IEIE Transactions on Smart Processing and Computing, vol. 3, no. 4, August 2014
http://dx.doi.org/10.5573/IEIESPC.2014.3.4.221

IEIE Transactions on Smart Processing and Computing

RF Energy Harvesting and Charging Circuits for Low Power Mobile Devices

Chang-Jun Ahn[1], Takeshi Kamio[2], Hisato Fujisaka[2], and Kazuhisa Haeiwa[2]

[1] Graduate School of Engineering, Chiba University / Chiba, Japan junny@m.ieice.org
[2] Faculty of Information Sciences, Hiroshima City University / Hiroshima, Japan
{kamio, fujisaka, haeiwa}@hiroshima-cu.ac.jp

***** Corresponding Author: Chang-Jun Ahn

Received December 20, 2013; Revised February 27, 2013; Accepted May 12, 2014; Published August 31, 2014

** Short Paper*

** Extended from a Conference: Preliminary results of this paper were presented at the IEEE ISCE 2014. This present paper has been accepted by the editorial board through the regular reviewing process that confirms the original contribution.*

***Abstract*: Low power RF devices, such as RFID and Zigbee, are important for ubiquitous sensing. These devices, however, are powered by portable energy sources, such as batteries, which limits their use. To mitigate this problem, this study developed RF energy harvesting with W-CDMA for a low power RF device. Diodes are required with a low turn on voltage because the diode threshold is larger than the received peak voltage of the rectifying antenna (rectenna). Therefore, a Schottky diode HSMS-286 was used. A prototype of RF energy harvesting device showed the maximum gain of 5.8dBi for the W-CDMA signal. The 16 patch antennas were manufactured with a 10 dielectric constant PTFT board. In low power RF devices, the transmitter requires a step-up voltage of 2.5~5V with up to 35 mA. To meet this requirement, the Texas Instruments TPS61220 was used as a low input voltage step-up converter. From the evaluated result, the achievable incident power of the rectenna at 926mV to operate Zigbee can be obtained within a distance of 12m.

***Keywords*: RF energy harvesting, Rectenna, Charging circuits, Low power mobile devices, Patch antenna, Rectenna

1. Introduction

Energy harvesting has been around for centuries in the form of windmills, watermills and passive solar power systems. In recent decades, technologies, such as wind turbines, hydro-electric generators and solar panels have turned harvesting into a small but growing contributor to the world's energy needs. This technology offers two significant advantages over battery-powered solutions; virtually inexhaustible sources and little or no adverse environmental effects. Recently, the availability of free RF energy has increased due to advent of wireless communications and broadcasting systems. RF energy harvesting is the process of extracting small amounts of energy from the ambient environment. This energy can be used to power either portable electronic devices, such as wireless sensing nodes, mobile phones and medical devices, or to charge electrical storage devices (rechargeable battery or capacitor), which can be used at different time intervals for power applications. RF energy harvesting technology is strongly depended on the rectifying antenna (rectenna) technique in the wireless power transmission. Wireless power transmission technology via microwaves was advanced from the 1960's [1]. Wireless power transmission is the transmission of electrical energy from a power source to an electrical load without artificial interconnecting conductors [2-8]. This technique is useful in cases where the interconnecting wires are inconvenient, hazardous or impossible. The rectenna is one of the primary components in the applications of wireless power transmission system. The rectenna for receiving and converting microwave power to direct current (DC) power has attracted considerable attention in the development of the wireless power transmission. The application of this technology can be used in low power mobile devices, such as radio-frequency identification (RFID) and Zigbee. For environments with little or no ambient energy, a wireless energy supply is a reliable way pf powering the low power mobile devices.

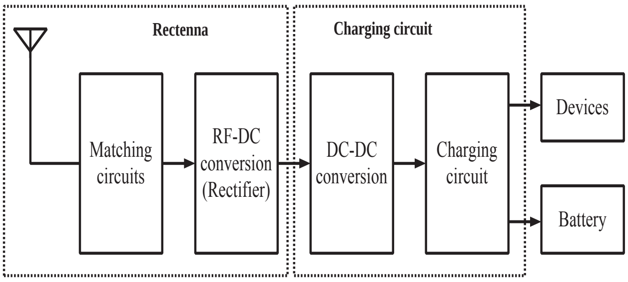

Fig. 1. Diagram of RF energy harvesting devices.

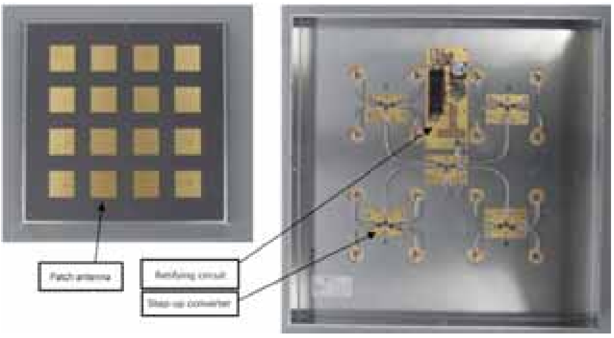

Fig. 2. Manufactured RF harvesting device.

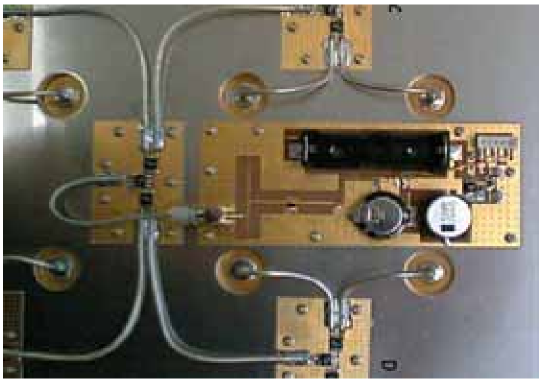

Fig. 3. Manufactured rectifying circuit, set-up converter, and charging circuits.

Recently, many rectennas have been reported, including rectennas using a rhombic hula loop antenna [9], dual-frequency rectenna [10], and dual-diode rectenna [11].

Until this time, the electrical power generated using RF energy harvesting techniques is small, and depending on techniques, it is sufficient to drive low power consumption devices. Therefore, it is possible to increase the battery life and reduce the environmental pollution. Radio waves are ubiquitous in daily lives in the form of signals transmission from TV, radio, wireless LAN, and mobile phone. Wireless communication devices generally have omni-directional antennas that propagate RF energy in most directions, which maximizes the connectivity for mobile applications. The energy transmitted from the wireless sources is much higher, but only a small amount can be scavenged in a real environment. The rest is dissipated as heat or absorbed by other materials. This study focused on the RF energy harvesting and the design of a rectenna with a 4×4 patch antenna of 2.13 GHz for low power mobile devices. This paper is organized as follows. Section 2 describes the RF energy harvesting devices. Section 3 reports the system experimental results. Section 4 resents the conclusions.

2. RF Energy Harvesting Devices

2.1 Rectenna Design

The RF energy harvesting devices consisted of a rectenna and charging circuits, as shown schematically in Fig. 1.

The rectenna, i.e. rectifying antenna, is one of the primary components in the application of RF energy harvesting devices. The rectenna consists of an antenna, matching circuit, and rectifying circuit. A highly efficient rectenna has been studied, assuming its use in solar power stations (SPSs) [12-15]. Although wireless communications use UHF waves, such as CDMA and WCDMA, the basis is almost identical. Previously, the prototype of 5.8 GHz rectenna was developed for an electric vehicle system [16]. In this paper, a 2.13 GHz rectenna was developed using the previous developed rectenna of 5.8 GHz because the frequencies of 2.12 GHz and 2.14 GHz are the CDMA and WCDMA frequency bands, respectively. Microstrip dipole and patch antennas are used widely in the design of rectennas. Microstrip antenna has the characteristics of light, easy and small-size manufacturing. On the other hand, it has demerits due to the relatively narrow bandwidth, restricted incident power and low gain. In this paper, however, the microstrip patch antenna was adopted because of its large size and no polarization characteristics. Figs. 2 and 3 show the manufactured RF energy harvesting devices. The rectifying circuit is a key element to improve the RF-DC conversion efficiency. A Schottky diode HSMS-2862 was chosen for the rectifying circuit. The measured gain of the manufactured rectenna is shown in Fig. 4. The rectenna showed the maximum gain of 5.8dBi at a frequency of 2.13 GHz with a PTFT (Teflon) board with a dielectric constant of 10 and 1.6 mm thick. The frequencies of 2.12 GHz and 2.14 GHz are within the half power bandwidth of the rectenna.

2.2 Charging Circuits

In low power mobile devices, such as Zigbee, a stepped-up voltage, such as 2.5~5V, is needed to drive the transmitter up to 35mA. For this reason, the Texas Instruments TPS61220 was adopted as a step-up converter [17]. The step-up converter was operated with a load at 0.7 V to 5.5 V. The adjustable output voltages ranged from 1.8 V to 5.5 V. Fig. 5 shows a simplified schematic diagram of the step-up converter with TPS61220. TPS61220 provides a power-supply solution for products powered by either a single-cell, two-cell or three-cell alkaline NiCd or NiMH, or one-cell Li-Ion or Li-polymer battery. In the prototype, a one-cell Li-Ion battery was used as a battery powered application.

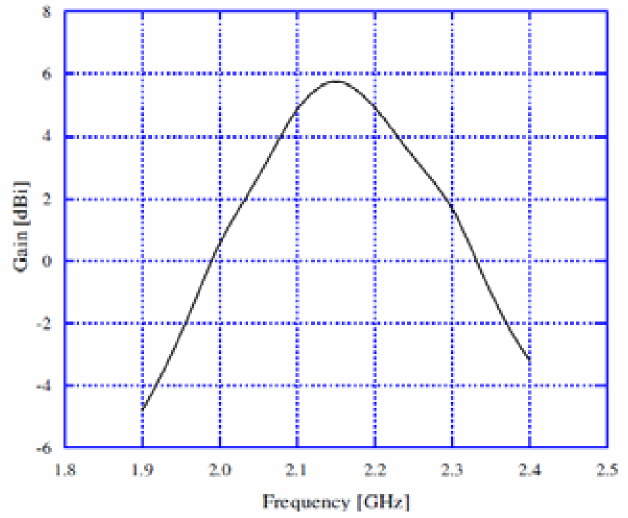

Fig. 4. Measured gain of the rectenna versus various frequencies.

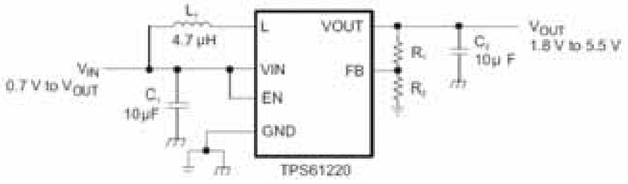

Fig. 5. Simplified schematic of the step-up converter with TPS61220.

3. Experimental Results

A rectenna was designed using a 1.6 mm thick PTFT board with a dielectric constant of 10. The 4×4 rectenna array consisted of 16 patch antennas and each patch antenna size was 39mm×31mm. The patch antennas were in the front and the rectifying and charging circuits were in the back of the antenna, as shown in Fig. 2. A 2.13 GHz rectenna was adopted because the frequencies of 2.12 GHz and 2.14 GHz are the CDMA and WCDMA frequency bands. The 4×4 rectenna array was used and the load resistance was chosen as 50Ω. The RF-DC conversion efficiency is defined as

$$\eta = \frac{P_{dc}}{P_r} \times 100\% \tag{1}$$

where P_{dc} is the DC output power and P_r is the power received by the array rectenna that was calculated using the Friss transmission equation [18]. By changing the distance between the transmitting antenna and rectenna array, the efficiencies for different power densities can be determined. The power density P_d is given by

$$P_d = \frac{P_t G_t}{4\pi D^2} \tag{2}$$

where P_t is the transmit power, G_t is the transmit antenna gain, and D is the distance between the transmit antenna and the center of the rectenna array, respectively.

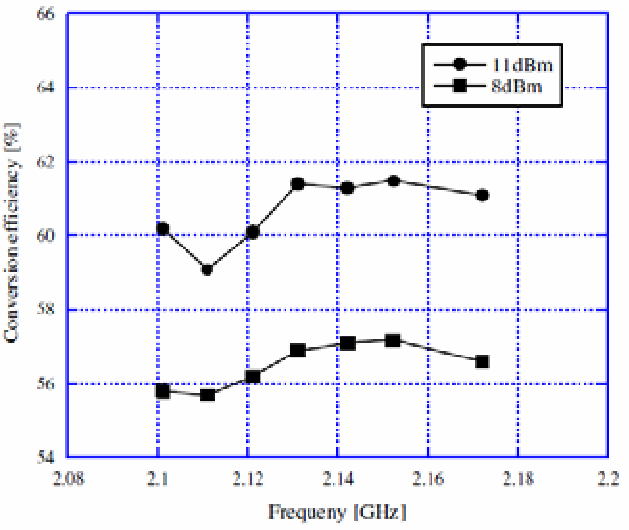

Fig. 6. RF-DC conversion efficiency of the rectenna versus various input frequency.

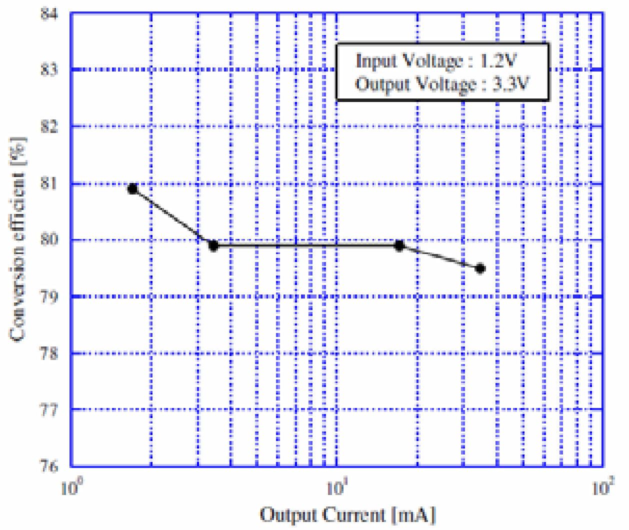

Fig. 7. Conversion efficiency of low input voltage set-up converter.

Fig. 6 shows the frequency characteristics of the manufactured rectenna. The vertical axis represents the conversion efficiency of the manufactured rectenna. The incident power was varied from 8dBm to 11dBm, and input frequency was varied from 2.1GHz to 2.171GHz. Note that the weaker incident power shows a poor conversion property. The conversion efficiency was improved significantly with increasing incident power. This means that higher incident power can increase the conversion efficiency.

Fig. 7 shows the conversion efficiency of a low input voltage set-up converter. A set-up converter operates when the input voltage is higher than 0.7 V. When the input voltage was set to 1.2 V, the conversion efficiency varied due to the output current. If the output current is 1.7mA, a

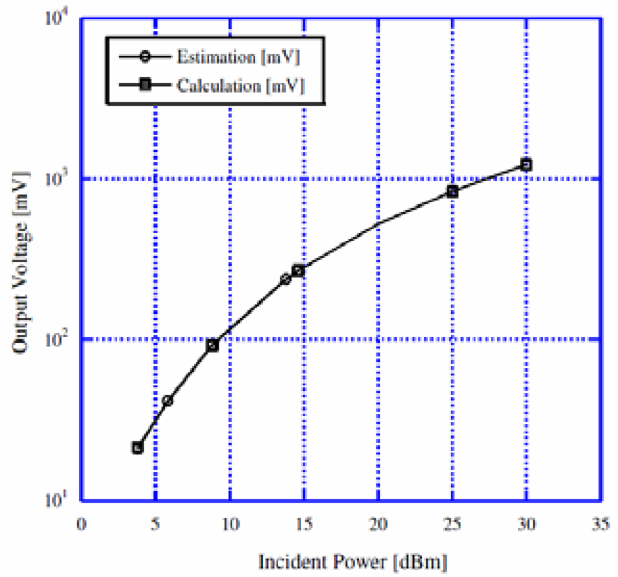

Fig. 8. Output voltage versus incident power.

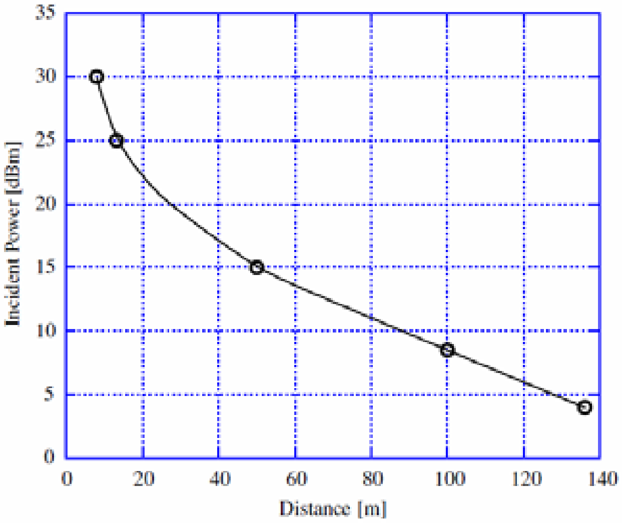

Fig. 9. Incident power of rectenna versus distance.

conversion efficiency of 80.9% can be achieved. With increasing output current, the conversion efficiency was also degraded.

Fig. 8 shows the output voltage vs. various incident powers. From the evaluated result, the output voltage of 21mV, 134mV and 926mV can be obtained at an incident power of 4dBm, 14dBm and 25dBm, respectively. As a result, it is necessary to achieve a higher output voltage of 926mV to power a low power RF device.

Fig. 9 shows the incident power of a rectenna versus the distance. Because the incident power of a rectenna is degraded by the square of the distance, RF energy harvesting is strongly dependent on the distance. From the evaluated result, the achievable incident power of the rectenna (926mV) to operate Zigbee can be obtained within a distance of 12m.

5. Conclusion

In this paper, a 4×4 rectenna of 2.13 GHz was developed for low power mobile devices. The rectenna element is a microstrip patch antenna with a PTFT board of a 10 dielectric constant and 1.6 mm thick, which has a gain of 5.8dBi. A step-up converter was comprised of a Texas Instruments TPS61220. The step-up converter was operated with a load at 0.7 V to 5.5 V. The conversion efficiency was 80.9 % at an output current of 1.7mA. From the evaluated results of the RF energy harvesting system, the low power mobile devices, such as Zigbee, can be operated at a distance of up to 12m.

Acknowledgement

This study was funded in part by a Grant of Scientific Research (C) No. 26420339 from the Japan Society for the Promotion of Science (JSPS) and the Telecommunications Advancement Foundation (TAF).

References

[1] W.C. Brown, "The history of power transmission by radio waves," *IEEE Transactions on Microwave Theory and Techniques*, vol.32, no.9, pp.1230-1242, September 1984. Article (CrossRef Link)

[2] N. Tesla, "Apparatus for transmitting electrical energy," *US patent number 1,119,732*, issued in December 1914.

[3] A. Kurs, A. Karalis, R. Moffatt, J.D. Joannopoulo, P. Fisher, M. Soljacic, "Wireless Power Transfer via Strongly Coupled Magnetic Resonances," *Science*, vol. 317, pp.83-86, July 2007. Article (CrossRef Link)

[4] S.C. Liu, L.W. Zhou, "Modeling and analysis of near-field magnetic resonant coupling energy transfer systems," *Journal of power supply*, vol.1, pp.50-55, 2011.

[5] J.O McSpadden, R.M. Dickinson, L. Fan, and K. Chang, "Design and experiments of a high-conversion-efficiency 5.8-GHz rectenna," *IEEE Transactions on Microwave Theory and Techniques*, vol. 46, no.12, pp.1161–1164, 1998. Article (CrossRef Link)

[6] N. Shinohara and H. Matsumoto, "Experimental study of large rectenna array for microwave energy transmission," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 46, No. 3, pp. 261–267, March 1998. Article (CrossRef Link)

[7] J.A. Hagerty, F. Helmbrecht, W. McCalpin, R. Zane, Z. Popovic, "Recycling ambient microwave energy with broadband antenna arrays," *IEEE Transactions on Microwave Theory and Techniques*, pp. 1014–1024, March 2004. Article (CrossRef Link)

[8] R. Trew, "SiC and GaN Transistors - Is There One Winner for Microwave Power Applications?" *Proceedings of the IEEE*, vol. 90, No. 6, pp. 1032–1047, June 2002. Article (CrossRef Link)

[9] B. Strassner, and K. Chang, "5.8GHz circularly polarized rectifying antenna for wireless microwave power transmission," *IEEE Transactions on Microwave*

Theory and Techniques, vol.50, no.8, pp.1870-1876, August 2003. Article (CrossRef Link)

[10] J. Heikkinen, and M. Kivikoski, "A novel dual-frequency circularly polarized rectennas," *IEEE Antennas and Wireless Propagation Letter*, vol.2, no.1, pp.330-333, February 2003. Article (CrossRef Link) http://dx.doi.org/ 10.1109/LAWP.2004.824166

[11] Y. Ren, and K. Chang, "5.8GHz circularly polarized dual-diode rectenna and rectenna array for microwave power transmission," *IEEE Transactions on Microwave Theory and Techniques*, vol.54, no.4, pp.1495-1502, April 2006. Article (CrossRef Link)

[12] G. Landis, M. Stavnes, S. Oleson and J. Bozek, "Space transfer with ground-based laser/electric Propulsion," *(AIAA-92-3213) NASA Technical Memorandum TM-106060*, 1992. Article (CrossRef Link)

[13] N. Shinohara, and H. Matsumoto, "Microwave power transmission system with phase and amplitude controlled magnetrons," *in Proc. of Recent Advances in Space Technologies (RAST2005)*, pp.28-33, Istanbul, Turkey, 2005. Article (CrossRef Link)

[14] J. Wang and J. Jiang, "Experience on 10kW grid-connecting solar power station," *in Proc. of International Conference on Electrical Machines and Systems (ICEMS 2008)*, pp.2654-2656, 2008.

[15] H. Matsumoto, "Space solar power station (SSPS) and microwave power transmission (MPT)," *in Proc. of IEEE Topical Conference on Wireless Communication Technology*, 2003. Article (CrossRef Link)

[16] C. Ahn, T. Kamio, H. Fujisaka and K. Haeiwa, "Prototype of 5.8GHz Wireless Power Transmission System for Electric Vehicle System," *in Proc. of IEEE International Conference on Environmental Science and Technology (ICEST 2011)*, Singapore, vol.1 pp.128-131, February 2011. http://www.ti.com/product/tps61221

[17] C. Ahn, "OFDM technology and its applications," *Corona Publishing* Co., LTD., ISBN978-4-339-00815-9, September 2010 (in Japanese).

Chang-Jun Ahn received his Ph.D. degree from Keio University, Japan, in 2003. From 2001 to 2003, he was a Research Associate in the Department of Information and Computer Science, Keio University. From 2003 to 2006, he was with the National Institute of Information and Communications Technology. From 2006 to 2010, he was with the Faculty of Information Science, Hiroshima City University. In 2010, he joined the Faculty of Engineering, Chiba University. Currently, he is an Associate Professor in the Department of Electrical and Electronic Engineering. His current research interests include channel coding, and signal processing for telecommunications. Dr. Ahn received an ICF research grant award for Young Engineers in 2002 and a Funai Information Science Award for Young Scientists in 2003. He is a senior member of IEICE and IEEE.

Takeshi Kamio received his B.E., M.E. and Ph.D. degrees from Shizuoka University, Japan, in 1994, 1996, and 1999, respectively. From 1996 to 1999, he was a Research Fellow with the Japan Society for the Promotion of Science. In 1999, he joined the Faculty of Information Science, Hiroshima City University. Currently, he is a Lecturer in the Department of Systems Engineering. His research interests are intelligent signal processing including neural networks. He is a member of the IEICE.

Hisato Fujisaka received his Dr.Eng. degree from Keio University, Japan, in 1994. From 1994 to 1997, he was with the Department of Optical Communications, Osaki Electric Co. Ltd. In 1997, he joined the Faculty of Information Science, Hiroshima City University. Currently, he is a Professor in the Department of System Engineering. His research interests include analysis and synthesis of nonlinear signal processing and communication circuits. He is a member of IEICE.

Kazuhisa Haeiwa graduated from the Department of Electrical Engineering, Tokushima University, Japan. He received his Dr.Eng. degree from University of Tokyo, Japan, in 1988. In 1970, he joined Japan Broadcasting Corporation and engaged in the design and development of broadcasting transmitters. From 2004 to 2013, he was a Professor in the Faculty of Information Science, Hiroshima City University. Currently, he is professor emeritus at the university. Dr. Haeiwa received the Invention and Research Achievement Award from the Tokyo Metropolitan Government in 1997. He has received many awards including Development Award from the Image and Information Media Society.