A Compact High-Efficiency Rectifier With a Simple Harmonic Suppression Structure

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***Abstract*— In this letter, a compact high-efficiency radio frequency (RF) rectifier based on a series harmonic suppression structure is proposed for wireless power transmission (WPT). The proposed structure removes the cascading bandpass between the RF source and the diode, and the dc-pass filter between the diode and the dc load, simultaneously. The harmonic suppression structure consists only of a short-ended eighth-wavelength microstrip line, which shows an inductive impedance to compensate the rectifying diode's capacitive impedance at fundamental frequency and changes to open circuit to reflect the second harmonic for rectifying again. Two Schottky diodes are used in this design for voltage-doubling rectifying. For fabrication, a rectifier operating at 2.45 GHz was designed, fabricated, and tested. The measurement results show that the maximum RF–dc conversion efficiency is over 80% at 25 dBm. Meanwhile, the fabricated rectifying is compact with 20 mm × 5 mm.**

***Index Terms*— Double voltage, harmonic suppression structure, high efficiency, rectifier, wireless power transmission (WPT).**

I. Introduction

Wireless power transmission (WPT) has been successfully applied to charge electronic devices, which gets rid of the shackles of power lines [1]. The radio frequency (RF) rectifier is an important component to convert RF power to dc power in WPT systems [2]–[7]. The essential requirement of a rectifier is high RF–dc conversion efficiency, which is critical for the performance of a WPT system [8]–[14]. Moreover, miniaturization is another requirement for microwave rectifier integrated to other components, such as antennas [15] and power amplifiers [16].

Some research groups have carried out a lot of work in improving the performance of the rectifier. It has been proven that harmonic suppression and harmonic recycling in the rectifier are effective in enhancing RF–dc conversion efficiency. In [17], a Class-C 2.45-GHz microwave rectifier with short-circuit second- and third-harmonic terminations was designed and measured. It demonstrates a maximum RF–dc conversion efficiency of 72.8% at an input power of 8 dBm with $R_{\mathrm{dc}} = 742\ \Omega$. In [11], a Class-F rectifier with high RF–dc conversion efficiency is given based on an analytical mode considering each kind of diode power losses during rectifying. Finally, one Class-F rectifier working at 900 MHz is designed with the maximum measured efficiency of 80.4%. In [18], a Schottky diode is connected to the output of the rectifier for rectifying the harmonics to increase the output dc level. Two dc-pass filters are also applied to reject the RF signals for rectifying again. The measurement shows that the peak efficiency is 34% at 35 GHz with an input power of 20 mW. In [19], a harmonic signal control technique is used to improve the RF–dc conversion efficiency of the rectifier. A quarter-wave length open stub of 8.25 GHz effectively terminates the harmonic signal. The rectifier realizes the RF–dc conversion efficiency of 64.8% at 2.45 GHz. The design of a filter in the input and output of voltage-doubling rectifier is reported in [20]–[22], respectively.

In this letter, we propose a compact high-efficiency rectifier with a harmonic suppression structure for WPT. Two eighth-wavelength microstrip lines short-ended at RF are applied to compensate the imaginary part of a diode's impedance and reject the second harmonics during rectifying to improve the RF–dc conversion efficiency. With the harmonic suppression structure, a simple circuit structure was realized, resulting in decrease in the insertion loss and circuit size. The measurement results show that the proposed voltage doubling rectifier achieves a maximum efficiency of 80.2% at 2.45 GHz with an input power of 25 dBm and a dc load of 400 Ω. It also maintains a compact size of 20 mm × 5 mm.

II. Principle and Design Method

A. Principle of the Harmonic Suppression Structure

A conversional voltage-doubling rectifier is shown in Fig. 1(a), in which a bandpass filter and a dc-pass filter were inserted between the rectifying diode and the microwave resource and the dc load to suppress the harmonics produced by the rectifying diodes. Usually, the filters will introduce an insertion loss for the RF signal and increase the rectifier circuit size. These make it difficult to enhance RF–dc conversion efficiency and realize circuit miniaturization.

Different from the traditional voltage-doubling rectifier, we proposed another harmonic suppression topology for improving its performance, which removes the cascading bandpass filter and the dc-pass filter, as shown in Fig. 1(b). The proposed structure has an inductive impedance at fundamental frequency and changes to an open-ended circuit at the second-harmonic frequency. The input impedance of a Schottky diode can be obtained by $Z_{\mathrm{D}} = R - jX$ when the operating frequency, input power, and dc load are given. Its imaginary part will be compensated by the harmonic

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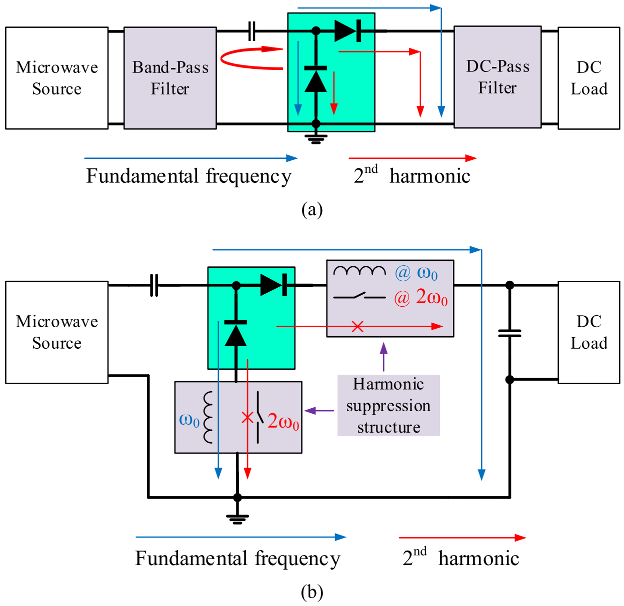


Fig. 1. (a) Circuit configuration of the conversional and (b) proposed voltage-doubling rectifier.

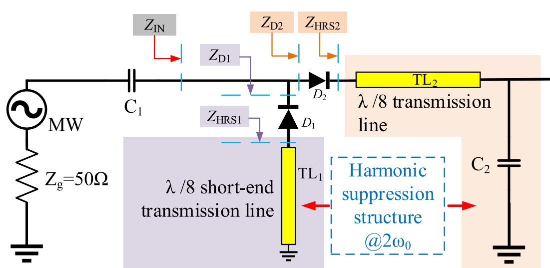


Fig. 2. Schematic of the proposed voltage-doubling rectifier.

suppression structure with an inductive impedance leading Z_D changes to a pure resistance at fundamental frequency. Then, it is very easy to match Z_D to Z_g (internal resistance of the microwave source). At the second-harmonic frequency, the proposed harmonic suppression structure will block the harmonic signals. Then, they will be reflected into two Schottky diodes for rectifying again. What is more, the connection between the diode and the ground at the second harmonic is cut off due to the harmonic suppression structure switching to an open-ended circuit at $2\omega_0$. Thus, the second harmonic may not form a loop circuit, and the diodes are isolated from the ground, which results in the bandpass filter between the source and diodes being removed in the rectifier.

Thus, the proposed voltage-doubling rectifier with a harmonic suppression structure is competitive compared with the conversional one. The novel structure can improve the RF–dc conversion efficiency and reduce the physics size simultaneously.

B. Rectifier Design

Fig. 2 shows the schematic of the proposed voltage-doubling rectifier with a harmonic suppression structure. It consists of a dc block C_1, two Schottky diodes D_1 and D_2 (both HSMS282), a short-ended transmission line TL_1, an output transmission line TL_2, a parallel capacitance C_2, and a dc load R_L, from left to right. TL_1 and TL_2 are used to compensate the imaginary parts of D_1 and D_2, respectively. Then, Z_{D1} and Z_{D2} change to a pure resistance, and the input impedance of the proposed rectifier Z_{IN} will be matched to Z_g.

TL_1 is a short-ended eight-wavelength microstrip line with a characteristic impedance of Z_1. From the transmission line theory, the input impedance of TL_1 at dc, fundamental frequency, and harmonics can be obtained as follows:

$$Z_{HRS1} = jZ_1 \tan\left(\frac{\pi}{4}\frac{\omega}{\omega_0}\right) = \begin{cases} 0, & \omega = 0 \\ jZ_1, & \omega = \omega_0 \\ \infty, & \omega = 2\omega_0 \\ -jZ_1, & \omega = 3\omega_0. \end{cases} \quad (1)$$

At dc, TL_1 presents a short-circuit, which is required to provide dc path during rectifying. Thus, it satisfies the rectification mechanism. At fundamental frequency, TL_1 can compensate the imaginary part of D_1's impedance by choosing a proper value of Z_1. Thus, $Z_{D1} = R - jX + jZ_1 = R$. Then, it is convenient to math Z_{D1} to Z_g. At the second-harmonic frequency, TL_1 becomes a quarter-wavelength transmission line and changes to an open circuit, resulting in a perfect harmonic suppression structure. The second-harmonic RF power is blocked by TL_1 and reflected into diode D_1 for rectifying again.

TL_2 is another eight-wavelength transmission line with a characteristic impedance of Z_2 as a harmonic suppression structure at $2\omega_0$. Similarly, the input impedance of the rectifier's output port can be given by

$$Z_{HRS2} = Z_2 \frac{Z_L + jZ_2 \tan\left(\frac{\pi}{4}\frac{\omega}{\omega_0}\right)}{Z_2 + jZ_L \tan\left(\frac{\pi}{4}\frac{\omega}{\omega_0}\right)} = \begin{cases} R_L, & \omega = 0 \\ Z_2 \dfrac{Z_L + jZ_2}{Z_2 + jZ_L}, & \omega = \omega_0 \\ \dfrac{Z_2^2}{Z_L}, & \omega = 2\omega_0 \end{cases} \quad (2)$$

where $Z_L = 1/(j\omega C_2 + 1/R_L)$ and $1/R_L$ is close to 0, since the dc load of a rectifier is more than 100 Ω usually. Then, $Z_L = 1/j\omega C_2$. Thus, Z_{HRS2} can be rewritten as

$$Z_{HRS2} = \begin{cases} R_L, & \omega = 0 \\ jZ_2 \dfrac{Z_2 - 1/\omega C_2}{Z_2 + 1/\omega C_2}, & \omega = \omega_0 \\ j\omega C_2 Z_2^2, & \omega = 2\omega_0. \end{cases} \quad (3)$$

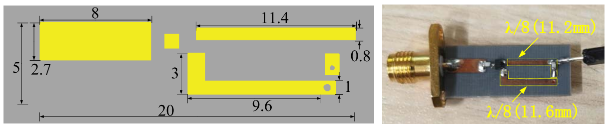
When the operating frequency and dc load are determined, we can make $1/\omega C_2$ much less than Z_2 and $\omega C_2 Z_2^2$ is ∞ through selecting C_2 and Z_2 carefully. Then, Z_{HRS2} can be obtained by

$$Z_{HRS2} = \begin{cases} R_L, & \omega = 0 \\ jZ_2, & \omega = \omega_0 \\ \infty, & \omega = 2\omega_0. \end{cases} \quad (4)$$

At dc, the input impedance of the harmonic suppression structure $Z_{HRS2} = R_L$, meaning that TL_2 will not affect the

TABLE I
SPICE PARAMETER 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



(a) (b)

Fig. 3. (a) Layout of the proposed rectifier. (b) Fabricated rectifier.

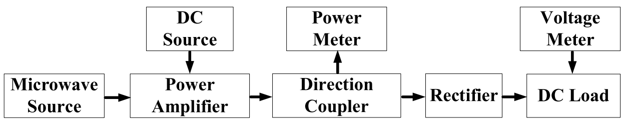


Fig. 4. Diagram of the measurement system.

value of the dc load. TL_2 also provides the dc path for the output power. At fundamental frequency, the harmonic suppression structure presents inductive impedance to compensate the capacitive impedance of the diode D_2. Then, the impedance of Z_{D2} changes to a pure resistance. At the second-harmonic frequency, Z_{HRS2} is ∞ to suppress the harmonic power.

An HSMS282 diode's main parameter is listed in Table I. Then, the input impedance of a Schottky diode is [23]

$$Z_D = \frac{\pi R_s}{\cos\theta_{on}\left(\frac{\theta_{on}}{\cos\theta_{on}} - \sin\theta_{on}\right) + j\omega R_s C_j\left(\frac{\pi-\theta_{on}}{\cos\theta_{on}} + \sin\theta_{on}\right)} \tag{5}$$

where R_s, θ_{on}, and C_j are the series resistance, the turnon angle, and the junction capacitance of the diode, respectively. From (5), the impedance of the HSMS282 diode Z_D is evaluated to be 90–j95 Ω. Thus, the characteristic impedance of TL_1 and TL_2 should be 95 Ω.

III. Implementation and Measurement

A voltage-doubling rectifier operating at 2.45 GHz was implemented and measured. The substrate of F4B was used in this design with a thickness of 1 mm, a loss tangent of 0.0012 at *S*-band, and a relative dielectric constant of 2.65. The layout and the photograph of the fabricated rectifier are shown in Fig. 3. The fabricated rectifier is about 0.27 λ_g × 0.07 λ_g, meaning the dimension is 20 mm × 5 mm. It is a very compact structure due to the removal of the bandpass filter and dc-pass filter between the diode and microwave source and the dc load. A capacitor C_1 (22 pF) is introduced as a dc clock, and the value of C_2 is 82 pF. A dc load of 400 Ω is applied in the design.

Fig. 4 depicts the measurement system. A microwave source (E8730C, Agilent) was applied to generate a small signal, which will be amplified by a power amplifier (ZHL-30W-262, Mini-Circuits). Then, a direction coupler and a power meter were used to monitor the output power of the amplifier. Finally, a resistance and a voltage meter were used to absorb the dc power and measure the dc voltage, respectively.

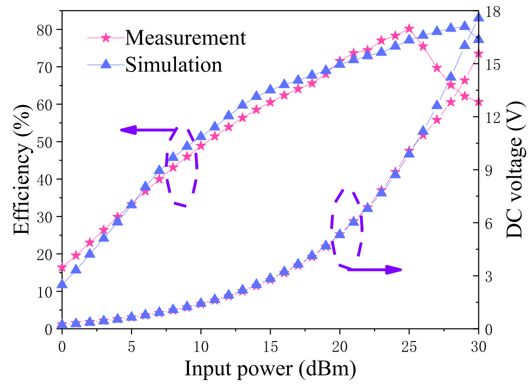


Fig. 5. Efficiency of the simulation and measurement versus the input power at 2.45 GHz.

TABLE II
COMPARISON WITH PRIOR RECTIFIERS

Ref.	Freq. (GHz)	Diode	Max. Eff. (%)	Input Power (dBm)	Size (mm^2)
[2]	2.45	HSMS282	80.9	20	18×16
[17]	2.45	SMS7630	72.8	8	55×55
[11]	0.9	HSMS820	80.4	13.4	95×75
[19]	2.45	HSMS286	64.8	11	48.1×40.1
This work	**2.45**	**HSMS282**	**80.2**	**25**	**20×5**

The efficiency of simulation and measurement are shown in Fig. 5, which present a good agreement. The proposed voltage-doubling rectifier reaches a maximum RF–dc conversion efficiency of 80.2%. The output voltage is more than 15 V, which is the reverse break down voltage of a single diode HSMS282. In the high input power, the measured efficiency is a little lower than the simulated one, since the nonlinear model of the diode HSMS282 may become not so accurate with high reverse dc voltage.

Table II shows the comparison of the operating frequency, diodes, maximum efficiency with input power, and dimensions between the proposed voltage-doubling rectifier and prior works. The proposed rectifier shows competitive in RF–dc conversion efficiency and circuit size, due to the novel design concept and simple structure.

IV. Conclusion

A compact high-efficiency rectifier is designed, fabricated, and tested in this letter. The input bandpass filter and output dc-pass filter in the conversional voltage-doubling rectifiers were removed. A novel harmonic suppression structure was used in this design, leading to a simple design. This structure consists of a series eighth-wavelength short-ended transmission line, whose input impedance is inductive at fundamental frequency and changes to infinity at the second harmonic. Thus, it can be used to compensate the capacitive impedance of the rectifying diode and reject the second-harmonic signal for rectifying again. The measurement results show that the proposed voltage-doubling rectifier can achieve a peak efficiency of 80.2% at an input power of 25 dBm. Moreover, its dimension is only 20 mm × 5 mm.

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