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ORIGINAL PAPER

Investigation on Rectifiers and Rectennas with Various Input Power Levels for the Applications of Space Solar Power Station

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Abstract

Rectifiers and rectennas have been receiving great attention for the applications of wireless power transmission and energy harvesting. This paper describes the challenges and solutions of the rectifiers and rectennas in enhancing conversion efficiency at low and high input power levels for the applications of space solar power station (SSPS). We reviewed the developments of the rectifiers for the applications of wireless power transmission, described the SSPS system, retrospect the history of SSPS, and presented the requirements of rectifiers and rectennas in SSPS systems. Key technologies of high-efficiency rectifiers and rectennas at various input power levels are also proposed. In high power levels, reducing harmonic loss and diode loss is valid to enhance rectifying efficiency. When the input power is low, using booster-voltage technology with low turn-on voltage diodes can improve rectifiers' performance. To keep a high efficiency in low and high power levels, rectifiers with wide input power dynamic ranges are proposed with various structures.

Keywords Rectifier · Rectenna · Wireless power transmission · High efficiency · Space solar power station

Abbreviations

DC	Direct current
DOE	Department of energy
EH	Energy harvesting
MIT	Massachusetts Institute of Technology
MPT	Microwave power transmission
NASA	National aeronautics and space administration
PCB	Printed circuit board
RF	Radio frequency
SSPS	Space solar power station
WPT	Wireless power transmission
UAV	Unmanned aerial vehicle
ZBD	Zero-bias diode

1 Introduction

Since Nicholas Tesla pioneered electromagnetic WPT, it has a history of more than 100 years. In 2007, MIT research team lit a 60-W light bulb 2 m away through magnetic resonance WPT technology, and published it in Science [1]. Then, WPT attracted people's attention once again. WPT plays an important role in many fields, such as SSPS [2], WPT between space satellites [3], stratospheric solar power station [4], UAV wireless power supply in air [5].

2 SSPS System

Figure 1 depicts the SSPS system, which is mainly composed of solar power generation device, power conversion and transmission devices, receiving system and conversion device. Its main working principle is:

First, solar power plant converts solar power into DC power.

Second, the DC power is converted into RF by power conversion device.

Third, the transmitting device sends the microwave beam to the ground.

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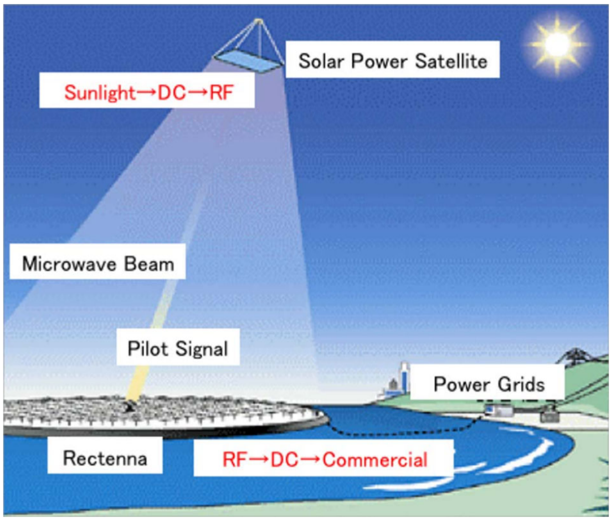

Fig. 1 Configuration of the SSPS system [2]

Finally, the receiving system on the ground receives these beams and converts it into DC power through conversion device.

Commonly, in the space, the power conversion order is sunlight → DC → RF. On the ground, it is RF → DC → commercial. In the receiving end of SSPS system, there are rectennas (antennas + rectifiers) to convert RF power into DC power. If the input power of the rectifier is P_{IN} and its conversion efficiency is η_{Rec}, the output DC power is

$$P_{out} = P_{IN} \times \eta_{Rec}. \tag{1}$$

Compared with the increasingly exhausted, nonrenewable fossil energy which will bring environmental pollution problems. Solar energy is more efficient, durable, and pollution free. And compared with wind power and hydropower, it is less affected by natural factors and has a wider coverage. The SSPS can supply power to remote areas, disaster-stricken areas, moving targets and other specific areas. At the same time, it can make spacecraft get rid of the huge solar cell wings, then greatly improve the power levels and control accuracy. In the future, SSPS can even be applied for space fuel production and space processing and manufacturing, and promote space industry development.

2.1 Development of SSPS

In 1964, W. C. Brown from the Raytheon Company showed the MPT technology through charging a UAV wirelessly [6]. Before W. C. Brown, N. Tesla proposed the concept of WPT at the end of the nineteenth century. In 1968, P. Glaser from Arthur D. Little, Inc. presented the design method of SSPS in Science firstly [7], and detailly described the necessity and feasibility of SSPS. Then, the SSPS received much concern with the development of MPT.

Due to the close attention to energy, America is the first nation to start SSPS research. After two serious energy crises in the world in 1973 and 1979, respectively, NASA and DOE proposed a NASA/DOE model for SSPS, whose total efficiency is 7% [8]. In 1995 and 1999, NASA studied two programs including Fresh Look Study [9] and Exploratory Research & technology, then proposed the Sun Tower and Integrated Symmetrical Concentrator systems, respectively. In 2011, J. C. Mankins from Artemis Innovation Management Solutions LLC proposed an arbitrarily large phased array solar power satellite, which used sandwich structure [10, 11].

Since 1980s, Japan has been conducting research of SSPS concerning its limited energy and source. Government, universities, and companies supported the research, including the Japan Aero-space Exploration Agency, the University of Tokyo, Kyoto University, and Mitsubishi Electric Corporation. A Solar Power Radio Integrated Transmitter in 2000 [12], a parabolic antenna phased array in 2001 [13, 14], and a phased array with active integrated antennas [15] were developed by the SSPS Study Team in Japan. Besides, a simple model, tethered solar power satellite, was proposed in 2006. Its transmitting power is 1.2 GW and receiving power is 0.75 GW on the ground [16].

In China, the study of SSPS was relatively late. After 2010, some companies, research institutes, and universities developed the research of SSPS, including China Aerospace Science and Technology Corporation, Chinese Academy of Sciences, China Academy of Engineering Physics, China Academy of Space Technology, Xi'an University, Chongqing University, and Sichuan University. Through their demonstration, there will be two steps in the development of SSPS in China. In 2030, SSPS experiment with MW power level will be conducted. In 2050, the commercial SSPS with GW power level will be realized.

2.2 Rectifiers and Rectennas in SSPS Systems

There are many complex and critical structures in SSPS system including solar power generation device, power conversion and transmission devices on the satellite, receiving system and conversion device on the earth. Rectifiers and rectennas play important roles on the ground receiving end. They can convert RF power to DC power.

High efficiency is the essential demand for the designs of rectifiers and rectennas. When the receiving microwave power is constant on the ground, it will output more DC power using high-efficiency rectifiers and rectennas. Usually, harmonics suppression or recycling technologies are applied in rectifiers designs to achieve high efficiency. Thus, harmonics disturbance can be avoided on the ground.

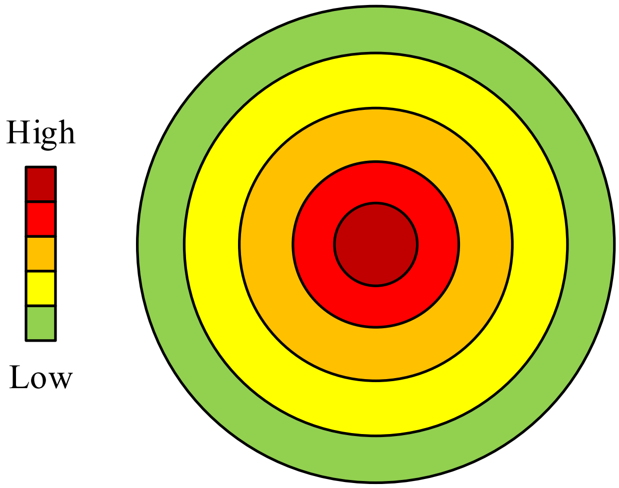

Fig. 2 Power distribution in the receiving antenna array

In the receiving end, to receive more microwave power, the system uses antenna arrays, causing a large aperture area. In the antenna array, the receiving microwave power of each antenna unit is different. The receiving power is high in the center and it is low in the outer area, as shown in Fig. 2. Usually, a rectifier has a narrow dynamic range, which cannot meet the requirement of wide input power range. Thus, high-efficiency rectifiers for different input power levels are required.

Good stability is another requirement for the designs of rectifiers and rectennas. The receiving system on the ground works outdoors, so it is necessary to consider the waterproof, sunscreen, lightning protection, dustproof and windproof features of the rectifiers and antennas in the design.

3 Key Technologies of Microwave Rectifiers with Various Input Power Levels

It is challenging to build a SSPS, which includes many key technologies, such as giant antenna technology in space, high power microwave source, high-efficiency microwave transmission technology, and high-efficiency rectifier and rectenna technology. In this section, we will discuss different high-efficiency rectifying technologies for different microwave power levels.

Rectifying diodes is the most important component in rectifiers. They can convert microwave power into DC power due to their specificity of one-way electric conduction. When the input microwave voltage just exceeds the forward conduction voltage of the rectifying diode to make it turn on, the rectifier circuit can output DC power. At this time, because the conduction current of the diode is very small, the loss on the diode is very small compared with the DC output power, so the conversion efficiency should show an upward trend with the increase of input power. When the input power continues to increase, the diode's conduction angle increases and the forward conduction current increases. When the loss of diode cannot be ignored compared with the value of output DC power, the RF–DC conversion efficiency of rectifier will show a downward trend. Usually, the maximum efficiency can be achieved when the DC voltage is a half of the breakdown voltage and forward voltage, which is given as following,

$$V_{DC} = (V_{br} + V_{th})/2, \tag{2}$$

where V_{DC} is the dc voltage, V_{dr} is the breakdown voltage, and V_{th} is the forward voltage.

When the input power is high, it is easy to output a high DC volage. While it is difficult to reach a high DC voltage when the input power is very low, such as − 20 dBm or − 30 dBm. Thus, the maximum RF–DC conversion efficiency of rectifier is higher with high power than that with low power, usually.

3.1 High Microwave Input Power Levels

To enhance the RF–DC conversion efficiency, power loss during rectifying should be decreased. Usually, there are four losses in rectifier, including the conductor and substrate loss on PCB, the mismatch loss, harmonics loss, and diode loss. PCB loss can be reduced by selecting a suitable PCB with a low loss tangent. Impedance matching is the essential requirement in rectifier design. Thus, mismatch loss of a rectifier is very low with good impedance matching. To reduce the harmonics loss and diode loss, harmonics-control technologies are applied in rectifier design, which is popular recently.

3.1.1 Reducing Harmonic Losses

Harmonics loss will be reduced through applying harmonics suppression networks or harmonics recycling networks. Harmonics will enter the diode for rectifying again with these harmonic networks to output more DC power. Usually, the 2nd and 3rd harmonics power account for most of these high-order harmonics power. Thus, it is effective to enhance RF–DC conversion efficiency by suppressing or recycling the 2nd and 3rd harmonics.

Reference [17] proposed a single-diode rectifier with a series band-stop structure, whose schematic and photography are shown in Fig. 3. A short-ended λ/8 wavelength microstrip transmission line was introduced to rectifier design in series with the rectifying diode to achieve an open circuit in 2nd

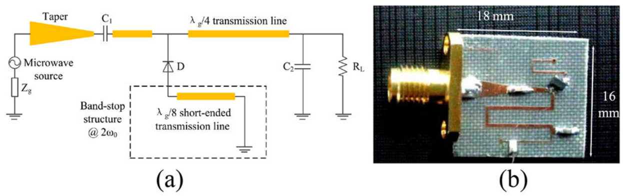

Fig. 3 **a** Schematic and **b** photography of the propose rectifier [17]

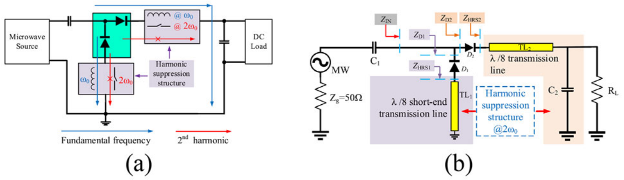

Fig. 4 **a** Equivalent circuit and **b** schematic of the voltage-doubling rectifier [18]

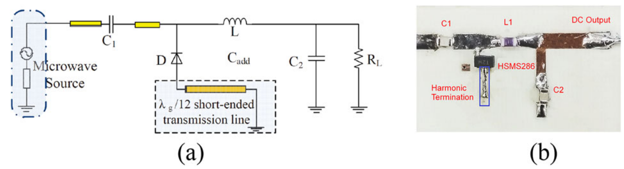

Fig. 5 **a** Schematic and **b** photography of the propose rectifier [19]

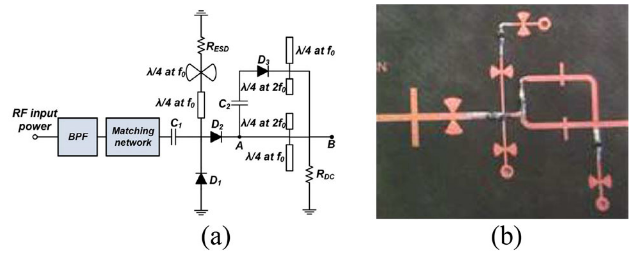

Fig. 6 **a** Schematic and **b** photography of the proposed rectifier [21]

harmonic. The input impedance of the short-ended λ/8 wavelength microstrip transmission line is

$$Z_{\lambda/8} = jZ_1 \tan\left(\frac{\pi}{4}\frac{\omega}{\omega_0}\right) = \begin{cases} 0, & \omega = 0 \\ jZ_1, & \omega = \omega_0 \\ \infty, & \omega = 2\omega_0 \\ -jZ_1, & \omega = 3\omega_0 \end{cases}, \tag{3}$$

where Z_1 is the characteristic impedance of the transmission line. In 2nd harmonic, the input impedance $Z_{\lambda/8}$ changes to infinite, meaning an open circuit to cut off the 2nd harmonic circuit. Thus, the 2nd harmonic is suppressed in the design and its maximum efficiency is 80.9% at 20 dBm.

A voltage-doubling rectifier with two short-ended λ/8 wavelength microstrip transmission lines was presented in [18], as shown in Fig. 4. Its RF–DC conversion efficiency is over 80% at 25 dBm.

A high-efficiency rectifier with the 3rd harmonic suppression was proposed in [19], as shown in Fig. 5. A short-ended λ/12 wavelength microstrip transmission line was introduced to achieve open circuit in 3rd harmonic. The input impedance of the short-ended λ/12 wavelength microstrip transmission line is

$$Z_{\lambda/12} = jZ_2 \tan\left(\frac{\pi}{6}\frac{\omega}{\omega_0}\right) = \begin{cases} 0, & \omega = 0 \\ 0.58jZ_2, & \omega = \omega_0 \\ 1.73jZ_2, & \omega = 2\omega_0 \\ \infty, & \omega = 3\omega_0 \end{cases}, \tag{4}$$

where Z_2 is the characteristic impedance of the transmission line. In 3rd harmonic, the input impedance changes to infinite to suppress the 3rd harmonic. When the operating frequency is 5.4 GHz, its maximum efficiency is 75.6% at 13 dBm.

Recently, millimeter-wave rectifiers have been drawn a lot of attention for their advantages of size reduction and longer transmission distance [20]. Harmonic recycling network is employed in the millimeter-wave rectifier design to enhance the conversion efficiency [21], as shown in Fig. 6.

In the output port, an additional rectifier is introduced to recycling harmonics produced during rectifying. At 35 GHz, the maximum conversion efficiency is 34% when the input power is 13 dBm.

3.1.2 Reducing Diode Losses

During rectifying another main power loss is diode loss, caused by the resistance of diode. To decrease the diode loss, a method is to reduce the overlap of the diode's voltage and current to achieved a low ohm loss. Harmonic load network is an effective structure to sharp the waveforms of the diode's volage and current. Recently, Class-C [22, 23], Class-E [24, 25], Class-F [26–29], and inverse Class-F [30] rectifiers are proposed by serval research teams.

Similar to harmonic-load power amplifiers, harmonic-load rectifiers sharp the diode's voltage and current waveforms through adjusting harmonics phases. It can reduce the diode loss to achieve a high conversion efficiency. Table 1 lists the impedance and waveform comparison of different harmonic-load rectifiers.

Figure 7 shows the ideal diode's waveforms of voltage and current with different harmonic load. In Class-C rectifiers, the impedances in all high harmonics are zero. The current wave is pulse and the voltage is zero accordingly. So, the diode loss is zero. The diode's voltage and current waveforms in other harmonic-load rectifiers are similar to Class-C rectifier. At any time, the diode's voltage or current is always zero, causing the power is zero and diode loss is also zero.

Reference [22] presented a traditional Class-C rectifier operating at 2.45 GHz, as shown in Fig. 8a. When the input power is 8dBm, the maximum efficiency of 72.8% is realized.

Table 1 Comparison of different harmonic-load rectifiers

	Class-C	Class-E	Class-F	Class-F^{-1}
Impedance in even harmonics	Low	–	Low	High
Impedance in odd harmonics	Low	–	High	Low
Voltage waveform	Sine	Half sine	Square	Half sine
Current waveform	Pulse	Half sine	Half sine	Square

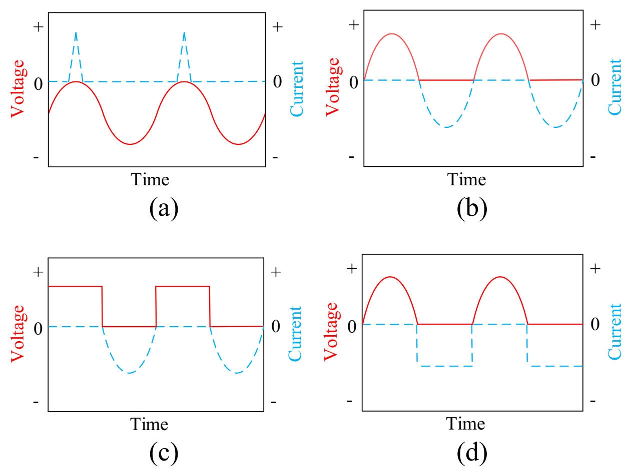

Fig. 7 Waveforms of different harmonic-load rectifiers. **a** Class-C, **b** Class-E, **c** Class-F, **d** Class-F^{-1} rectifiers

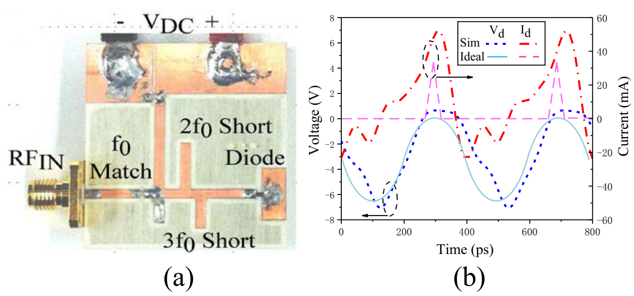

Fig. 8 **a** Class-C rectifier operating at 2.45 GHz [22], **b** diode's waveforms in Class-C rectifier [23]

In [23], a novel Class-C rectifier was designed, fabricated, and tested. Its diode's waveform is shown in Fig. 8b. The ideal pulse wave is different to achieve using a common diode. Thanks to the low diode loss, the rectifier in [23] has a peak efficiency of 82.7% at 25d Bm.

Figure 9 shows the drain voltage and current waveforms of CMOS rectifier in [24]. Their overlaps are very small meaning a low resistance loss during rectifying. When the input power is 10 dBm, its peak efficiency of 30% is measured at 2.4 GHz. In [25], an E-pHEMT was applied in the Class-E rectifier operating at 950 MHz, as shown in Fig. 10. The maximum efficiency of 83% is realized at 17 dBm.

The Class-F rectifiers are popular in the design of WPT system, since its simple structure and high efficiency, as shown in Fig. 11. The efficiency of Class-F rectifiers at different frequencies and input power levels is list in Table 2. It is clear that the conversion efficiency of rectifiers is high with Class-F load.

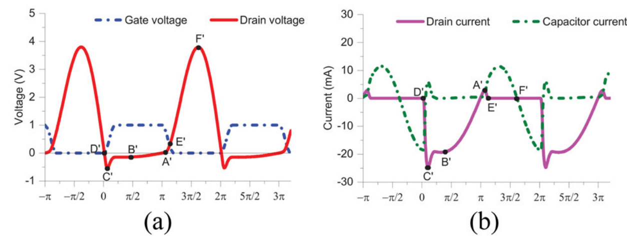

Fig. 9 **a** Voltage and **b** current waveforms for the CMOS class-E rectifier [24]

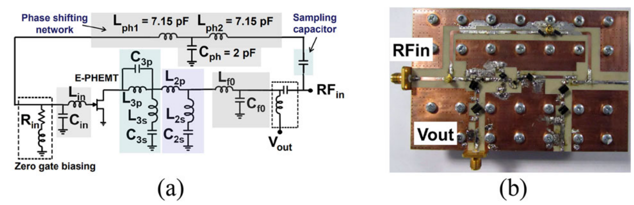

Fig. 10 **a** Schematic and **b** photography of the Class-E rectifier based on E-PHEMT [25]

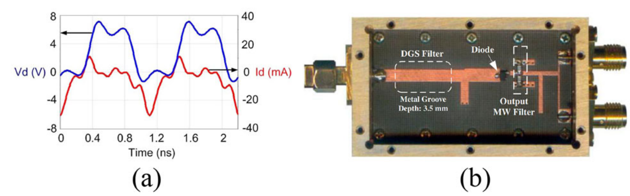

Fig. 11 **a** Diode's voltage and current waveforms in 900 MHz Class-C rectifier [26]. **b** 5.8 GHz Class-F rectifier with cavity [28]

Table 2 Efficiency of Class-F rectifiers at various frequencies and input power levels

References	Frequency (GHz)	Input power (dBm)	Efficiency (%)
[26]	0.90	13.4	80.4
[27]	2.45	16.8	83.5
[28]	5.80	15.0	72.1
[29]	24.0	–	65.6

Reference [30] proposed a Class-F^{-1} rectifier, whose diode's voltage and current waveforms are converse to those of Class-F rectifier. A 2.14 GHz Class-F^{-1} is designed based

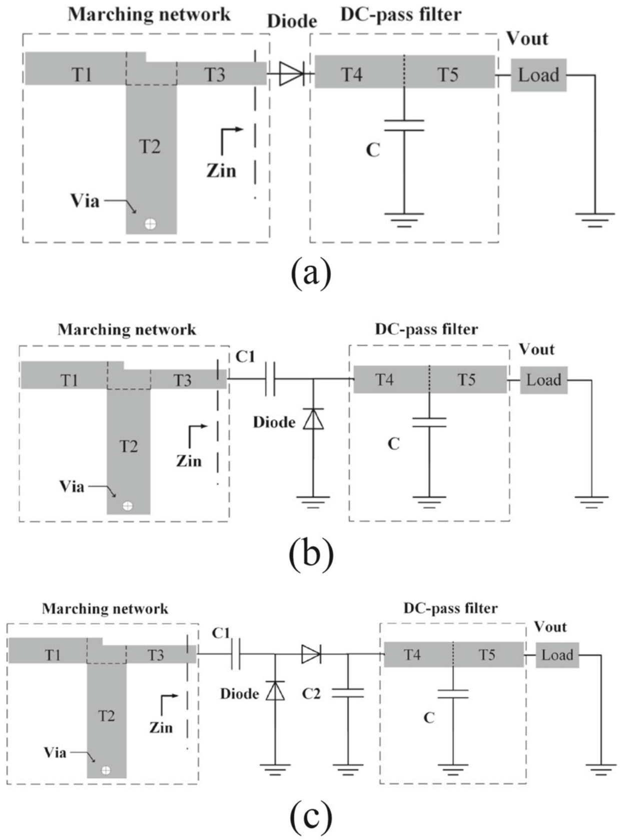

Fig. 12 Three rectifying structures: **a** series, **b** Villard, and **c** Greinacher [31]

on a GaN HEMT. Its maximum efficiency is 85% at the input power of 40 dBm.

3.2 Low Microwave Input Power Levels

Designs of high-efficiency rectifiers with low input power is more challenging than those designs with high power, since the nonlinear characteristics of rectifying diodes are not obvious and the output DC component is small. Some technologies are applied to improving the rectifiers' performance at low power levels.

Reference [31] simulated rectifiers based on traditional rectifying diodes with three typical structures: series, Villard, and Greinacher, as shown in Fig. 12. Figure 13 shows the simulated results that the efficiency of the rectifier with a diode in series is highest.

Rectifiers based on different zero-bias diodes (VDI ZBD, BAT15, SMS7630) are presented in [32]. Their pictures are shown in Fig. 14. The efficiency is improved by using a VDI W-band ZDB, which is not often used in a rectifier design (Fig. 15).

Heterojunction backward tunnel diodes are also employed in low-power rectifier designs [33]. The diode's schematic

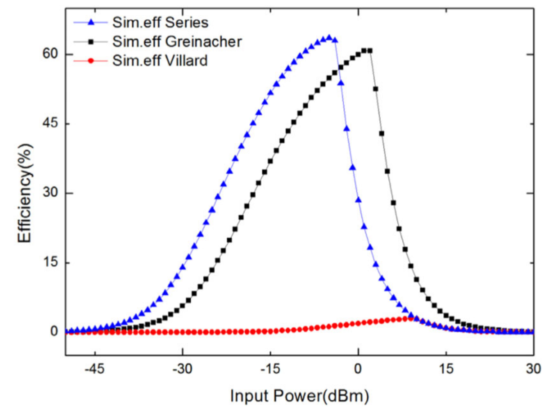

Fig. 13 Simulated results of three rectifiers [31]

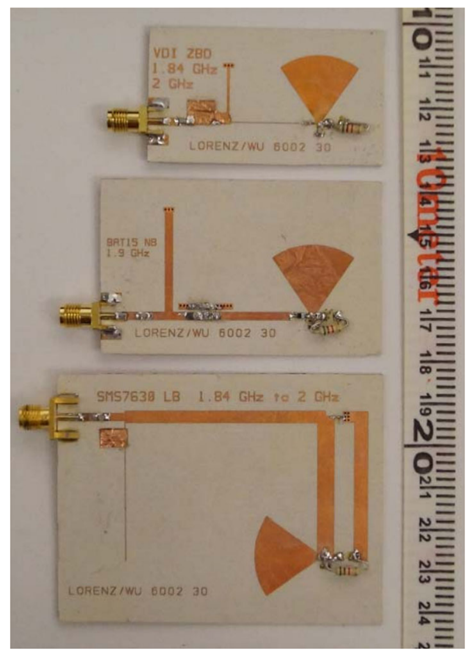

Fig. 14 Photography of the rectifiers in [32]

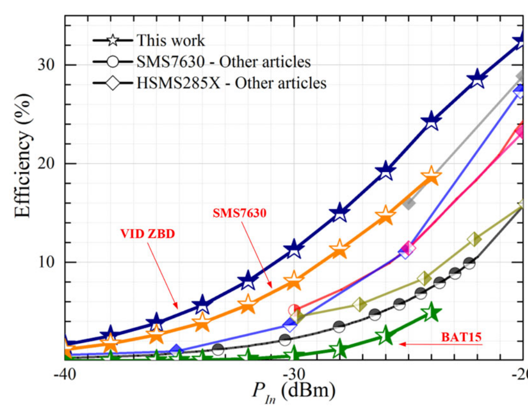

Fig. 15 Conversion efficiency based on different diodes [32]

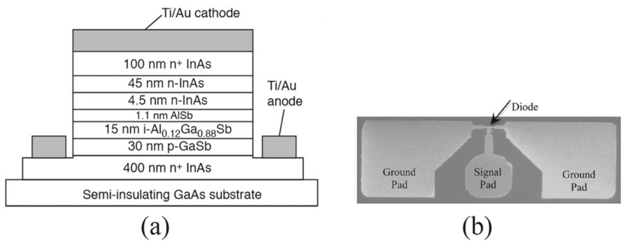

Fig. 16 **a** Backward tunnel diode's schematic cross-section diagram and **b** scanning electron micrograph [33]

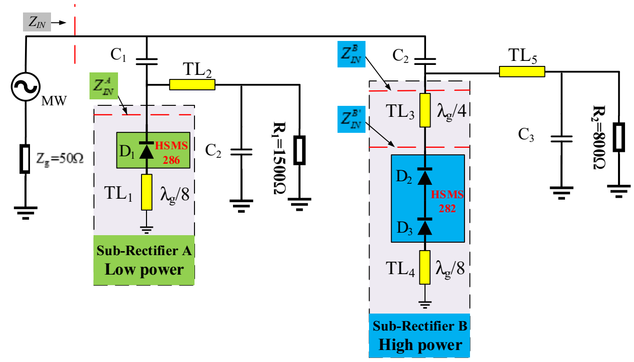

Fig. 17 Schematic of the rectifier with two sub-rectifiers for different power levels [36]

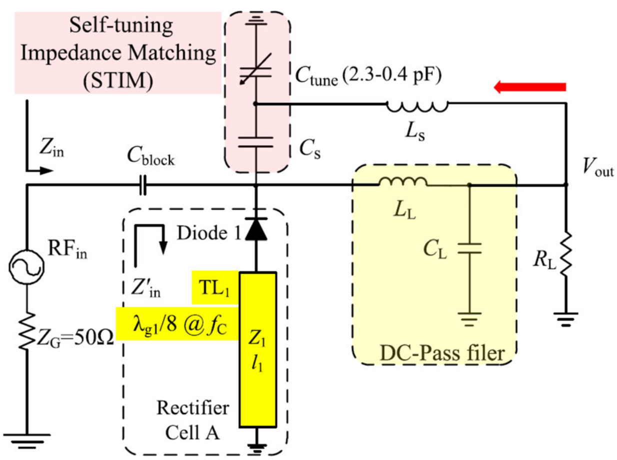

Fig. 18 Schematic of the rectifier with self-tuning impedance matching [42]

cross-section diagram and scanning electron micrograph are shown in Fig. 16. High efficiency can be achieved in low power levels using this diode for its improved zero-bias curvature and low turn-on voltage.

To enhance the value of rectifier's output DC voltage, technologies of internal threshold voltage cancelation [34] and rectifier-booster regulation [35] are introduced. Output higher DC voltage is achieved to drive electronic devices.

Usually, the breakdown voltages of the diodes for low-power rectifying are low. It is necessary to protect the diode from broke down reversely. For example, a Zener diode can be inserted in the output port of the rectifier to limit the DC voltage.

3.3 Wide Microwave Input Power Ranges

Rectifiers with wide dynamic range can realize high efficiency in low and high power. Mainly three technologies have been presented to decrease the sensitivity of the rectifying efficiency to input power variation, increasing the breakdown voltage of a rectifying diode [36–39], introducing power recycling [40, 41], and reducing the variation of input impedance caused by the input power [42].

Reference [36] proposed a wide dynamic rectifier based on two sub-rectifiers for low and high power, as shown in Fig. 17. With two HSMS282 diodes in series, the breakdown voltage of rectifying diode is enhanced. Finally, the power range of conversion efficiency over 50% is extended from − 1 to 30 dBm (31 dB).

A high-efficiency rectifier with self-tuning impedance matching based on a varactor was proposed in [42], as shown in Fig. 18. The value of varactor is controlled by the output DC voltage, which is related to the input power. The diode's impedance also will change with the input power variation. Thus, the varactor can be applied to compensating the variation of diode's impedance caused by the change of input power.

The measured results show that the maximum efficiency of 81.2% is realized. This rectifier has a wide power range from 2.5m to 25.5 dBm (23 dB) for efficiency over 50%.

4 Conclusions

In this paper, the development of microwave rectifiers, antennas, and SSPSs are reviewed. Key technologies to enhance conversion efficiency of rectifiers are proposed. When the input microwave power levels are high, harmonics produced during rectifying are taken into consideration to improve the rectifiers' performance. Harmonics suppression networks are applied to reducing harmonic losses. Harmonic-loaded networks, such as Class-C, Class-E, Class-F, and Class-F^{-1} loads, are employed to decrease overlapping of diode's voltage and current waveforms leading to a low diode loss. In low microwave input power levels, it is more challenging to design high-efficiency rectifiers. Traditional Schottky diodes may not be suitable for rectifying in very low power levels, such as − 20 dBm, − 30 dBm. A W-band ZBD and backward tunnel diodes have been used in rectifier designs for high-efficiency rectifying. What is more, some circuit technologies, including internal threshold voltage cancellation and rectifier-booster regulation, are also introduced to output higher DC voltage when the input microwave power is low. Finally, serval design methods of rectifiers with wide input power dynamic ranges are presented as well.

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Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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