this design. In [18], two Class-F rectifiers are designed with harmonics suppression network, which consists of $\lambda/4$, $\lambda/12$, and $\lambda/8$ transmission lines. Additional matching network is required in [16]–[18]. Fan-shaped stubs have been successfully applied in both dual-band and broadband rectifiers with better frequency response [19]–[21].

In this letter, a novel compact Class-C rectifier with high-efficiency based on a simple network is proposed for WPT. The proposed network insists of an open-end 12th wavelength microstrip line and a short-end quarter wavelength microstrip line, which shape the voltage waveform to sine wave and current waveform to pulse wave. Another transmission line is used for matching input impedance to source. With this design concept, an uncomplicated structure with three transmission lines is achieved, leading reduction in insertion loss and physics size. As a result, the highest efficiency of 82.7% at 25 dBm and compact circuit size with $0.35\lambda_g\times 0.13\lambda_g$ are realized.

II. Principle and Design

A. Principle of the Novel Network

Fig. 1(a) shows the simplified schematic of conventional Class-C rectifier. It consists of an eighth wavelength microstrip line, a 1/12th wavelength microstrip line, a 1/16th wavelength microstrip line, and a 1/20th wavelength microstrip line in parallel. With the four lines, the input impedance Z_{in} shows zero at high harmonic frequencies, which will shape the voltage and current waveforms. An inductance L and a capacitance C_2 are required to realize a dc-pass filter to block RF power.

Different from the conventional Class-C rectifier, the proposed rectifier only consists of a dc block C_1, a 12th wavelength microstrip line in parallel, a diode, a quarter wavelength microstrip line, and a capacitance, from left to right. With the two lines, the input impedance Z_{in} also shows zero at high harmonics. Thus, the voltage and current waveforms of diode will be shaped as conventional Class-C rectifier.

Manuscript received August 15, 2020; revised September 9, 2020; accepted September 28, 2020. Date of publication October 26, 2020; date of current version December 4, 2020. This work was supported in part by the National Natural Science Foundation of China (NSFC) under Grant 62071316 and Grant 61931009. *(Corresponding author: Changjun Liu.)*

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Digital Object Identifier 10.1109/LMWC.2020.3029441

TABLE I

PERFORMANCE COMPARISON OF RECENTLY REPORTED RECTIFIER

Reference	Freq. (GHz)	Diode	Max. Eff.	Input Power	Size (λ_g^2)	Technology	Harm. Term. Network for Impedance Matching	*Num. of Microstrip Lines	Num. of Inductors	Years
[4]	2.45	HSMS282	80.9%	20 dBm	0.051	Bandstop	Yes	4	0	2017
[15]	2.45	HSMS282	80%	28 dBm	0.92	Coupler	No	>10	0	2017
[16]	2.45	HSMS270	81.3%	31 dBm	0.20	Harm. Term	Yes	3	1	2019
[17]	2.45	SMS7630	72.8%	8 dBm	N.A.	Class-C	No	6	0	2012
[18]	0.8	HSMS392	60%	16 dBm	N.A.	Class-E	No	N.A.	4	2013
[19]	0.9	HSMS820	80.4%	13.4 dBm	0.23	Class-F	No	6	1	2014
This work	**2.45**	**HSMS282**	**82.7%**	**25 dBm**	**0.048**	**Class-C**	**Yes**	**3**	**0**	**2020**

* Lines for input and output are not considered

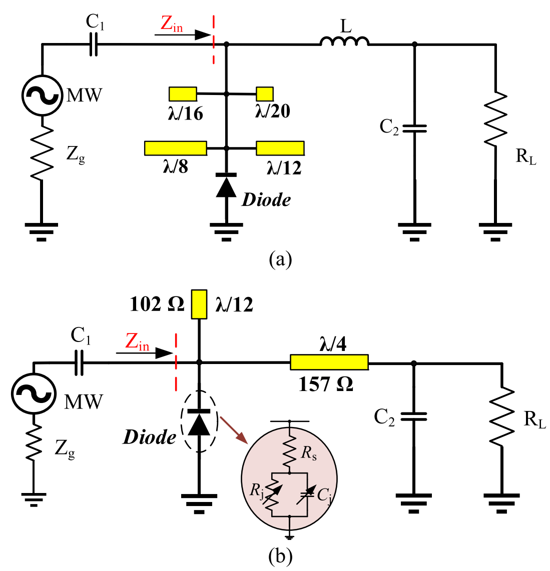

Fig. 1. Topology of the (a) conventional and the (b) proposed Class-C rectifier.

The proposed Class-C rectifier based on a novel network owns advantages compared with the conventional Class-C rectifier.

1) Zero Impedance at Higher Harmonics: The input impedance Z_{in} is zero at second, third, and fourth harmonics (including the main harmonic power), while it is inconvenient to tune the impedance to zero at higher harmonics in conventional Class-C rectifier, such as fourth and fifth harmonics, because the four open-circuit lines are connected to one point, as shown in Fig. 1.

2) Simple Structure: The eighth wavelength microstrip line and RF block L in a conventional Class-C rectifier are removed in the proposed rectifier, resulting in a compact size, reduction of insertion loss, and high efficiency.

Thus, it is a novel topology compared with a conventional Class-C rectifier and shows competitive in RF–dc conversion efficiency and circuit size.

B. Rectifier Design

In this design, two transmission lines are employed to shape the voltage and current waveforms. From transmission line theory, the input impedance of a quarter wavelength microstrip line with a capacitance and dc load, as shown in Fig. 2(a), can be obtained by

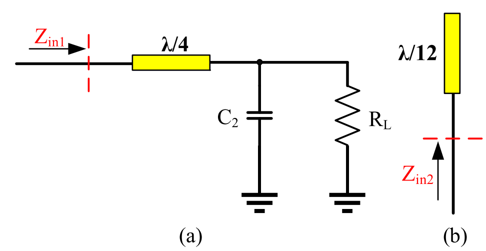

Fig. 2. Input impedance of a (a) quarter wavelength microstrip line with a capacitance and a resistance and an (b) open-end 12th wavelength microstrip line in this design.

$$Z_{in1} = \begin{cases} R_L, & \text{dc} \\ \infty, & \omega = \omega_0, 3\omega_0, \ldots \\ 0, & \omega = 2\omega_0, 4\omega_0, \ldots \end{cases} \quad (1)$$

From (1), at dc, the input impedance is R_L, which means the structure can provide dc path during rectifying. At fundamental frequency, Z_{in1} is infinite to block the RF power into dc load. At even harmonics, Z_{in1} is zero. Then, it presents a short circuit to shape the voltage and current waveforms.

The input impedance of an open-end 12th wavelength microstrip line, as shown in Fig. 2(b), is as follows:

$$Z_{in2} = \begin{cases} \infty, & \text{dc} \\ -1.73jZ_0; & \omega = \omega_0 \\ -0.58jZ_0; & \omega = 2\omega_0 \\ 0; & \omega = 3\omega_0 \\ 0.58jZ_0; & \omega = 4\omega_0 \end{cases} \quad (2)$$

where Z_0 is the characteristic impedance of the 12th wavelength transmission line. Its input impedance is infinite at dc from (2), meaning an open circuit and having no effect on dc path. At fundamental frequency, Z_{in2} is $-1.73jZ_0$. By selecting the value of Z_0 carefully, the real part of the rectifying diode's impedance will vary to Z_g (internal resistance of microwave source) for impedance matching easily. At the third harmonics, Z_{in2} is zero, leading the voltage and current waveforms shaped.

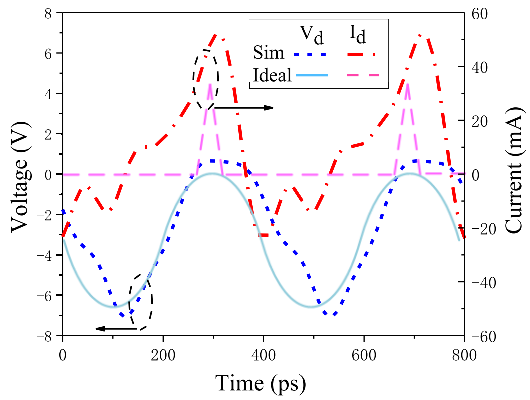

Fig. 3. Diode voltage and current waveforms in the proposed Class-C rectifier.

TABLE II
SPICE PARAMETERS OF AN HSMS282 DIODE

B_V	C_{j0}	I_S	R_S	V_{bi}
15 V	0.7 pF	0.022 μA	6 Ω	0.25 V

In Fig. 1(b), through parallel calculation with Z_{in1}, Z_{in2}, and Y_D (diode admittance, $Y_D = G + jB$), Z_{in} can be obtained by

$$Z_{in} = \frac{1}{\frac{1}{Z_{in1}} + \frac{1}{Z_{in2}} + Y_D} = \begin{cases} R_L, & \text{dc} \\ \frac{G - j(B + 0.58/Z_0)}{G^2 + (B + 0.58/Z_0)^2}, & \omega = \omega_0 \\ 0, & \omega = 2\omega_0, 3\omega_0, 4\omega_0. \end{cases} \quad (3)$$

From (3), at fundamental frequency, the real part of Z_{in} is only related to the characteristic impedance of the 12th microstrip line when the rectifying diode, operating frequency, input power, and dc load are determined (meaning G and B are determined). Thus, we can match the real part of Z_{in} to Z_g by choosing the value of Z_0 carefully. Then, it is easy to match it to microwave source.

At second, third, and fourth harmonics, the input impedances change to zero, meaning the network presents a short circuit at these harmonics. Thus, most harmonic signals produced by diode will be blocked and reflected into the diode to shape the voltage and current waveforms.

Fig. 3 depicts the simulated and ideal time-domain voltage and current waveforms, showing a good Class-C operation.

III. IMPLEMENTATION

The operating frequency of the rectifier is set to 2.45 GHz, which is in industrial, scientific, and medical (ISM) band. The proposed rectifier circuit was implemented and tested for verifying the accuracy of the design method. The substrate used in this design is F4B-2 (polytetrafluoroethylene (PTFE) microfiber glass) with a relative dielectric constant of 2.65, a thickness of 1 mm, and a loss tangent of 0.002. The fabricated circuit size is 27 mm × 10 mm, whose electric length is about $0.35\lambda_g \times 0.13\lambda_g$, as shown in Fig. 4. The proposed rectifier is compact due to the simple structure with only three microstrip lines in the design. A HSMS282 diode is used for rectifying, whose main SPICE parameters are listed in Table II. A capacitance C_1 (22 pF) is applied as a dc block, C_2 is 100 pF, and the dc load R_L is 280 Ω.

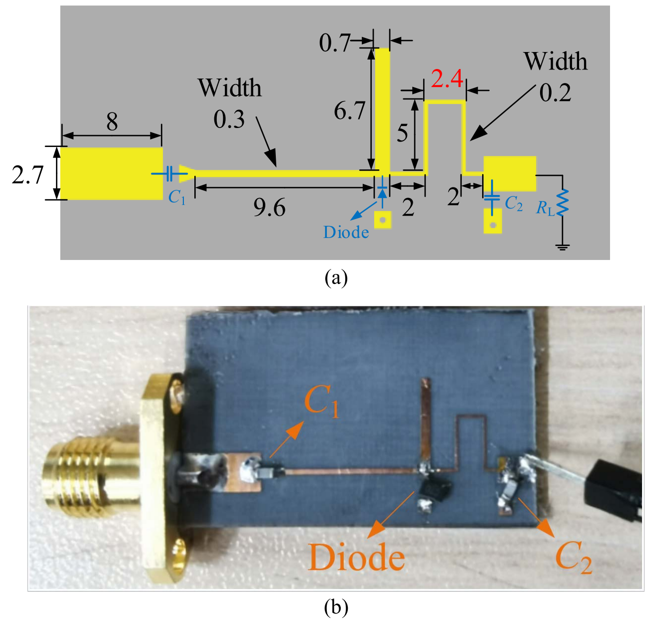

Fig. 4. (a) Layout and (b) photography of the proposed rectifier.

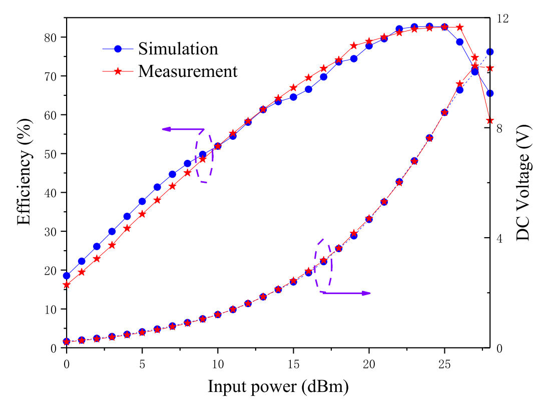

Fig. 5. Simulated and measured RF–dc conversion efficiency of the proposed rectifier versus input power.

IV. EXPERIMENTAL RESULTS

A microwave source (E8730C, Agilent) and a power amplifier (ZHL-30W-262, Mini-Circuits) are used to provide the RF power. A standard resistance box is applied as dc load and a voltage meter is for monitoring dc voltage.

The simulated and measured efficiency of the proposed rectifier is shown in Fig. 5, which is in good agreement. The maximum measured RF–dc conversion efficiency is 82.7% at the input power of 25 dBm and the peak output dc voltage is more than 10 V, which is two-thirds of HSMS282 diode's reverse breakdown voltage.

V. CONCLUSION

A novel Class-C rectifier is designed, fabricated, and tested in this letter. An open-end 12th wavelength microstrip line and a short-end quarter wavelength microstrip line are applied in this design, resulting in zero impedance at second, third, and fourth harmonics produced during rectifying. The measured maximum efficiency is 82.7% at the input power of 25 dBm. The fabricated rectifier is compact with the physics size of 27 mm × 10 mm.

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