PAPER *Special Section on Microwave and Millimeter-Wave Technologies*

Rectifier Circuit using High-Impedance Feedback Line for Microwave Wireless Power Transfer Systems

Seiya MIZUNO[†a)], ***Student Member***, **Ryosuke KASHIMURA**[††], ***Nonmember***, **Tomohiro SEKI**[†], ***Senior Member***, **Maki ARAI**[†], ***Member***, **Hiroshi OKAZAKI**[†††], ***and*** **Yasunori SUZUKI**[†††], ***Senior Members***

SUMMARY Research on wireless power transmission technology is being actively conducted, and studies on spatial transmission methods such as SSPS are currently underway for applications such as power transfer to the upper part of steel towers and power transfer to flying objects such as drones. To enable such applications, it is necessary to examine the configuration of the power-transfer and power-receiving antennas and to improve the RF-DC conversion efficiency (hereinafter referred to as conversion efficiency) of the rectifier circuit on the power-receiving antenna. To improve the conversion efficiency, various methods that utilize full-wave rectification rather than half-wave rectification have been proposed. However, these come with problems such as a complicated circuit structure, the need for additional capacitors, the selection of components at high frequencies, and a reduction in mounting yield. In this paper, we propose a method to improve the conversion efficiency by loading a high-impedance microstrip line as a feedback line in part of the rectifier circuit. We analyzed a class-F rectifier circuit using circuit analysis software and found that the conversion efficiency of the conventional configuration was 54.2%, but the proposed configuration was 69.3%. We also analyzed a measuring circuit made with a discrete configuration in the 5.8-GHz band and found that the conversion efficiency was 74.7% at 24 dBm input.

key words: *wireless power transfer, rectifier circuit, feedback line, microwave frequency, quasi-millimeter and millimeter-wave frequency*

1. Introduction

In 1968, Dr. P.E. Glaser proposed and conducted extensive research on space solar power systems (SSPS) [1]–[15]. In these systems, the microwaves received on the ground are converted into direct currents (RF-DC conversion) by a rectifier circuit and then used as energy sources. Wireless power transfer technology on the ground by applying microwave wireless power transfer has also been studied. In more recent years, wireless power supply to drones and, sensors, and base stations have been attracting interest [16]–[20].

Figure 1 shows an image of wireless power transfer between a base station installed on a building roof and several nearby sub base stations. This system makes it possible to simplify the preparation of signal lines and power supply lines when installing new base stations. In order to achieve this, it is necessary to develop elemental technologies for both power transfer and power receiving. For the power-transfer technology, a configuration method for the power-transfer antenna is needed, along with a power-transfer method using a narrow beam in order to overcome huge propagation loss. As for the power-receiving technology, we need a configuration method for the power-receiving antenna to improve system efficiency and increase the conversion efficiency of the rectifier circuit. In this study, we focus on the design of rectifier circuits to improve the conversion efficiency. There are already several methods for improving the efficiency by utilizing full-wave rectification rather than half-wave rectification [21]–[28]. However, these methods come with problems such as the necessity of mounting an additional capacitor, the necessity of selecting components at a high frequency, and the deterioration of the manufacturing yield. Therefore, in our proposed method, we aim to improve the conversion efficiency by using a high-impedance microstrip line (MSL) as a feedback line in the rectifier circuit [28]–[31].

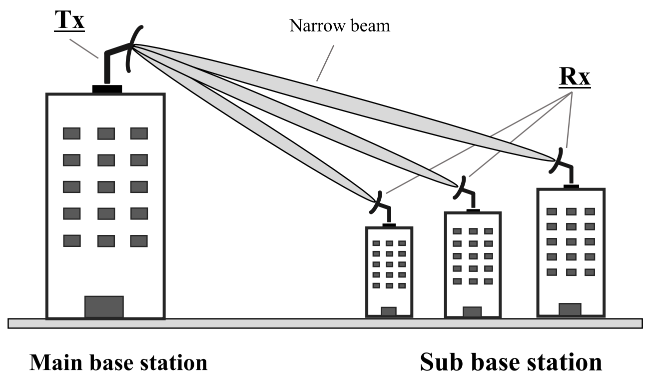

Fig. 1 Power transfer image.

2. Target Rectifier System

A rectenna is typically composed of a rectifier circuit and a power-receiving antenna, as shown in Fig. 2. The microwave received by the power-receiving antenna is converted into DC by the rectifier circuit and then DC power is obtained as the system output. In this paper, we assume the rectenna system in the power transfer system has a narrow beam characteristic. Undesirable power distribution tends to occur at the receiving antenna during wireless power trans-

Manuscript received October 27, 2020.
Manuscript revised February 3, 2021.
Manuscript publicized March 30, 2021.

[†]The authors are with Nihon University, Narashino-shi, 275–8575 Japan.
[††]The author is with Japan Radio Co., Ltd, NAKANO CENTRAL PARK EAST, Tokyo, 164–8570 Japan.
[†††]The authors are with NTT DOCOMO, INC, Yokosuka-shi, 239–0847 Japan.
a) E-mail: cise19019@g.nihon-u.ac.jp

DOI: 10.1587/transele.2021MMP0009

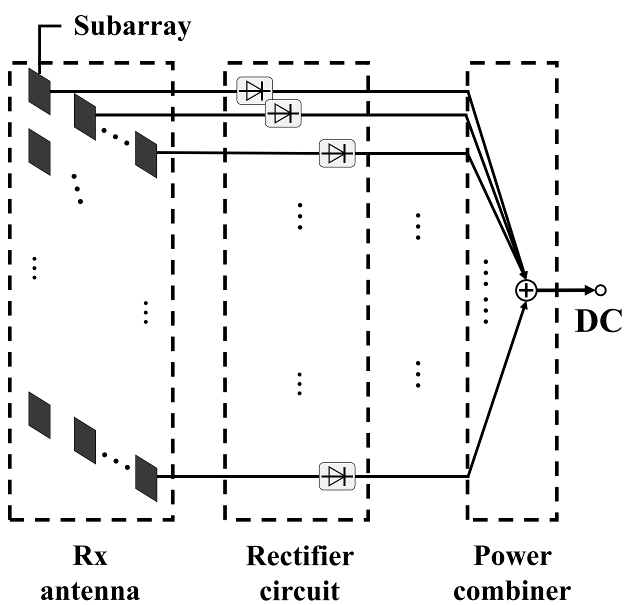

Fig. 2 Rectifier system block.

fer using a narrow beam, where the power density is high at the center of the power-receiving antenna and low at the antenna end. Since diodes have non-linear characteristics, RF-DC conversion efficiency decreases when the input power is low. Therefore, when a rectifier circuit is simply connected to each antenna element, the RF-DC conversion efficiency of the rectifier circuit is lower at the antenna end. To resolve this issue, we propose a configuration in which each subarray is connected to a rectifier circuit. Using this subarray configuration improves the RF-DC conversion efficiency at the antenna end because the difference of the input power levels among rectifiers is reduced. Also, since the input power levels are equalized, the rectifier system can be configured with only one rectifier circuit design.

3. Proposed Rectifier System

3.1 Circuit Design

In this paper, we have proposed a method to improve the conversion efficiency by loading a high-impedance MSL as a feedback line in the rectifier circuit. We used Advanced Design Systems (Keysight) to design the circuits. Figure 3 shows the configuration of the rectifier circuit, where a feedback line for feeding back only DC is added to a single shunt type rectifier circuit with class-F load. The operating frequency of the rectifier circuit is the 5.8-GHz band. We designed the circuit using PTFE [NPC-H220A, NIPPON PILLAR PACKING Co., Ltd.] as the dielectric substrate and Schottky Barrier Diode (SBD) [HSMS-2822, Agilent Technologies] as the diode. Tables 1 and 2 show the substrate parameters and the diode parameters, respectively.

As shown in Fig. 3, the matching circuit, DC cut capacitor, and feedback line output (point A) are connected to the input side of the diode. The matching circuit performs impedance matching between the capacitor and the circuit, and the DC cut capacitor prevents the DC component from flowing out. A matching stub is connected at point C to suppress harmonics generated by the diode. A $\lambda/4$ line, harmonic filter, and feedback line input (point B) are connected to the output side of the diode. The $\lambda/4$ line is connected between the diode and the load in order to make the diode operate in class-F mode.

Class-F amplifiers operate with high input impedance ($Z_{in} = \infty$) at odd harmonics and low input impedance ($Z_{in} = 0$) at even harmonics to shape the current and voltage waveforms of the circuit and improve the RF-DC conversion efficiency. In this configuration, the filter is designed considering the harmonic processing up to the fourth harmonic. The rectifier circuit with the feedback line is designed to increase the reference voltage input to the diode and to increase the conversion efficiency, similar to the charge pump

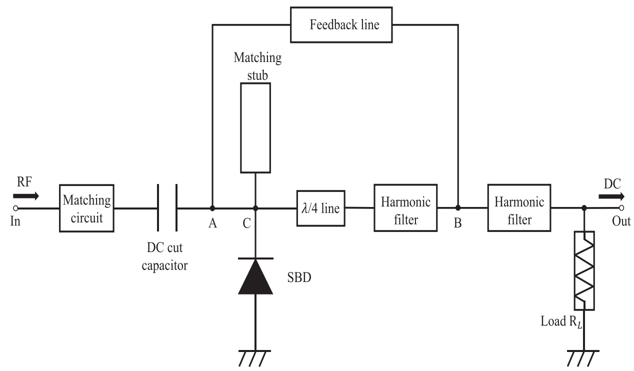

Fig. 3 Rectifier circuit model.

Table 1 Substrate parameters.

Parameter		Value	Unit
Substrate thickness	h	0.5	mm
Copper foil thickness	t	0.018	μm
Relative permittivity	ε_r	2.19	–
Loss $\tan\delta$	–	0.0006	–

Table 2 Diode parameters.

Parameter		Value	Unit
Reverse breakdown voltage	B_V	1.5	V
Junction capacitance	C_{j0}	0.7	pF
Band gap voltage	E_G	0.60	eV
Reverse breakdown start current	I_{bv}	0.1	mA
Saturation current	I_S	22	nA
Emission factor	N	1.08	–
Series resistance	R_S	8	ohm
Junction inclination factor	M	0.5	–

type rectifier circuit. Since the rectifier circuit with a feedback line does not require a capacitor for the charge pump, the number of circuit elements selected and the number of mounted circuit elements can be reduced, thus preventing deterioration of the mounting yield. Here, we show the principle of the operation of the circuit. The DC component is fed back from the output side (point B) of the diode to the input side (point A) via the feedback line. The RF-DC conversion efficiency is improved by increasing the reference voltage input to the diode by utilizing the DC feedback. In order to perform DC feedback, the feedback line needs to operate as a low-pass filter at high frequency, so we use a feedback line composed of MSL with high impedance. In this paper, a high-impedance line refers to an MSL with a characteristic impedance higher than 50 ohm. The calculated values of the characteristic impedance of the proposed feedback line are $w_{100} = 0.37$ mm at $Z_0 = 100$ ohm, $w_{150} = 0.1$ mm at $Z_0 = 150$ ohm, and $w_{200} = 0.02$ mm at $Z_0 = 200$ ohm. The RF-DC conversion efficiency η is obtained by

$$\boldsymbol{P_{DC}} = \frac{\boldsymbol{V_L^2}}{\boldsymbol{R_L}}, \tag{1}$$

$$\boldsymbol{\eta} = \frac{\boldsymbol{P_{DC}}}{\boldsymbol{P_{in}}} \times \mathbf{100}, \tag{2}$$

where P_{in} is the input power to the rectifier circuit, V_L is the voltage applied to the load resistance, R_L is the load resistance, and P_{DC} is the power consumed by the load resistance.

3.2 Simulation Results

We used a circuit simulator (ADS) to clarify the conversion efficiencies when the characteristic impedance of the proposed feedback line was $Z_0 = 100$ ohm, $Z_0 = 150$ ohm, and $Z_0 = 200$ ohm. Figure 4 shows the conversion efficiency for each characteristic impedance. In this simulation, the feedback line length was $L = 44.3$ mm and the load resistance was $R_L = 250$ ohm. As we can see in the figure, when $Z_0 = 100$ ohm, the efficiency saturated at a lower efficiency than the other two cases. In the cases of $Z_0 = 150$ ohm and $Z_0 = 200$ ohm, the efficiency continued to increase until the input power was about 23 dBm.

Figure 5 shows the RF-DC conversion efficiency when the feedback line length was changed. The input power was 23 dBm and the load resistance was $R_L = 250$ ohm. As we can see, the conversion efficiency changed periodically regardless of the characteristic impedance. We also found that the conversion efficiency was higher when $Z_0 = 150$ ohm and $Z_0 = 200$ ohm, $L = 44.3$ mm than when $Z_0 = 100$ ohm.

Figure 6 shows relationship of conversion efficiency to load resistance of the rectifier circuit. Here, the input power was 23 dBm and the feedback line length was $L = 44.3$ mm. As we can see, the conversion efficiency was maximized when $Z_0 = 150$ ohm and $R_L = 250$ ohm. This is presumably because the impedance at point A appeared sufficiently high for the harmonic component and it operated the same as the low-pass filter. It also seems that the DC resistance value of the feedback line did not look large for the DC component at point B, and the DC component was fed back, thus obtaining the highest efficiency.

Figure 7 shows the transient analysis results of the current on the feedback line when the optimum feedback line length, width, and load resistance were selected and the rectifier circuit was configured. As we can see, a reverse current

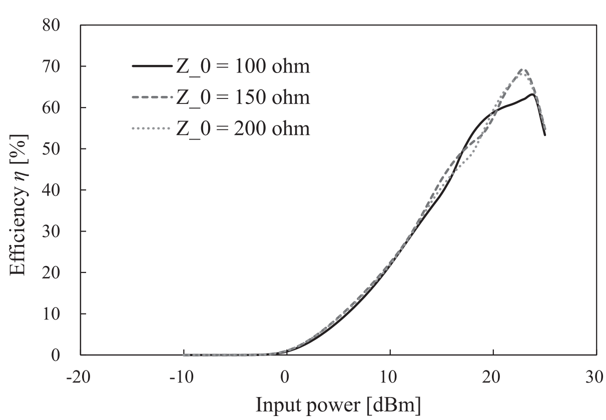

Fig. 4 Relationship of conversion efficiency to feedback line width.

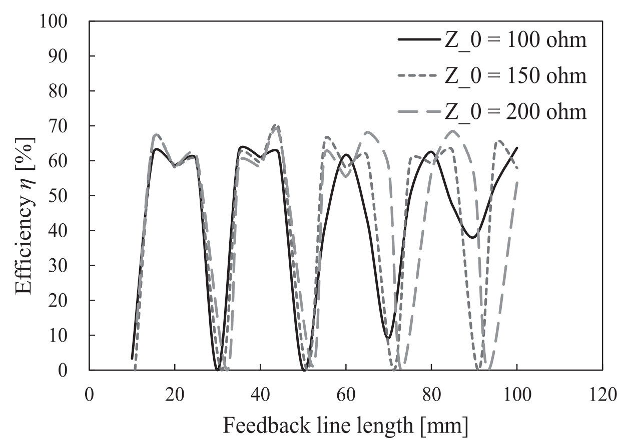

Fig. 5 Relationship of conversion efficiency to feedback line length.

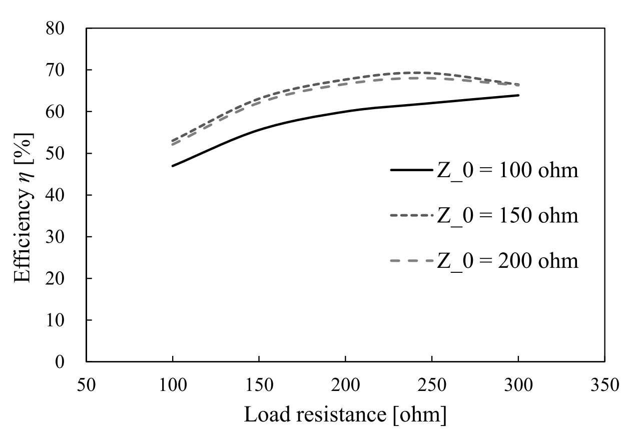

Fig. 6 Relationship of conversion efficiency to load resistance.

of about 1.7 A flowed after 150 μsec from the start of current flow. Therefore, the feedback line was a high-impedance MSL from the viewpoint of the high-frequency component, and it seemed to be acting as a low pass filter. In addition, we assume that when the power supply voltage became zero, the feedback line fed the DC component from the output side of the diode (point B in Fig. 3) to the input side of the diode (point A) to increase the reference voltage to the diode, thus improving the rectification efficiency.

Figure 8 shows the conversion efficiencies of the rectifier circuit with (our proposal) and without (conventional) a feedback line.

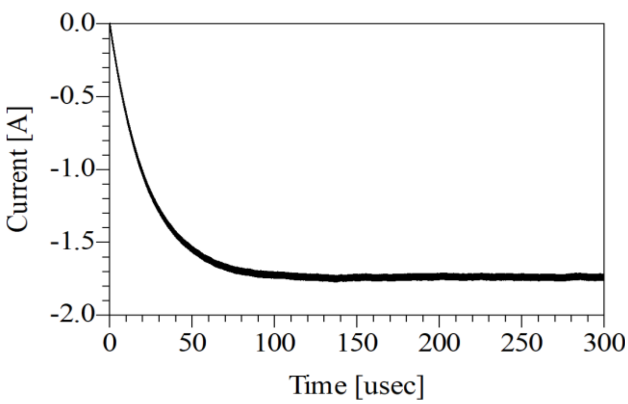

Fig. 7 Current on feedback line.

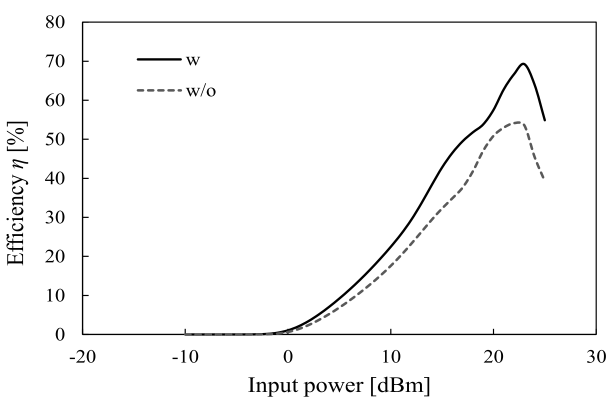

Fig. 8 RF-DC conversion efficiency with/without feedback line.

Table 3 Comparison of conversion efficiency with/without feedback line.

	Proposed circuit	Conventional circuit
Feedback line	with	without
R_L	250 ohm	250 ohm
Z_0	150 ohm	–
L	44.3 mm	–
Frequency band	5.8 GHz	5.8 GHz
Max efficiency (@23dBm)	69.3%	54.2%

Table 3 shows the comparison. According to Fig. 8, the maximum efficiency of the rectifier with the feedback line was 69.3% with 23 dBm input. We found that the RF-DC conversion efficiency could be improved by 15.1% compared to the conventional rectifier without the feedback line.

4. Measurement

We prototyped and measured the designed rectifier circuit with a feedback line and compared it with a conventional rectifier circuit. We used the PTFE dielectric substrate (parameters are shown in Table 1). In accordance with the analysis results, the feedback line was designed with the width w = 0.1 mm and the characteristic impedance Z_0 = 150 ohm. Figure 9 shows a circuit diagram of the rectifier circuit with the feedback line. In this configuration, the filter was designed with consideration of harmonic processing up to the fourth harmonic. Figure 10 shows a photograph of the prototyped rectifier circuit.

Figure 11 shows a block diagram of the measurement system. A 5.8-GHz sine wave was generated by the signal generator and the input power level of the rectifier circuit was tuned using an attenuator and amplifier. The amplified power was input to the rectifier circuit through a directional coupler and circulator. Power sensor A measured the input power and power sensor B measured the reflected power of

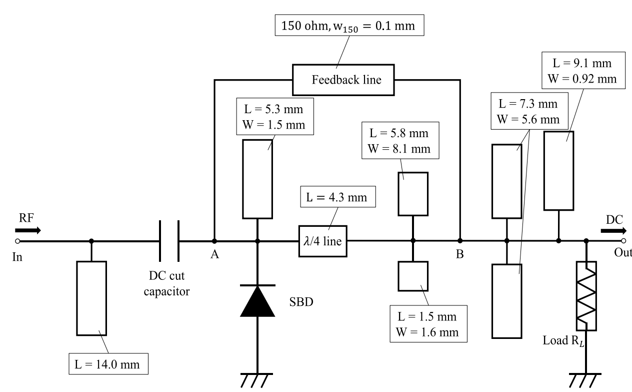

Fig. 9 Circuit design.

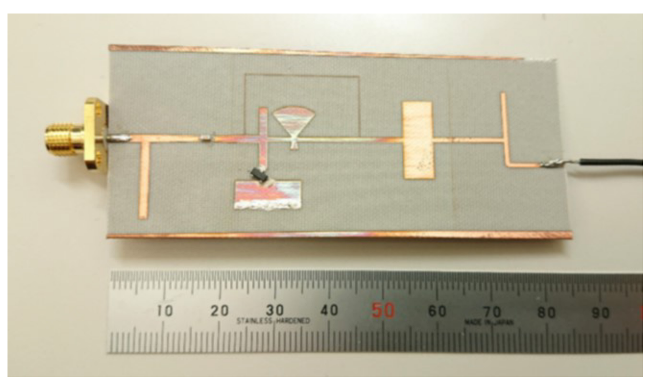

Fig. 10 Proposed rectifier circuit with feedback line.

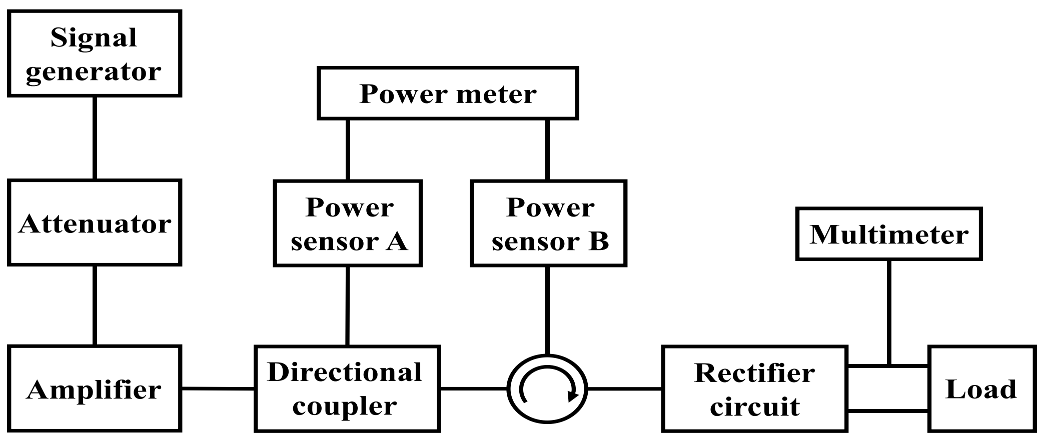

Fig. 11 Measurement system block.

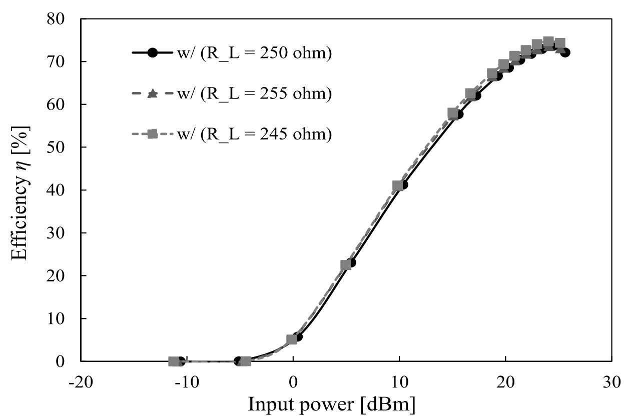

Fig. 12 Measurement results.

the rectifier circuit. The voltage of the DC output from the rectifier circuit was measured using a multimeter. Figure 12 shows the measured conversion efficiency of the rectifier circuit with feedback. In addition to connecting the optimum load obtained by analysis, measured data when the load resistance value was changed by ±5 ohms is plotted. When an optimum load of 250 ohm was connected and 23 dBm of power was input, the efficiency of the rectifier circuit with the feedback line was 69.3% on the simulator, but the measured result was 73.7%. The highest measured efficiency, 74.7%, was observed when the load resistance was 245 ohm and input power was 24 dBm. The output voltage when the conversion efficiency was maximized was about 5.9 V in the simulation and about 7.8 V in the measurement. The conversion efficiency obtained at 0 dBm input power was 1.1% in the simulation, but the measured result was 5.8%.

The measurement results of the rectifier circuit with feedback obtained in this experiment showed higher conversion efficiency than the simulation results. We presume this difference in the optimal load values and conversion efficiencies between the analytical and experimental results can be attributed to the incomplete reproducibility of the diode device model on the analytical simulator.

5. Conclusion

In this paper, we have proposed a configuration method of the rectifier circuit with a high-impedance feedback line for the 5.8-GHz band to improve RF-DC conversion efficiency. The feedback line is composed of MSL. The results of analyzing the designed rectifier circuit using circuit analysis software showed that the conversion efficiency improved by 15.1 points compared to the rectifier circuit without a feedback line. We also prototyped and measured a discrete rectifier circuit based on our design and found that a conversion efficiency of 74.7% was obtained at 24 dBm input.

References

[1] P.E. Glaser, "The Future of Power from the Sun," IECEC, pp.98–103, 1968.
[2] P.E. Glaser, "The potential of satellite solar power," Proc. IEEE, vol.65, no.8, pp.1162–1176, Aug. 1997.
[3] P.E. Glaser, "An over view of the solar power satellite potion," IEEE Trans., vol.40, no.6, pp.1230–1238, June 1992.
[4] P.E. Glaser, "The Satellite Solar Power Station," IEEE G-MTT International Microwave Symposium, pp.186–188, June 1973.
[5] W.C. Brown, "Optimization of the Efficiency and Other Properties of the Rectenna Element," MTT-S Int. Microwave Symposium, pp.142–144, 1976.
[6] W.C. Brown and E.E. Eves, "Beamed microwave power transmission and its application to space," IEEE Trans. Microwave Theory Tech., vol.40, no.6, pp.1239–1250, June 1992.
[7] I. Mikami, T. Mizuno, A. Yamato, H. Ikematsu, H. Satoh, K. Nakamura, N. Shinohara, K. Hashimoto, and H. Matsumoto, "Study on SPS with satellites in formation flight and high sensitivity rectenna," ISRSSP'07, pp.153–156, 2007.
[8] W.C. Brown, "The history of power transmission by radio waves," IEEE Trans. Microwave Theory Tech, vol.MTT-32, no.9, pp.1230–1242, Sept. 1984.
[9] N. Shinohara and H. Matsumoto, "Experimental Study of Large Rectenna Array for Microwave Energy Transmission," IEEE Trans. Microwave Theory Tech, vol.46, no.3, pp.262–268, March 1998.
[10] R.J. Gutmann and J.M. Borrego, "Power Combining in an Array Microwave Power Rectifier," IEEE Trans. MTT, vol.27, no.12 pp.958–968, 1979.
[11] J.O. McSpadden, L. Fan, and K. Chang, "Design and Experiments of a High-Conversion-Efficiency 5.8-GHz Rectenna," IEEE Trans.

MTT, vol.46, no.12, pp.2053–2060, 1998.
[12] H. Takhedmit, L. Cirio, B. Merabet, B. Allard, F. Costa, C. Vollaire, and O. Picon, "Efficient 2.45 GHz rectenna design including harmonic rejecting rectifier device," Electronics Letters, vol.46, no.12, pp.811–812, June 1998.
[13] K. Nishida, Y. Taniguchi, K. Kawakami, Y. Homma, H. Mizutani, M. Miyazaki, H. Ikematsu, and Naoki Shinohara, "5.8 GHz High Sensitivity Rectenna Array," Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications(IMWS), 2011 IEEE MTT-S International, pp.19–22, June 2011.
[14] N. Shinohara, "Development of High Efficiency Rectenna at mW input," Technical report of IEICE SPS, 2004–08.
[15] S. Hemour, Y. Zhao, C.H.P. Lorenz, D. Houssameddine, Y. Gui, C.-M. Hu, and K. Wu, "Towards low-power high-efficiency rf and microwave energy harvesting," IEEE Trans. Microw. Theory Tech., vol.62, no.4, pp.965–976, 2014.
[16] N. Shinohara, "Wireless Power Transfer via Radiowaves (Wave Series)," ISBN 978-1-84821-605-1, ISTE Ltd. and John Wiley & Sons, Inc., Great Britain and United States, 2014.
[17] N. Shinohara (ed.), "Recent Wireless Power Transfer Technologies Via Radio Waves," ISBN 978-879360-924-2, River Publishers, EU, 2018.
[18] ITU-R: Report ITU-R SM.2392-0, "Applications of wireless power transmission via radio frequency beam," http://www.itu.int/pub/R-REP-SM.2392, 2016.
[19] Ministry of Internal Affairs and Communications, "Technical Condition of In-Room Far-Field Wireless Power Transfer (in Japanese)," July 14th, 2020, https://www.soumu.go.jp/main_content/000697268.pdf
[20] T.D.P. Perera, D.N.K. Jayakody, S.K. Sharma, S. Chatzinotas, and J. Li, "Simultaneous Wireless Information and Power Transfer (SWIPT): Recent Advances and Future Challenges," IEEE Communications Surveys & Tutorials, vol.20, no.1, pp.264–302, 2018.
[21] K. Hatano, N. Shinohara, T. Mitani, K. Nishikawa, T. Seki, and K. Hiraga, "Development of Class-F Load Rectennas," Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications (IMWS), 2011 IEEE MTT-S International, pp.251–254, May 2011.
[22] K. Hatano, N, Shinohara, T. Mitani, T. Seki, and M. Kawashima, "Development of Improved 24GHz-band Class-F Load Rectennas," Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications (IMWS), 2012 IEEE MTT-S International, pp.163–166, May 2012.
[23] N. Shinohara, "Rectennas for Microwave Power Transmission," IEICE Electron. Express, vol.10, no.21, pp.1–13, 2013, doi:https://doi.org/10.1587/elex.10.20132009
[24] C. Wang, N. Shinohara, and T. Mitani, "Study on 5.8 GHz single-stage charge pump rectifier for internal wireless system of satellite," EUCAP2017, pp.350–353, March 2017.
[25] C. Wang, N. Shinohara, and T. Mitani, "Study on 5.8-GHz Single-Stage Charge Pump Rectifier for Internal Wireless System of Satellite," IEEE Trans. Microwave Theory Tech., vol.65, no.4, pp.1058–1065, April 2017.
[26] C. Wang, N. Shinohara, and T. Mitani, "Study on 5.8 GHz band rectenna rectifying circuit for internal wireless system of satellite," WPTC2016, pp.1–4, June 2016.
[27] T. Ichikawa, T. Mitani, N. Shinohara, and H. Yong, "Study on an Intermittent Microwave Power Transmission to a ZigBee device II," IEICE Technical Report in Japan, pp.46–50, March 2013.
[28] H. Sakaki, M. Tsujii, K. Nishikawa, K. Kawai, H. Okazaki, and S. Narahashi, "5.8 GHz Reflecting Power Reuse Type Single Shunt Rectifier," Joint Conference of Electrical, Electronics and Information Engineers in Kyushu 2014, p.402, Sept. 2014.
[29] R. Kashimura, T. Seki, and K. Sakaguchi, "A study of Bias Controlled High Efficiency Rectifying Antenna Structure," IEICE Technical Report. Wireless Power Transfer, vol.116, no.321, pp.1–6, Nov. 2016.
[30] R. Kashimura, T. Seki, K. Sakaguchi, and K. Nishikawa, "Rectifying Circuit with High Impedance Microstrip Line for Wide Dynamic Range Characteristics," WPTC2017, pp.1–4, May 2017.
[31] R. Kashimura, T. Seki, and K. Sakaguchi, "A Study of Rectenna Receiving Area Division for Microwave Wireless Power Transfer Systems," APMC2017, pp.229–232, Nov. 2017.

Seiya Mizuno received the B.S. degree from the Department of Electrical Engineering, College of Industrial Technology, Nihon University, Chiba, Japan, in 2019. He is currently pursuing the M.S. degree in Electrical and Electronic Engineering at the same university. His research interests include wireless power transmission systems and rectenna design.

Ryosuke Kashimura received the B.S. and M.S. degrees from the Department of Electrical Engineering, College of Industrial Technology, Nihon University, Chiba, Japan, in 2017, 2019. He joined Japan Radio Co., Ltd. in 2019.

Tomohiro Seki received his B.E., M.E. and Dr. Eng. degrees in electrical engineering from the Tokyo University of Science, Tokyo, Japan, in 1991, 1993 and 2006, respectively. In 1993, he joined NTT and has been engaged in research on planar antennas and active integrated antennas for the millimeter-wave and microwave bands. In 2015, he joined Nihon University. Now he is a professor of College of Industrial Technology. He is currently interested in system-on-package technologies for millimeter-wave communication systems and wireless power transfer technologies for micro-wave and quasi-millimeter-wave frequency bands. He received the 1999 Young Engineer Award presented by the IEICE, the 2006, 2015 Best Paper Award presented by IEICE Communications Society and 2016 Best Paper Award presented by IEICE. He is a senior member of IEICE and a member of IEEE.

Maki Arai received the B.E., M.E., and D.E. degrees in electrical and electronic engineering from the Tokyo Institute of Technology, Japan, in 2010, 2012, and 2018, respectively. She joined the NTT Network Innovation Laboratories, Nippon Telegraph and Telephone Corporation (NTT) in 2012. From 2020, she is engaged in Nihon University. Her current research interests are high speed wireless communication systems and analysis and design of MIMO antennas. She received the Research Encouragement Award of the Institute of Electrical Engineers of Japan (IEEJ) in 2010, the Antenna and Propagation Research Commission Student Award from the Institute of Electronics, Information and Communication Engineers (IEICE) in 2012, and the Young Engineers Award from the IEICE in 2015.

Hiroshi Okazaki received the B.E. and M.E. degrees from Osaka University, Osaka, Japan, in 1988 and 1990, respectively, and Dr. Eng. degree from Tokyo Institute of Technology, Tokyo, Japan, in 2011. In 1990, he joined NTT Radio Communication Laboratories, Kanagawa, Japan, where he was engaged in research on RF circuits and equipment for several kinds of wireless communication systems. In 1990, he During 2001–2003, he was with NTT Electronics Corporation (NEL), Tokyo, Japan, where he was engaged in development of ultra-high-speed electronic devices for photonic communication systems. Since 2003, he has been with NTT DOCOMO, Inc., and involved in research on RF circuits for mobile communication systems. Dr. Okazaki was the recipient of the 1997 Young Engineer Award presented by the IEICE, the Japan Microwave Prize at the 1998 Asia-Pacific Microwave Conference, the 2011 IEICE Achievement Award and the 2012 IEICE Best Paper Award. He is a senior member of the IEEE and the IEICE.

Yasunori Suzuki received the B.E. and M.E. degrees from Nagaoka University of Technology, Niigata, Japan, in 1993 and 1995, respectively, and the Ph.D. degree from Hokkaido University, Sapporo, Japan, in 2011. In 1995, he joined NTT Mobile Communications Network Inc. (now NTT DOCOMO, INC.) where he was engaged in research on base station equipment for mobile communications. He is currently a manager of 6G Laboratories. He is a senior member of the IEICE. He is a member of the IEEE.