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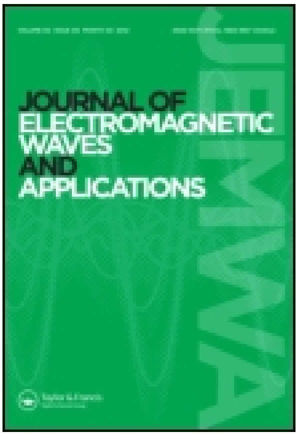

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A novel dual-frequency microwave rectifier at 2.45 and 5.8 GHz with harmonic recycling

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A novel dual-frequency microwave rectifier at 2.45 and 5.8 GHz with harmonic recycling

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A novel dual-frequency microwave rectifier that operates at 2.45 GHz alone, 5.8 GHz alone, or their combination has been developed in this paper. It is the first approach to microwave rectifying for a situation of the incoherent microwave power combination. We focused on the two primary components, i.e. the regulation of impedance matching and the recycling of the second harmonics. A quarter-wave short-ended microstrip line at 5.8 GHz is shunted at the input of the rectifier to enhance the impedance matching at 2.45 GHz. A microstrip line band-stop filter (BSF) and a quarter-wave short-ended microstrip line are introduced to improve the recycling of the second harmonics. The measured microwave to DC (MW-DC) conversion efficiencies are 57.5, 46.5, and 40.7% at 2.45, 5.8 GHz, and their combination, respectively, with an input microwave power at 17 dBm. It may be applied to a dual-frequency microwave power wireless transmission system.

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1. Introduction

Microwave power transmission is to realize a wireless point-to-point energy transmission with microwave. Main parameters of a microwave power transmission system include transmission efficiency, power capacitance, and transmitting distance. An essential component of a microwave power transmission system is the microwave rectifier, which converts microwave power into DC. Conventional microwave rectifiers have been extensively studied.[1–5] Peter Glaser proposed the concept of Solar Power Satellite (SPS), which aimed at the energy crisis in 1968.[6] Microwave power transmission technology becomes the most available wireless power transmission scheme for SPS due to the advantages of high efficiency, guaranteed safety, and long range.[7–9] It has been developed with the advance of space solar power system.[10,11]

Currently, most microwave rectifiers are developed for single frequency application. The conventional choice on frequency for a rectifier in a microwave power transmission system is at either 2.45 or 5.8 GHz due to its low cost and low attenuation through atmosphere. Both frequencies belong to the industrial, scientific, and medical band.[12] Dual-band components and systems, e.g. dual-frequency antennas and filters, have gained more and more attention in microwave community. Many studies have been carried out at dual frequency in wireless communication systems.[13] It is interesting to consider a dual-frequency microwave power transmission system, which may switch freely between two frequencies and choose one to obtain a better performance. We have proposed that a rectifier works at dual frequency with a small separation of 2 MHz, which is focused on the intermodulation recycling.[14] The frequencies separation should be much larger in a dual-frequency microwave power transmission system, in

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which dual-frequency microwave rectifiers are the bottle-neck. Thus, we focus on the design and implementation of dual-frequency microwave rectifiers.

This paper presents a novel dual-frequency microwave rectifier operating at 2.45 and 5.8 GHz. We selected HSMS-286C Schottky diode as the rectifying component which is presently considered as a mature device.[15] They belong to the Avago's HSMS-286x family and are designed and optimized for operating from 915 MHz to 5.8 GHz especially. A quarter-wave short-ended microstrip line is introduced to enhance the impedance matching of the microwave rectifier. A band-stop filter (BSF) and a quarter-wave short-ended microstrip line are applied to blocking the second-order harmonics, which are generated by the diode during rectifying. The conversion efficiency of the dual-frequency microwave rectifier reaches around 50% which is lower than a single-frequency one. The proposed dual-frequency microwave rectifier is the first step to approach a dual-frequency microwave power transmission system.

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2. Dual-frequency microwave rectifier design and implementation

A dual-frequency microwave rectifier should own impedance matching at either frequency [16,17] and be able to recycling harmonics of each frequency. Serious difficulties are encountered to simultaneously achieve the goals due to the interinfluence of the circuit at two frequencies, e.g. the impedance matching circuit at one frequency will impact the impedance matching at the other frequency. For a dual-frequency microwave rectifier, there are two input impedance matching and two classes of high-order harmonics to recycling. It is critical to introduce independent parameters for circuit tuning and make a performance trade-off between two frequencies.

We have selected 2.45 and 5.8 GHz as the operating frequencies of the dual-frequency microwave rectifier. The scheme, layout, and photo of the proposed dual-frequency microwave rectifier are shown in Figures 1(a)–(c), respectively. A BSF at 4.9 GHz is introduced between the diode and microwave source to reflect the second harmonic of 2.45 GHz microwave back to the diode. The series transmission line MLIN-2 is a quarter-wave short-ended transmission line at 11.6 GHz to block the second harmonic of 5.8 GHz microwave. Microstrip tapers are applied to impedance matching. The input impedance of a microstrip transmission line is

$$Z_{IN} = Z_0 \frac{Z_L + jZ_0 \tan \beta l}{Z_0 + jZ_L \tan \beta l} \tag{1}$$

where, Z_L, Z_{IN}, and Z_0 are the load, input, and characteristic impedance, respectively. β is the wave number, and l is the length of the transmission line. The quarter-wave short-ended microstrip line MLINE-1 is an open circuit at 5.8 GHz and applied as an independent impedance tuning component at 2.45 GHz.

2.1. Band-stop structures for harmonics recycling

Schottky diodes are nonlinear components, which produce high-order harmonics during rectifying. High-order harmonics take away power and reduce the rectifying efficiency. The second harmonic usually carries most power among the harmonics. Thus, we mainly focus on the recycling of the second harmonic. There are two band-stop structures, i.e. the BSF and the MLIN-2, in Figure 1. The BSF is a narrow band-rejection filter with center frequency at 4.9 GHz, and the MLIN-2 is a quarter-wave short-ended microstrip line at 11.6 GHz.

Although many different structures of BSF have been studied, such as a BSF with tunale central frequency and bandwidth,[18] they are complex. The layout of the proposed BSF is shown in Figure 1(b), which is just before TAPER-1. The center frequency of the BSF is at 4.9 GHz which is the second harmonic of 2.45 GHz. There are two shunt short-ended microstrip lines of half-wave

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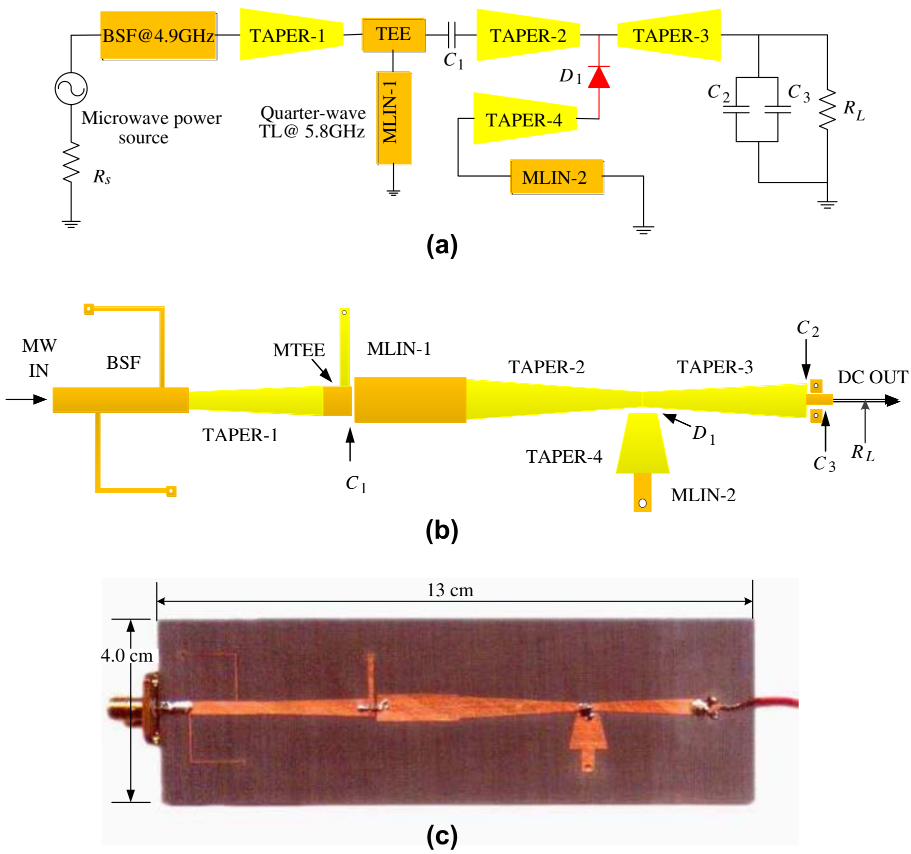

Figure 1. The (a) scheme, (b) layout, and (c) photo of the dual-frequency rectifier.

at 4.9 GHz to form the BSF. The input impedance of this microstrip line is zero, and microwave at 4.9 GHz will be totally reflected here. The BSF has a narrow rejection band, which does not affect microwave at 5.8 GHz. The BSF is simulated and optimized by IE3D. The simulated $|S_{11}|$ and $|S_{21}|$ are shown in Figure 2(a). The voltage reflections are −0.69 dB, −34.0 dB, and −38.0 dB at 4.9, 2.45, and 5.8 GHz, respectively. The insertion losses are 65.19, 0.047, and 0.239 dB at 4.9, 2.45 and 5.8 GHz, respectively.

The microstrip line MLIN-2 in Figure 1(b) is a quarter-wave short-ended microstrip line at 11.6 GHz, which is the second harmonic of microwave at 5.8 GHz. This microstrip line leads to high input impedance at 11.6 GHz. Thus, the second harmonic of microwave at 5.8 GHz is limited inside the rectifier and recycled by the diode. The simulated input impedance of MLIN-2 is shown in Figure 2(b), in which the input impedance reaches $510 + j49.0$ ohm at 11.6 GHz.

2.2. *Dual-frequency microwave rectifier design*

The series capacitor C_1 is applied to blocking DC and avoiding the damage to the microwave power source. The two shunt capacitors C_2 and C_3 compose a DC-pass filter to pass the DC power and reflect microwave and its harmonics back to the rectifier.[19] Two shunt capacitors reduce the effects of the parasitic inductance and enhance the performance of the DC-pass filter. When the two shunt capacitors are symmetrically placed, it resembles the defected ground structure, which can enhance the characteristics of the DC-filter.[20]

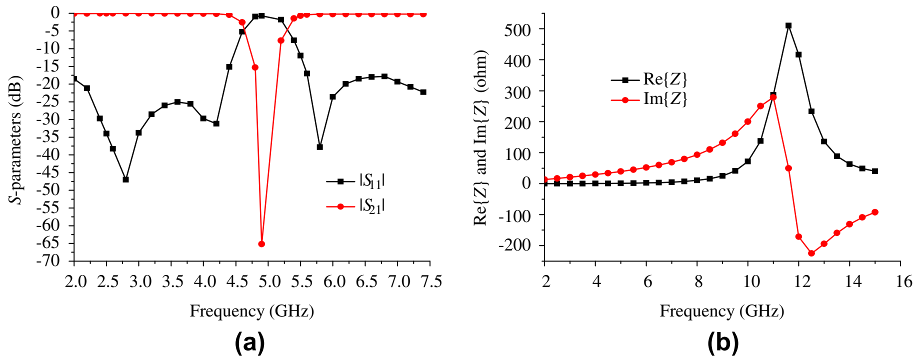

Figure 2. Simulated $|S_{11}|$ and $|S_{21}|$ of the BSF and input impedance of MLIN-2.

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According to the large signal model of the Schottky diode,[21] the Schottky diode has complex impedance. The impedance of the diode Z_D is

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

$$\tan\theta_{on} - \theta_{on} = \frac{\pi R_S}{R_L\left(1 + \frac{V_{bi}}{V_0}\right)} \tag{3}$$

where, θ_{on}, R_s, and C_j are the turn-on angle, series resistance, and junction capacitance, respectively. The junction capacitance is $C_j = C_{j0}\sqrt{\frac{V_{bi}}{V_0+V_{bi}}}$, where C_{j0}, V_{bi}, and V_0 are the junction capacitance under zero bias, the build-in voltage, and the biasing voltage, respectively. The parameters of HSMS286C diode used in the calculation are listed in Table 1. The HSMS-286C diode has a capacitive imaginary of the diode impedance. We take the imaginary part into consideration so as to improve the conversion efficiency.[2] MTAPER-3 and MLIN-2 in Figure 1(a) compose a series short-ended microwave strip line, which presents an inductive impedance. The capacitive impedance of the diode is canceled if the following condition holds

$$\text{Im}\{Z_D + jZ_0\tan\theta_{TL}\} = 0 \tag{4}$$

where, Z_0 and θ_{TL} are the characteristic impedance and the electrical length of the short-ended microstrip transmission line.

A dual-frequency microwave rectifier has to obtain impedance matching at either frequency to reach a high microwave-to-DC (MW-DC) conversion efficiency. A quarter-wave short-ended microstrip line (MLIN-1) at 5.8 GHz is shunted at the input to tune the impedance at 2.45 GHz independently. Agilent's Advanced Design System software (ADS) has been applied to optimizing the impedance matching and rectifying efficiency. The simulated normalized input impedances are $0.978 - j0.011$ and $0.997 - j0.016$ at 2.45 and 5.8 GHz, respectively.

The band-stop structures are simulated and optimized by IE3D. The simulation and optimization of the dual-frequency microwave rectifier are carried out by Agilent ADS, in which the band-stop structures are replaced by the exported S-parameters from IE3D. The dual-frequency microwave rectifier is realized on F4B substrate which has a relative dielectric constant $\varepsilon_r = 2.65$ and thickness of 1 mm. The fabricated dual-frequency microwave rectifier is shown in Figure 1(c).

Table 1. The parameters of diode HSMS-286C using in the calculation.

Parameter	Units	Value
C_{j0}	pF	0.18
R_s	Ω	6.0

3. Experimental results and discussion

3.1. Rectifying at a single frequency

An Agilent E8267C microwave vector signal generator is applied as the microwave power source. A standard resistor box is used as DC load. The output DC voltage is measured by an Agilent 34970 data acquisition. The (MW-DC) conversion efficiency of the dual-frequency microwave rectifier is defined as

$$\eta = \frac{P_{DC}}{P_{MW}} \times 100\% = \frac{(V_{DC})^2}{R_L} \times \frac{1}{P_{MW}} \times 100\% \tag{5}$$

where, P_{DC}, P_{MW}, V_{DC}, and R_L are the DC output power, microwave input power, DC output voltage, and load resistance, respectively.

Figure 3 shows the simulated and measured MW-DC conversion efficiency of the proposed rectifier at 17 dBm input power with respect to DC load. The measurement and simulation agree well at 2.45 GHz. The measured efficiencies are worse than the simulations at 5.8 GHz since the diode model is not so accurate at 5.8 GHz and its harmonics. The best DC loads at two frequencies are different. For the dual-frequency microwave rectifier, the highest conversion efficiencies are 57.5% at 2.45 GHz with a 200 Ohm load and 46.5% at 5.8 GHz with a 50 Ohm load. The output voltages at two frequencies are 2.40 and 1.08 V, respectively. Figure 4 shows the measured efficiencies of the dual-frequency rectifier at 2.45 and 5.8 GHz with respect to input power. The DC loads are 200 ohm and 50 ohm at 2.45 and 5.8 GHz, respectively. This measurement results that agree well with the design for the best input power are at 50 mW.

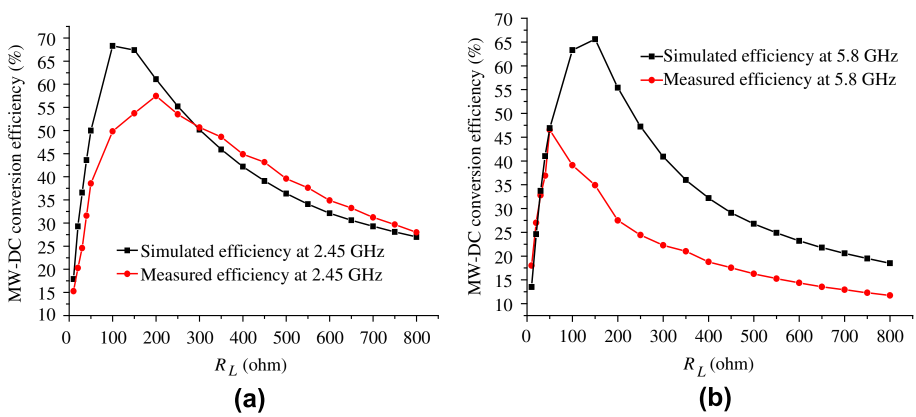

Figure 3. Simulate MW-DC conversion efficiency at (a) 2.45 GHz, and (b) 5.8 GHz of the proposed dual-frequency microwave rectifier. The input microwave power is 17 dBm.

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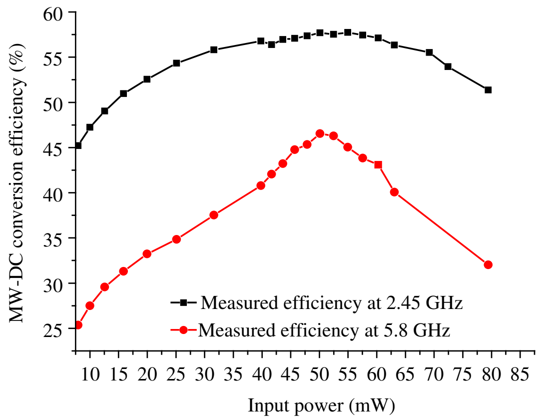

Figure 4. The measured MW-DC efficiency of the proposed rectifier at 2.45 and 5.8 GHz, respectively, with respect to input microwave power.

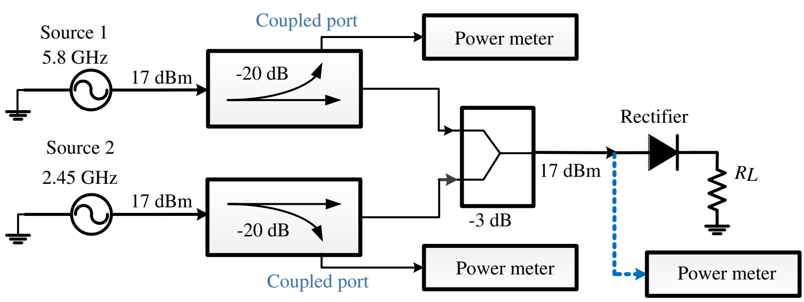

Figure 5. Measurement system at dual frequencies.

3.2. Rectifying with incoherent microwave power combination

It is interesting to explore the rectification of the proposed dual-frequency microwave rectifiers with microwave input at both 2.45 and 5.8 GHz, which is an incoherent microwave situation. The conversation efficiencies at dual frequencies are measured, and the measurement system is shown in Figure 5. An Agilent E8267C microwave vector signal generator and a 2.45 GHz solid state microwave generator are applied to generate the input microwave power. Two 20 dB directional couplers and an AV2433 dual-channel power meter are applied to monitoring the input microwave power. The microwave's power at dual frequencies are combined by a 3 dB power divider, and the output power is verified by an Agilent U2000A power meter because it may be unstable,[22] as shown with a dashed line in Figure 5. The output DC voltage is measured with an Agilent 34970 data acquisition. The microwave to DC efficiency is defined in (5) as well.

Figure 6 shows the measured microwave to DC conversion efficiency with respect to DC load at microwave input with dual frequencies. Microwave power at either frequency is 17 dBm, and they are composed to 17 dBm by a 3 dB power divider. The measured highest efficiency is 40.7% with a 50 ohm load and the output DC voltage is 1.01 V. This efficiency is lower than that at either frequency mainly due to the intermodulation that has not been recycled. It is reasonable to build an incoherent microwave power transmission system, in which two microwave sources at different frequencies are applied simultaneously.

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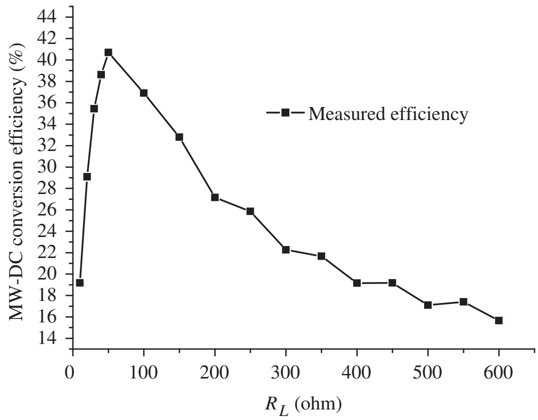

Figure 6. The MW-DC conversion efficiency with respect to DC load.

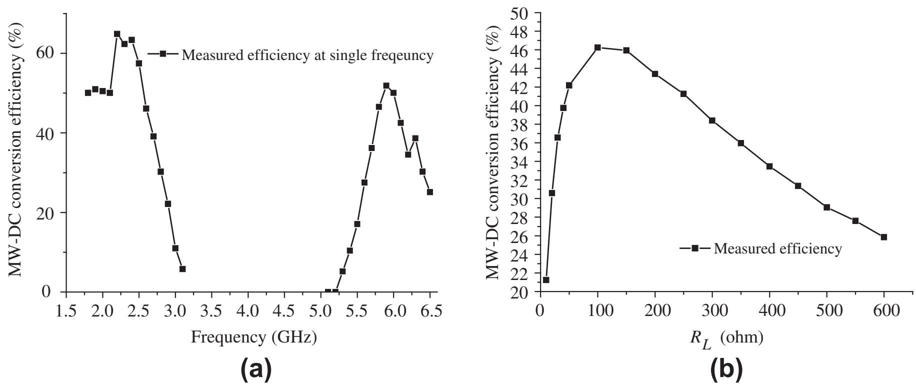

Figure 7. Frequency deviation and efficiency with respect to DC Load. (a) Frequency deviation. (b) Efficiency with respect to DC Load.

3.3. *Frequency deviation*

Figure 7(a) shows the frequency deviation of the proposed rectifier dependent on single frequency input with 17 dBm input power. The highest conversion efficiencies are 64.9% at 2.2 GHz with 200 ohm DC load and 51.9% at 5.9 GHz with 50 ohm DC load. There is a frequency deviation to the original design due to fabrication and lumped elements tolerance. When the input frequencies are 2.2 and 5.9 GHz, the best DC load is 100 ohm and the efficiency reaches 46.2%, as shown in Figure 7(b).

4. Conclusions

This paper proposes a novel dual-frequency microwave rectifier for 2.45 and 5.8 GHz microwave power transmission systems. A method for dual-frequency microwave rectifier design is presented. The introduced band-stop structures recycle the second-order harmonics efficiently at either frequency. Impedance matching at two frequencies is realized with independently tunable microstrip structures. The measured data show that the proposed dual-frequency rectifier achieves efficiencies of 57.5, 46.5, and 40.7% at 2.45 GHz alone, 5.8 GHz alone, and their combination, respectively. The highest efficiency reaches 46.2% at the incoherent microwave input at 2.2 and 5.9 GHz. It is the first approach to microwave rectifying at an incoherent microwave power combination situation. In future, a microwave wireless power transmission system with incoherent microwave power sources will be built to demonstrate a new microwave power transmission mechanism. The proposed dual-frequency microwave rectifier may find applications in the system.

We will enhance the MW-DC conversion efficiency at incoherent microwave input situation by recycling the intermodulation products besides the harmonics. Moreover, artificial transmission lines may be applied to the rectifier to make it more compact,[23,24] and the power capacitance may be enhanced by the diode array technique.[25] With the development of accurate diode models, the design of a microwave rectifier is more reliable to achieve higher rectifying efficiency. Microwave power transmission systems will find more applications in various areas.

Acknowledgements

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