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Rectennas for microwave power transmission

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Abstract: Microwave power transmission (MPT) has had a long history before the more recent movement toward wireless power transmission (WPT). MPT can be applied not only to beam-type point-to-point WPT but also to an energy harvesting system fed from distributed or broadcasting radio waves. The key technology is the use of a rectenna, or rectifying antenna, to convert a microwave signal to a DC signal with high efficiency. In this paper, various rectennas suitable for MPT are discussed, including various rectifying circuits, frequency rectennas, and power rectennas.

Keywords: wireless power transfer, microwave power transmission, rectenna

Classification: Microwave and millimeter wave devices, circuits, and systems

References

[1] W. C. Brown: IEEE Trans. Microw. Theory Tech. **32** [9] (1984) 1230.
[2] N. Shinohara: IEEE Microw. Mag. **12** [7] (2011) S64.
[3] N. Shinohara: Journal of the Korean Institute of Electromagnetic Engineering and Science **10** [4] (2011) 224.
[4] N. Shinohara: IEICE Trans. Commun. (Japanese Edition) **J96-B** [9] (2013) in print.
[5] B. L. Diamond: Proc. IEEE **56** (1968) 1837.
[6] L. Stark: Proc. IEEE **62** (1974) 1661.
[7] K. Itoh, T. Ohgane and Y. Ogawa: Space Power **6** (1986) 193.
[8] T. Saen, K. Itoh, S. Betsudan, S. Makino, T. Hirota, K. Noguchi and M. Shimozawa: Proc. IMWS-IWPT2011 (2011) 255.
[9] T. Ohira: IEICE Electron. Express **10** [11] (2013) 1.
[10] R. J. Gutmann and J. M. Borrego: IEEE Trans. Microw. Theory Tech. **27** (1979) 958.
[11] K. Hatano, N. Shinohara, T. Seki and M. Kawashima: Proc. RWS (2013) 199.
[12] A. Noda and H. Shinoda: Proc. IMS2012 (2012) TH1A-5.
[13] J. Guo and X. Zhu: Proc. IMS (2013) WE4G-1.
[14] M. Roberg, E. Falkenstein and Z. Popovic: Proc. IMS2012 (2012) TH1A-4.
[15] M. N. Ruiz, R. Marante and J. A. García: Proc. IMS2012 (2012) TH1A-3.
[16] N. Shinohara: Proc. 42nd EuMW (2012) 1347.

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Received September 22, 2013
Accepted October 09, 2013
Published November 10, 2013

[17] T.-W. Yoo and K. Chang: IEEE Trans. Microw. Theory Tech. **40** [6] (1992) 1259.
[18] J. O. MaSpadden, L. Fan and K. Chang: IEEE Trans. Microw. Theory Tech. **46** [12] (1998) 2053.
[19] W. C. Brown: Proc. SPS Microwave Systems Workshop at JSC-NASA (1980) 271.
[20] W. C. Brown: Proc. IEEE GMIT Int. Microwave Symposium (1978) 349.
[21] W. C. Brown: MTT-S Int. Microwave Symp. (1976) 142.
[22] T. Itoh, Y. Fujino and M. Fujita: IEICE Trans. Commun. **E76-B** [12] (1993) 215.
[23] Y. Kobayashi, H. Seki and M. Itoh: Proc. IEICE in Spring (in Japanese) (1993) 2-37.
[24] S. Kim, N. Shinohara and H. Matsumoto: Proc. 5th SPS symposium (in Japanese) (2002) 83.
[25] S. Kim, N. Shinohara and H. Matsumoto: Proc. IEICE in Spring (in Japanese) (2003) C-2-97.
[26] M. Roberg, T. Reveyrand, I. Ramos, E.A. Falkenstein and Z. Popović: IEEE Trans. Microw. Theory Tech. **60** [12] (2012) 4043.
[27] T. Shibata, Y. Aoki, M. Otsuka, T. Idogaki and T. Hattori: IEICE Trans. Electron. **80-C** [2] (1997) 303.
[28] S. Ladan and K. Wu: Proc. IMS2013 (2013) WE4G-2.
[29] A. Collado and A. Georgiadis: Proc. IMS2013 (2013) WE4G-3.
[30] J. O. McSpadden, K. Chang and A. D. Patton: Space Energy and Transportation **1** [4] (1996) 368.
[31] H. Gao, M. K. Matters-Kammerer, D. Milosevic, A. van Roermund and P. Baltus: Proc. IEEE RFIC2013 (2013) RMO3B-5.
[32] X. Wang and A. Mortazawi: Proc. IMS2013 (2013) WE4G-4.
[33] A. P. Sample and J. R. Smith: Proc. RWS2009 (2009) 16.
[34] Y. Kawahara, W. Wei, Y. Narusue, R. Shigeta, T. Asami and M. Tentzeris: Proc. RWS2013 (2013) 37.
[35] http://www.powercastco.com/products/powerharvester-receivers/
[36] N. Zhu, R. W. Ziolkowski and H. Xin: IEEE Antennas Wireless Propag. Lett. **10** (2011) 935.
[37] L. W. Epp, A. R. Khan, H. K. Smith and R. P. Smith: IEEE Trans. Microw. Theory Tech. **48** [1] (2000) 111.
[38] A. Takacs, H. Aubert, L. Despoisse and S. Fredon: Proc. IMS2013 (2013) WE3G-1.
[39] Y.-H. Suh and K. Chang: IEEE Trans. Microw. Theory Tech. **50** [7] (2002) 1784.
[40] B. L. Pham and A.-V. Pham: Proc. IMS2013 (2013) WE3G-5.
[41] J. A. Hagerty, F. B. Helmbrecht, W. H. McCalpin, R. Zane and Z. B. Popovic: IEEE Trans. Microw. Theory Tech. **52** [3] (2004) 1014.
[42] K. Mori, A. Katayama, K. Tsutusmi, K. Nishikawa, A. Kurita, T. Kamemaru and N. Suematsu: Proc. of IEICE in Spring (in Japanese) (2006) CBS1-6.
[43] C.-L. Yang, Y.-L. Yang and C.-W. Yang: Proc. IMS2013 (2013) WE3G-3.
[44] H. Kitayoshi and K. Sawaya: Proc. IEICE in Spring (in Japanese) (2006) CBS1-5.
[45] T. Yamashita, K. Honda and K. Ogawa: Proc. URSI EMTS2013 (2013) 823.
[46] Y. Ueda, K. Fujimori, S. Nogi and M. Sanagi: Proc. IEICE (in Japanese) (2004) SBC-1-9.
[47] N. Shinohara, H. Matsumoto, A. Yamamoto, H. Okegawa, T. Mizuno, H.

DOI: 10.1587/elex.10.20132009
Received September 22, 2013
Accepted October 09, 2013
Published November 10, 2013

Uematsu, H. Ikematsu and I. Mikami: IEICE Technical Report SPS2004-08 (2005) 15.
[48] N. Shinohara: Proc. 2nd International Conference on Telecommunications and Remote Sensing (ICTRS2013) (2013) 49.
[49] J. A. G. Akkermans, M. C. van Beurden, G. J. N. Doodeman and H. J. Visser: IEEE Antennas Wireless Propag. Lett. **4** (2005) 187.
[50] J. Zbitou, M. Latrach and S. Toutain: IEEE Trans. Microw. Theory Tech. **54** [1] (2006) 147.
[51] N. Shinohara and H. Matsumoto: IEEE Trans. Microw. Theory Tech. **46** [3] (1998) 261.
[52] N. Shinohara and H. Matsumoto: Electrical Engineering in Japan **125** [1] (1998) 9.
[53] T. Miura, N. Shinohara and H. Matsumoto: Electronics and Communications in Japan, Part 2 **84** [2] (2001) 27.

1 Introduction

Wireless power transfer (WPT) is one of the hot topics in microwave and millimeter wave devices, circuits, and systems. Some short-distance WPT systems involving inductive coupling and resonance coupling have already been applied for commercial applications. The next logical application will be long-distance WPT. Historically, WPT via microwaves, or microwave power transmission (MPT), was started in 1960s [1, 2] and resonance coupling WPT was proposed by MIT in 2006. Microwaves are suitable for focusing wireless power. To increase beam efficiency over long distances, the frequency should theoretically be increased [3, 4]. But higher frequency decreases the circuit efficiency in transmitters, receivers, and rectifying circuits. Energy harvesting from broadcast radio waves is the other potential application of WPT and is the focus of this paper. For energy harvesting, the efficiency of the rectifying circuit and antenna (the rectenna) is also important. In this paper, various types of rectenna are discussed.

2 Rectenna – rectifying antenna –

A rectenna is a passive element with rectifying diodes that operates without an internal power source. It can receive and rectify microwave power to DC power. A general block diagram of a rectenna is shown in Fig. 1. A low-pass filter is installed between the antenna and the rectifying circuit to suppress re-radiation of higher harmonics from the diodes. An output filter is used not only to stabilize DC current but also to increase RF-DC conversion efficiency at a single shunt rectifier as described later.

We can apply various antennas and rectifying circuits. The selection depends on requirements for a system and its users. When we use a rectenna array, the antennas in the rectennas can absorb 100% of input microwaves [5, 6, 7]. Higher efficiency rectifying circuits are required because the WPT system is an energy system. There are various rectifying circuits that can

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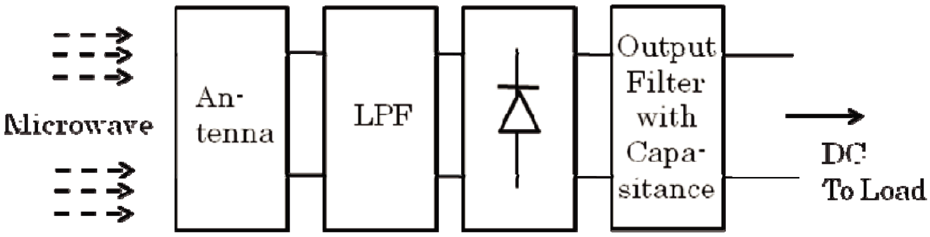

Fig. 1. General block diagram of rectenna.

reach 100% efficiency in theory. Details of general rectifying circuits are described in [8, 9].

In MPT, a single-shunt full-wave rectifier is often used. The single-shunt rectifier is composed of a diode and a capacitor in parallel connection and a $\lambda_\mathrm{g}/4$ distributed line. λ_g is the effective wavelength of an input radio wave (microwave or millimeter wave). The $\lambda_\mathrm{g}/4$ distributed line and the parallel capacitance work in tandem as an output filter. The single-shunt rectifier can theoretically rectify the input microwave at 100% with only one diode because of the effect of the output filter [10].

Fig. 2 shows the block diagram of a rectenna with a single-shunt rectifier and an explanation of the 100% rectifying theory. A low-pass filter and a capacitance for DC conversion are usually installed between an antenna and a rectifier. An input impedance Z to the right of the diode is formulated as follows:

$$Z_L = \frac{R_L}{1 + j\omega C R_L} \tag{1}$$

$$Z = \frac{Z_L + jZ_0 \tan(\beta l)}{Z_0 + jZ_L \tan(\beta l)} Z_0 \tag{2}$$

where R_L is the load resistance, C is the capacitance of the output filter, Z_0 is the characteristic impedance of a distributed line and its circuit, l is the length of the distributed line, β is a phase constant ($= 2\pi/\lambda_\mathrm{g}$), and ω is the angular frequency of the input electromagnetic wave. For odd harmonics, $3\omega,\ 5\omega\ \ldots$, $\tan\beta l$ becomes infinity and Z becomes infinity when $l = \lambda_\mathrm{g}/4$ and C is large enough ($Z = Z_0^2/Z_L$). For even harmonics, $2\omega,\ 4\omega\ \ldots$, $\tan\beta l$ becomes zero and Z becomes zero when $l = \lambda_\mathrm{g}/4$ and C is large enough ($Z = Z_L$). By the effect of the output filter that passes only even harmonics, the diode becomes a half-wave doubler and the $\lambda_\mathrm{g}/4$ distributed line becomes a full-wave rectifier. Thus, the single-shunt rectifier is very similar to a class-F amplifier. The class-F rectenna was originally proposed by Kyoto University [11]. A second group developed a class-F rectenna with 77.9% efficiency at 2.45 GHz [12]; theoretical analysis of the class-F rectenna is described in [13]. Class-C, class-E, and class-inverse F rectennas have also been proposed and developed [14, 15]. In these reports, the RF-DC conversion efficiencies of class-C, class-E, and class-inverse F rectennas were 72.8% at 2.45 GHz, 83% at 950 MHz with HEMT diodes, and 85% at 2.14 GHz with GaN HEMT diodes, respectively.

Many rectennas using a single-shunt rectifier have demonstrated 70–80% RF-DC conversion efficiency [16]. Compared to a bridge rectifier with four

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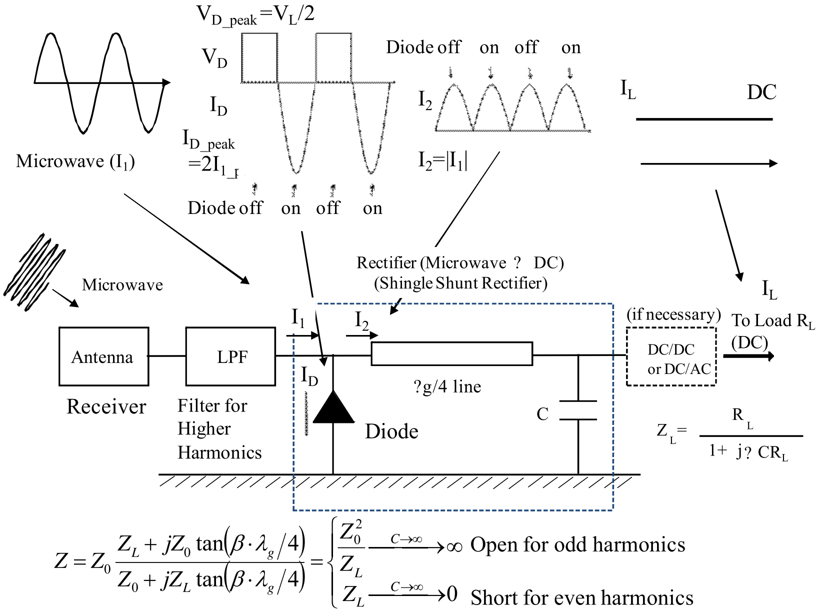

$$Z = Z_0 \frac{Z_L + jZ_0 \tan(\beta \cdot \lambda_g/4)}{Z_0 + jZ_L \tan(\beta \cdot \lambda_g/4)} = \begin{cases} \frac{Z_0^2}{Z_L} \xrightarrow{C\to\infty} \infty \\ Z_L \xrightarrow{C\to\infty} 0 \end{cases}$$

Fig. 2. Block diagram of a rectenna with a single-shunt full-wave rectifier and its theoretical waveform.

diodes, the efficiency of the single-shunt rectifier is higher because there is only one diode with a resistance loss factor in the single-shunt rectifier.

Theoretically, the RF-DC conversion efficiency of a rectenna is 100%. But a real diode and a real circuit have loss factors. The V-I characteristics of the diode in particular determine the RF-DC conversion efficiency [17, 18]. Fig. 3 indicates typical RF-DC conversion efficiency of the rectenna showing not only single shunt but also all rectifying circuits with diodes. V_J is the junction voltage of a diode and V_{br} is the breakdown voltage of a diode. Based on Fig. 4, the RF-DC conversion efficiency is theoretically calculated with the real diode parameters R, L, and C [18]. This characteristic also holds with a connected load instead of the input power.

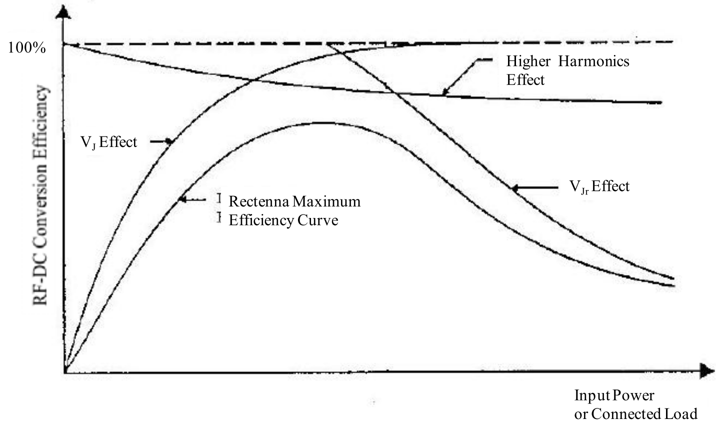

Fig. 3. Typical relationship between RF-DC conversion efficiency and input power.

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3 Various rectennas I – rectifying circuits –

The single shunt is not the only rectifying circuit available. Various rectennas have been proposed. The world's first rectenna developed by W. C. Brown in 1963 was a normal bridged rectifier [19]. The operating frequency was 2.45 GHz. 2.45 GHz (and 5.8 GHz) lies in the industrial, science, and medical (ISM) band. The rectenna was a string-type rectenna developed for a fuel-free helicopter experiment in 1964. It was conceived at Raytheon Co., and a power output of 7 W was produced at approximately 40% efficiency with four point-contact diodes.

Next, Brown developed the first single-shunt rectenna (Fig. 4) [20]. It was developed for low-cost production. The same type of rectenna was adopted for a 1.6 mile MPT field experiment in Goldstone in 1975 [1]. Brown developed a large rectenna array with a size of 3.4 m × 7.2 m. The transmitted microwave power from the klystron source was 450 kW at a frequency of 2.388 GHz in the field experiment, and the achieved rectified DC power was 30 kW DC with 82.5% rectifying efficiency. At last, Brown achieved 90% efficiency of the rectenna at 2.45 GHz [21].

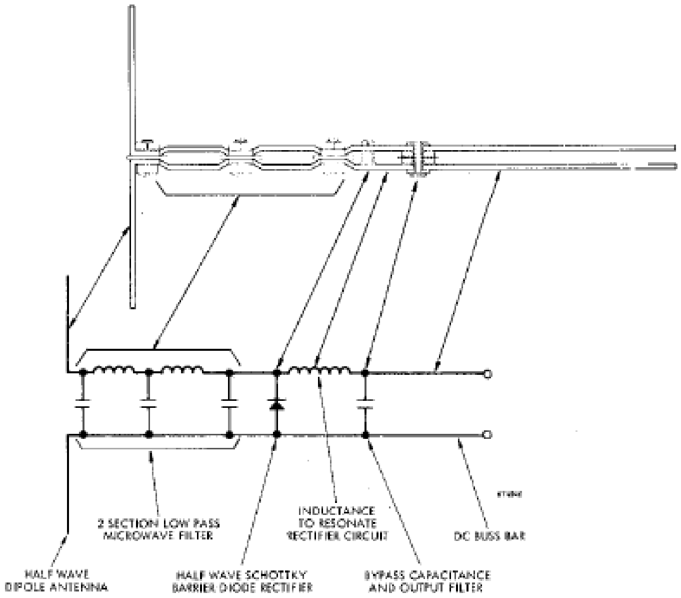

Fig. 4. Single-shunt rectenna developed by W. C. Brown [20] (© IEEE 1978).

After the progress of the rectenna achieved by Brown, some interesting approaches were taken to increase efficiency. Fig. 5 shows a full-wave rectifier with 0°–180° combination through an antenna [22]. In that rectifier, a combination of reverse phase microwave was used to realize full-wave rectifying. The antenna plays an important role to create the reverse phase. The other approach using a 0°–180° combination had a rat-race hybrid circuit (Fig. 6) [23]. The frequency was 2.45 GHz in both rectennas developed in [22, 23].

A diode used in a rectifying circuit is a nonlinear device. So we cannot

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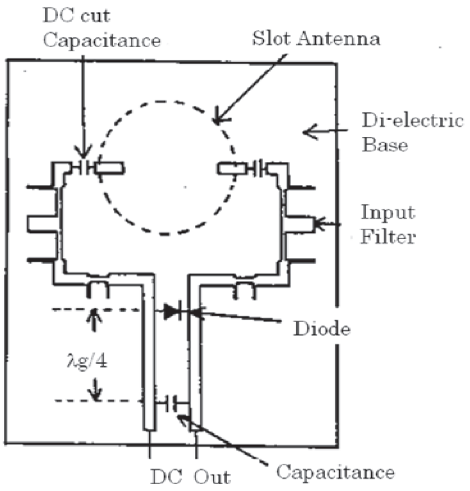

Fig. 5. Full-wave rectifier with 0°–180° combination through the antenna [22] (© IEICE 1993).

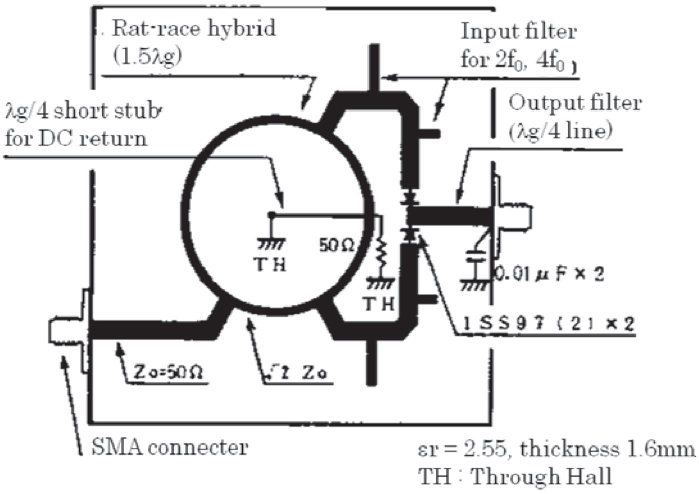

Fig. 6. Full-wave rectifier with 0°–180° combination through a rat-race hybrid (Originally in Japanese) [23] (© IEICE 1993).

match its impedance to suppress reflection from the rectifying circuit with varying microwave input or connected load. In an optimum microwave circuit with optimum input and optimum load, the reflected microwave signal is less than 1%, but RF-DC conversion efficiency becomes less than 10% and the reflected microwave is over 50% when the input microwave and the connected load are not optimum (See Fig. 3). So a rectenna with utilization of the reflected microwave was proposed by Kyoto University [24, 25]. We proposed and developed three types of rectennas, called “feedback rectenna” (Fig. 7 (a)), “feedback rectenna with rat-race hybrid” (Fig. 7 (b)), and “rectenna with direct utilization of reflected microwave” (Fig. 7 (c)), all operating at 2.45 GHz.

All rectennas in this paper have diodes to rectify microwaves. But, Prof. Popovic group adopt a FET to rectify microwaves. She proposed and de-

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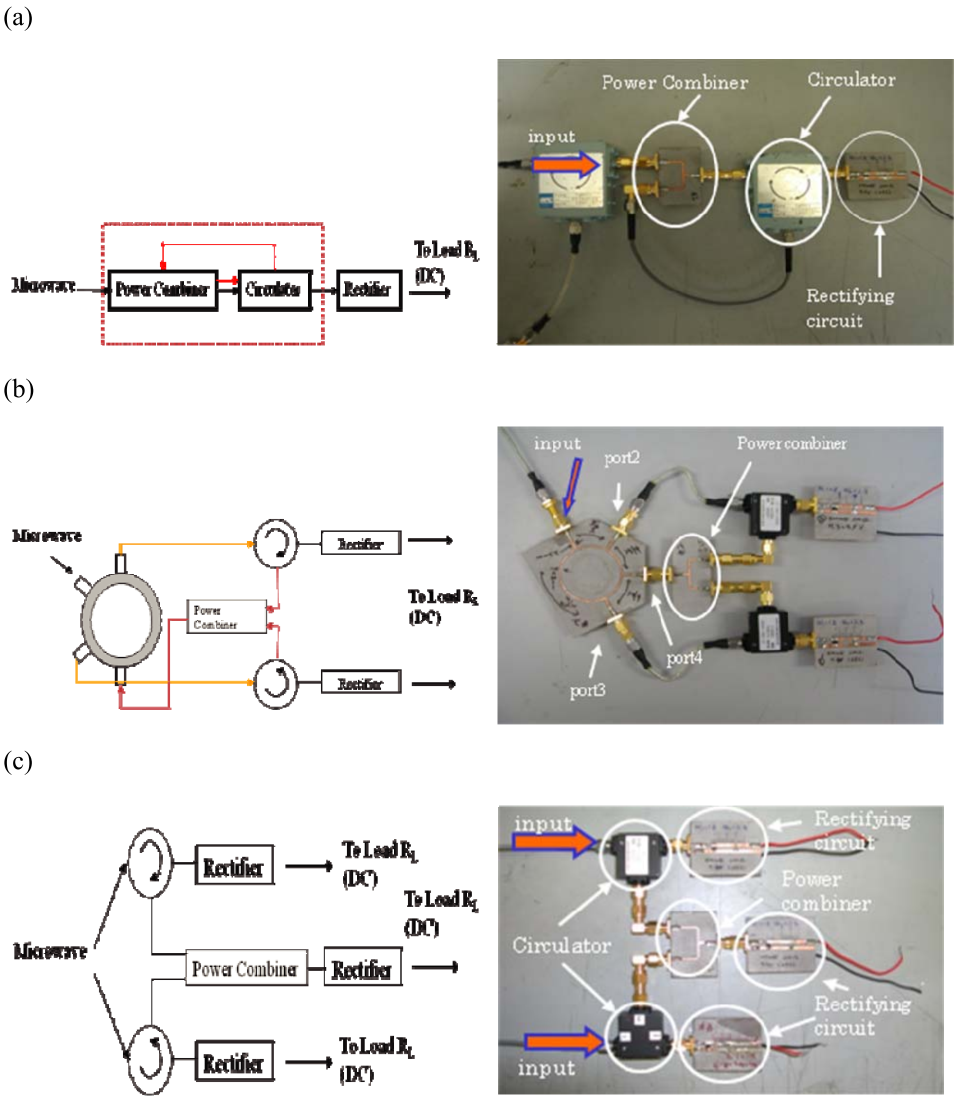

Fig. 7. (a) Feedback rectenna, (b) feedback rectenna with rat-race hybrid, and (c) rectenna with direct utilization of reflected microwave [24].

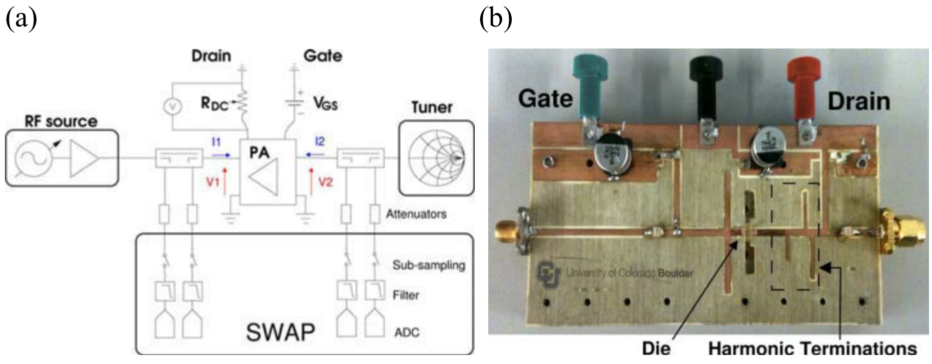

Fig. 8. (a) Block diagram of PA-rectifier, (b) Developed PA-rectifier with class inverse-F [26] (© IEEE 2012).

veloped a rectenna with FET which is the same as class inverse-F amplifier (Fig. 8) [26]. Any amplifier will function as a rectifier, and at microwave frequencies as a self-synchronous rectifier without any gate drive. She calls it

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‘PA-rectifier’ and achieves 85% efficiency at 2.11 GHz, 8-10 W input. It can be used as class inverse-F amplifier whose PAE (Power Added Efficiency) is 83% at 2.11 GHz, 8 W input.

4 Various rectennas II – higher frequency and dual bands –

Antenna theory determines beam efficiency based on the parameters of antenna diameter, distance, and frequency [4]. Higher frequency will reduce the size of the antennas for MPT. Some trials were conducted for development of rectennas at higher frequencies.

The next ISM band after 2.45 GHz is 5.8 GHz. Research groups have developed 5.8 GHz rectennas [17]. In particular, a rectenna developed at Texas A&M University has the highest RF-DC conversion efficiency at 5.8 GHz; the efficiency is over 80% even when the load varies from 300 to 500 Ω with a VSWR of 1.29 at 50 mW of input microwave power [17].

Denso Corp. in Japan developed 14 GHz rectennas for a moving robot in a tube. The size of the tube determined the frequency. A monopole antenna and a voltage doubler were adopted in this system [27]. RF-DC conversion efficiency was approximately 39% at 14–14.5 GHz, 100 mW, and 2 kΩ.

Kyoto University and NTT Corp. in Japan collaborated to produce a MPT to feed a Fixed Wireless Access (FWA) network. As a final example, we consider a simultaneous wireless system with information and power at millimeter wave levels. First, we developed a 24 GHz MMIC rectenna [11]. 24 GHz is also on ISM band. We chose a class-F load as an output filter to increase efficiency at higher frequencies. Dimensions of the 24 GHz MMIC rectenna are 1 mm × 3 mm on GaAs (Fig. 15), with a maximum RF–DC conversion efficiency of 47.9% for a 210 mW microwave input signal at 24 GHz with a 120 Ω load. A Canadian group and a Spanish group have also developed 24 GHz rectennas for energy harvesting [28, 29].

A 35 GHz rectenna was developed at Texas A&M University [17, 30]. The first 35 GHz rectenna was developed with 39% power conversion efficiency at approximately 100 mW and 400 Ω [17]. The researchers then modified the

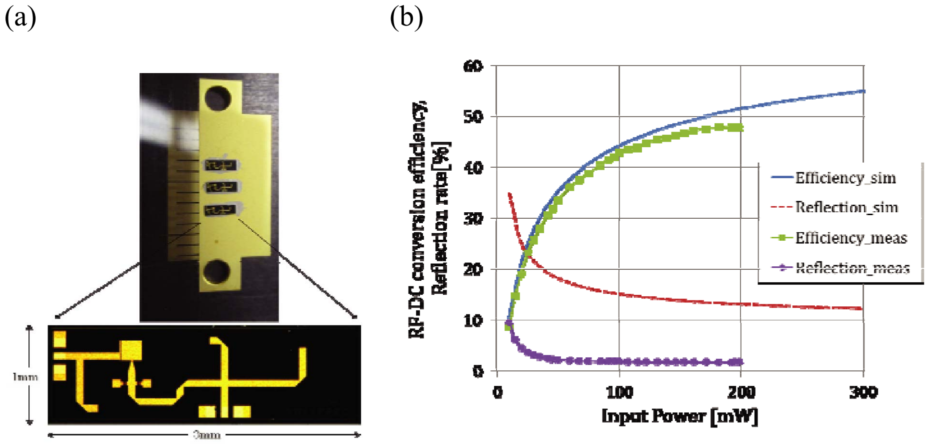

Fig. 9. (a) Developed MMIC rectenna at 24 GHz and (b) RF-DC conversion efficiency [11] (© 2013 IEEE).

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35 GHz rectenna by replacing the dipole with a rectangular patch antenna and the modified rectenna showed an efficiency of 60% at an input power of 25 mW based on a free-space measurement [30].

Texas A&M also simultaneously developed a 10 GHz rectenna with 60% efficiency.

A 60 GHz rectenna was developed with MMIC technology at Eindhoven University of Technology, Netherland [31]. They indicated that several low impedance paths caused by parasitic capacitances lead to a trade-off between isolation and insertion-loss at 60 GHz. Therefore, the inductor-peaked rectifier structure was proposed and realized. An inductor-peaked diode connected transistor, self-threshold voltage modulation and a low-pass output filter are used to increase the sensitivity and the efficiency of the rectifier. The series input inductor can take advantage of the voltage boost effect. The designed rectifier reaches 7% efficiency at 62 GHz with −14 dBm input.

Various other RF and microwave harvester modules have been reported in the literature; AM broadcasting radio [32], broadcasting TV [33, 34], GSM [35], GPS [36], X-band [37], and K-band [38].

Dual-band rectennas are useful for various applications. A 2.45 GHz and 5.8 GHz dual-band rectenna, in which a single-shunt rectifier was used, was developed at Texas A&M University (Fig. 10) [39].

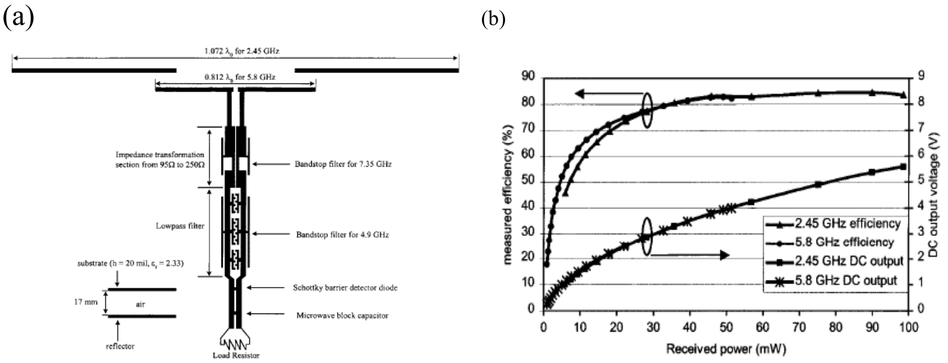

Fig. 10. (a) Dual-band rectenna developed at Texas A&M University and (b) RF-DC conversion efficiency and reflection ratio of dual-band rectenna [39] (© IEEE 2002).

A triple-band rectenna (900 MHz, 1.9 GHz, and 2.4 GHz) was also developed at the University of California, Davis [40]. The antenna was designed using a combination of three different design techniques including a composite right/left hand transmission line. For the rectifier, which was of the charge-pump type, they tuned each matching frequency independently.

Broad-band rectenna for 2-18 GHz was developed in University of Colorado in 2004. They developed rectenna array with 64 elements to apply it to harvest an ambient microwave [41].

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5 Various rectennas III – weak power and energy harvester –

For energy harvesting, a high efficiency rectenna capable of harvesting weak power signals is required. It is also important to realize a MPT to sensor network or weak power MPT applications suitable for an initial commercial phase. As mentioned in Section 2, a rectenna with a diode usually cannot realize high efficiency at weak power. The V_J effect cannot increase the efficiency. So we should consider how we can add a higher voltage to V_J on a diode without any extra power source.

There are some high efficiency rectennas operating at weak power, and they use various circuits as follows:

1) Charge-pump rectifier [37, 40, 42, 43]
2) Rectifier with a resonator [44, 45]
3) Rectifier using reflected microwaves [46]
4) Rectifier with the design of output filter [47, 48]
5) Analytical model with consideration of higher harmonics [49]

The charge-pump rectifier (Fig. 11) is recently in common use for energy harvesting or weak power MPT because the required diode voltage can be created. But its RF-DC conversion efficiency is generally low because many diodes and many capacitances are needed to increase the voltage.

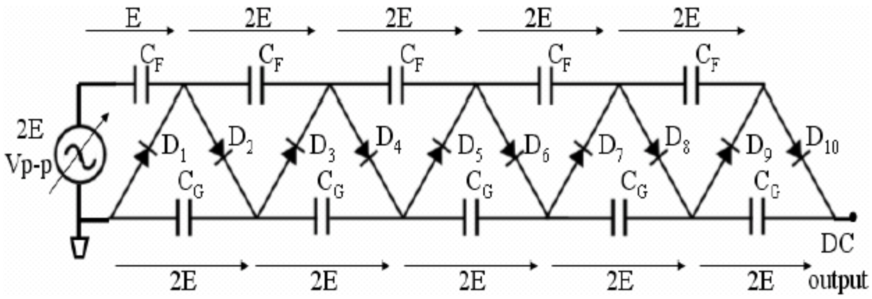

Fig. 11. Charge-pump rectifier [42] (© IEICE 2006).

To increase voltage on a diode, some groups have used a resonator. Tohoku University's group used a short-stub resonator (Fig. 12) [44]. They achieved RF-DC conversion efficiency of ~40% at 900 MHz and 10 μW. Toyama University's group adopted a L-C resonator and a dielectric resonator [45].

Utilization of the reflected microwave and the standing wave is a feasible means to increase the voltage on a diode. Okayama University's group tried to develop a system based on this concept [46]. They used the reflected microwave from an output filter. Kyoto University and Mitsubishi Electric Corp. also focused on the output filter to increase RF-DC conversion efficiency. For the output filter, a distributed line length of $\lambda_g/4$ must be used to realize a full-wave rectifier with a single shunt [10]. But we also searched for the optimum highest length of the distributed line on the output filter to achieve highest RF-DC conversion efficiency at 1 mW and 5.8 GHz. We found that $< \lambda_g/10$ distributed line is optimum [47, 48] (Fig. 13 (a)) and

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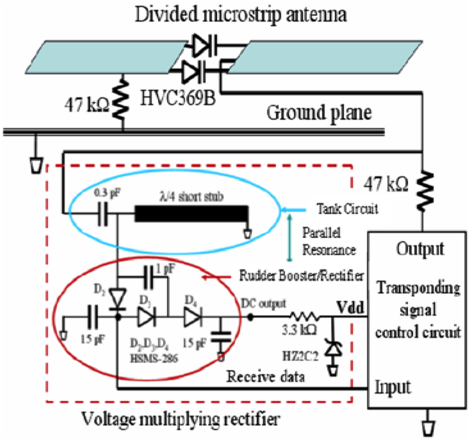

Fig. 12. Rectifier with a resonator with a short-stub [44] (© IEICE 2006).

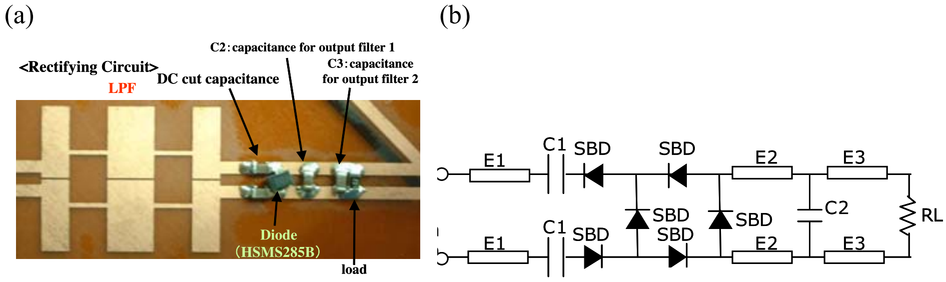

Fig. 13. Rectifier with the design of an output filter. (a) With $< \lambda_g/10$ distributed line at 5.8 GHz [47, 48] and (b) with optimization of number of diodes and length of distributed lines at 2.45 GHz [48].

we experimentally achieved over 50% efficiency at 1 mW and 5.8 GHz. For a 2.45 GHz rectenna, we additionally considered the number of diodes as shown in Fig. 13 (b). Finally, we achieved 55.3% efficiency at 0.1 mW and 8.2 kΩ at 2.45 GHz in a circuit simulation [48].

A zero-bias diode is a potential device to increase the RF-DC conversion efficiency for weak microwave signals. There have been some trials conducted using a zero-bias diode but the RF-DC conversion efficiency is still low [38, 50].

6 Conclusion

A rectenna is one of the key technologies for microwave power transmission and energy harvesting. Rectennas have various circuit types, and they operate at various frequencies and at various power levels. Past rectenna designs may provide guidance on achieving optimum modern day systems, and these designs should be analyzed with this purpose in mind. In this paper, a number of rectenna elements have been described. Additionally, research into rectenna arrays is very important and interesting [10, 51, 52, 53]. Rectenna technologies can be applied in the rectifying circuit of an inductive coupling and resonance coupling WPT at lower frequencies. The research and review

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performed in this paper will hopefully contribute to creation of a wireless power society in the near future.

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