Hindawi
Active and Passive Electronic Components
Volume 2020, Article ID 4072325, 8 pages
https://doi.org/10.1155/2020/4072325

*Research Article*

# Development of a 100 mW-Class 94 GHz High-Efficiency Single-Series Rectifier Feed by Finline for Micro-UAV Application

**Kosumo Matsui,[1] Kimiya Komurasaki,[1] Waku Hatakeyama,[1] Kohei Shimamura,[2] Kohei Fujiwara,[3] and Hidehiko Yamaoka[3]**

[1]*Department of Aeronautics and Astronautics, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656, Japan*
[2]*Department of Engineering Mechanics and Energy, University of Tsukuba, Tennoudai 1-1-1, Tsukuba-shi, Ibaraki 305-0877, Japan*
[3]*Tokyo Metropolitan Industrial Technology Research Institute, Aomi 2-4-10, Koto-ku, Tokyo 135-0064, Japan*

Correspondence should be addressed to Kimiya Komurasaki; komurasaki@al.t.u-tokyo.ac.jp

Received 26 January 2020; Revised 18 June 2020; Accepted 7 August 2020; Published 21 August 2020

Academic Editor: Stephan Gift



Wireless power transfer (WPT) is one solution to realize long flight times and accommodate various missions of micro-uncrewed aerial vehicles (MAVs). Reducing the constraint of power transmission distance and realizing high beam efficiency are possible because of the high directivity of WPT using millimeter wave (MMW) methods. Nevertheless, no report of the relevant literature describes an investigation of sending power to an MAV using MMW because MMW rectennas have low efficiency. The purpose of our study is to conduct fundamental research of a high-efficiency and high-power rectenna at 94 GHz aimed at MAV application using MMW. As described herein, we developed and evaluated a 100-mW-class single-diode rectifier at 94 GHz with a finline of a waveguide (WG) to a microstrip-line (MSL) transducer. With the optimum load of 150 Ω at input power of 128 mW, the output DC power and rectifying efficiency were obtained respectively as 41.7 mW and 32.5%. By comparison to an earlier study, measurement of 94 GHz rectifiers under high power input becomes more accurate through this study.

## 1. Introduction

In recent years, micro-UAVs (MAVs) have been developed extensively. They are used in various applications, from commercial to military. Among them, some types have less than 100 g weight, which makes them inexpensive and easy to use. However, because of the small payload, the installed batteries are a constraint, necessitating short flight times of MAVs. One solution to resolve this constraint is to send power from a ground base to a UAV using wireless power transfer (WPT). Using magnetic resonance, WPT can send sufficient power to drive UAVs stably, but it cannot realize long-distance transmission. Moreover, it restricts the free flight of MAVs. However, WPT using RF energy can reduce the distance limit. As an example of research on UAVs, a power transmission experiment from the ground to a small airplane (SHARP) [1] has been reported in Canada. In addition, the University of Kyoto conducted experiments on power transmission to model airplanes and airships [2]. In our research group, WPT to MAVs was conducted in the microwave region [3, 4]. According to beam efficiency [5], as introduced by the Friis transmission equation, the higher the operating frequency becomes, the more efficiently WPT is realized. Shimamura et al. introduced the relation between the MAV size and the received power ratio for operating MAVs [6], as shown in the following equation:

$$\eta_r = \eta_T\left[1 - \exp\left(-\frac{\pi k^2 S}{16}\right)\right], \quad k = \frac{f D_T}{cd}. \tag{1}$$

In this equation, $\eta_T$, $S$, $f$, $D_T$, $c$, and $d$ respectively denote the beam efficiency, the MAV wing area, the operating frequency, the transmitting antenna diameter, the speed of light, and the transmission distance. Using the equation and an MAV (HS210; Holy Stone), we calculated and compared the received power under two operating frequencies:

5.8 GHz and 94 GHz. The parameters used and the calculated results are presented in Table 1. From the results, one can infer that higher frequencies can produce higher transmission efficiency, given the same transmission distance. That relation demonstrates the superiority of millimeter-wave (MMW) transmission. Among the MMWs available for use, 94 GHz is an atmospheric window. It is therefore possible to transmit power to MAVs efficiently at that frequency. Nevertheless, no study has examined the transmission of power to MAVs at 94 GHz because the antenna directivity is too high [7, 8] and because the rectifier efficiency is too low. Additionally, in MMW circuits, the conductor and dielectric loss in the oscillator and transmission line parts become greater than those related to microwaves. Moreover, conversion efficiency at the diode is low. Consequently, the conversion efficiency of the rectenna decreases. Research on MMW power in the field of wireless power transmission has remained inadequate compared to that for microwave power [9–12].

A millimeter-wave circuit has a short wavelength. For that reason, the circuit is small and difficult to fabricate as designed. To create such a small circuit, improvements have been made by mounting circuits with rectifying elements on a semiconductor substrate using CMOS technology [13–16]. However, the rectifiers of these technologies have low withstand voltage. Many elements must obtain the power required by an MAV or a satellite. For that reason, concerns of increased weight and cost arise. Furthermore, even when using GSG probes, which are generally used to supply power to planar circuits, large withstand voltage cannot be achieved because the maximum power that can be input is limited to several milliwatts as the frequency increases. Even in studies using a packaged GaAs Schottky diode [17], 100 mW class rectification was not realized at 94 GHz. For a study using another diode [18], a high-power oscillation source gyrotron was used to supply high power to the rectenna and thereby achieve 100 mW class input. Nevertheless, difficulties persist because the rectifier circuit and the antenna cannot be evaluated separately: accurate performance evaluation and design modification are difficult; moreover, the rectification efficiency is as low as 20%.

The purpose of our study is to conduct fundamental research of a high-efficiency and high-power rectenna at 94 GHz, aiming at MAV application using MMW. For an earlier study [19], we developed 94 GHz rectenna using a microstrip line (MSL). First, we fabricated a single-series rectifier feed using a finline, which is a waveguide- (WG-) microstrip line (MSL) transducer, as shown at the bottom of Figure 1, to achieve 100 mW-class input to the rectifier. However, the rectification efficiency of the rectifier does not match that of the rectenna in the earlier study. That is true because we used an open stub as a second harmonics notch filter and because the finline transmitting efficiency is not accurate in the study [20].

For the present study, we evaluated the finline transmitting efficiency accurately and developed a 94 GHz rectifier that realizes 100 mW-class input. The finline realizes separate evaluation of a rectifier and an antenna, which engenders improved design accuracy of tiny MMW rectennas. We select a single-series rectifier considering the low conversion efficiency at a diode and large insertion loss of a DC block in the MMW region. After evaluating the transmission efficiency of the finline, the rectifying efficiency and power are measured. The rectifying efficiency ($\eta$rec) is calculated using equation (2). Also, $P_{\text{in}}$, $P_{\text{DC}}$, $P_{\text{o}}$, $\eta_{\text{fin}}$, $A_{\text{r}}$, $A_{\text{t}}$, $\lambda$, and $d$ respectively denote the input power to the rectifier, the rectified DC power ($P_{\text{DC}}$) obtained by measurement, power from the oscillator, the transmission efficiency of the finline, the effective area of a receiving antenna, the effective area of a transmitting antenna, the wavelength, and the transmission distance. The rectifying efficiency was compared to the rectifying efficiency of the rectenna in an earlier study [21].

$$\eta_{\text{rec}} = \frac{P_{\text{DC}}}{P_{\text{in}}} = \frac{P_{\text{DC}}}{\eta_{\text{fin}} P_{\text{o}}} = \frac{(\lambda d)^2 P_{\text{DC}}}{A_{\text{r}} A_{\text{t}} P_{\text{o}}}. \quad (2)$$

## 2. Design of a 94 GHz Rectifier

A microstrip line (MSL) is used as a transmission line because it is easy to fabricate on a printed circuit board (PCB) and easy to use for the design of filters and stubs. Considering the insertion loss of a DC block with a millimeter wave, a single-diode series-connected rectifier was selected and fabricated. Two filters are set to increase the rectifying efficiency in the rectifier, as presented in Figure 2. A second harmonic notch filter (filter 1) is used to prevent the second harmonic, which arises inside the diode, from flowing back to the input port. Furthermore, filter 1, which consists of a short stub, plays the role of maintaining electrical conduction between the top and bottom layer. A fundamental harmonic notch filter (filter 2) is used to prevent the fundamental harmonic from flowing out to the DC port. Filter 2 has narrower line width than other parts of the circuit, which contributes to reduction of the effect of discontinuity at the junction [22]. The MSL loss increases as the line width narrows. Therefore, choosing an appropriate line width contributes to high efficiency. We compared two versions: $W_{\text{s}} = 0.1$ and 0.15 mm. We used a substrate (relative permittivity $\varepsilon_{\text{r}} = 2.19$, loss tangent $\tan\delta = 0.003$ at 94 GHz, Cu thickness = 18 mm; NPC F220CJ; Nippon Pillar Packing Co., Ltd.). The Schottky barrier diode (MA4E1310; Macom) is chosen as a diode because it has durability and responsivity of high-power driving in the W-band. Several Schottky barrier diode parameters are presented in Table 2.

Filter 2 is simulated using the finite element method (FEM) with an electromagnetic simulator (EMPro; Keysight Technologies Inc.), as shown in the left panel of Figure 3. FEM realizes accurate modelling of the MMW region, but it cannot simulate nonlinear devices such as diodes. We simulated only MSL elements. The result is shown in the right panel of Figure 3. Actually, 0.1 mm shows better filtering characteristics than 0.15 mm at the operating frequency of 94 GHz. Therefore, we describe fabrication of the 0.1 mm-wide filter 2 in a later chapter.

Table 1: Calculated received power ratio for an MAV (HS210; Holy Stone) at operating frequencies of 5.8 GHz (microwave) and 94 GHz (MMW).

| Parameter | Weight | Wing area, $S$ | Transmission distance, $d$ | Transmitting antenna diameter, $D_T$ | Calculated result 5.8 GHz | Calculated result 94 GHz |
|---|---|---|---|---|---|---|
| Value | 0.022 kg | 0.0064 m$^2$ | 10 m | 1 m | 0.0028 | 0.43 |

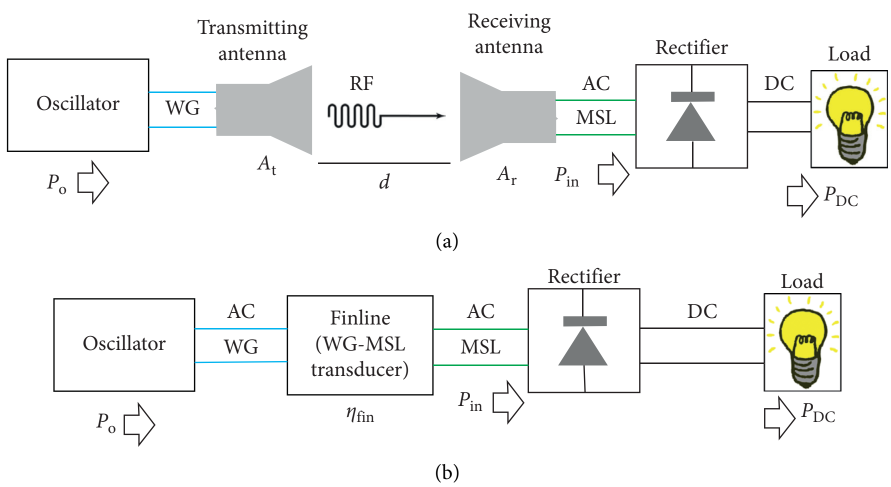


Figure 1: Rectenna (a) and rectifier (b) configurations. Each power and efficiency value used in later equations is presented in this figure. The rectifier is connected directly to the oscillator through a finline. The rectenna is fed power through free-space propagation.

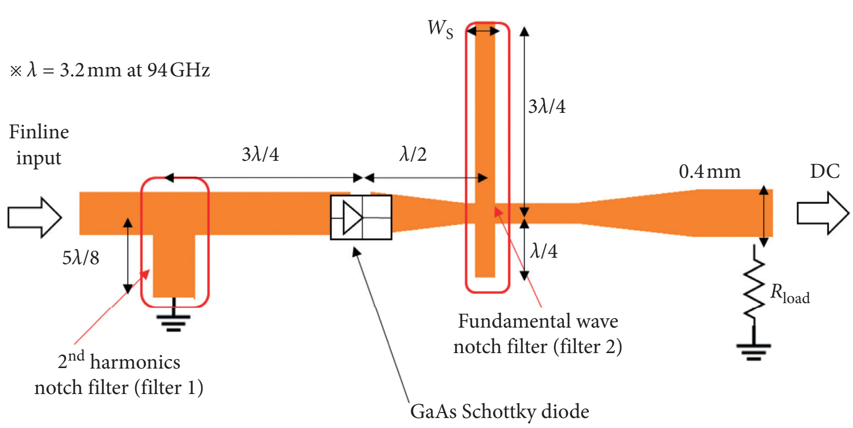


Figure 2: Design of a single-diode series-connected rectifier. A high breakdown voltage diode (MA4E1310; Macom) is selected. Two filters are used to increase the rectifying efficiency. Two widths of filter 2 are compared to obtain better filter properties.

Table 2: Several Schottky barrier diode parameters (MA4E1310; Macom).

| Parameter | Junction capacitance at 0 V, 1 MHz | Forward voltage at 1 mA | Reverse breakdown voltage at 10 $\mu$A | Incident maximum RF power |
|---|---|---|---|---|
| Value | 0.1 pF | 0.7 V | 7 V | 20 dBm |

## 3. Efficiency Measurements and Discussion

*3.1. Finline Transmitting Efficiency.* For this study, a finline [21–23] is used to input power to a rectifier. It realizes high-power operation. Although the transmission efficiency of a finline is necessary to evaluate the rectifying efficiency, it is impossible to measure the finline transmission efficiency ($\eta_{fin}$) directly because an end of a finline has MSL shape. Moreover, it is impossible to connect to the WG port of the W-band vector network analyzer (VNA). Therefore, a finline-MSL-finline (FMF) sample, as portrayed in Figure 4, was fabricated to allow that connection. Furthermore, to

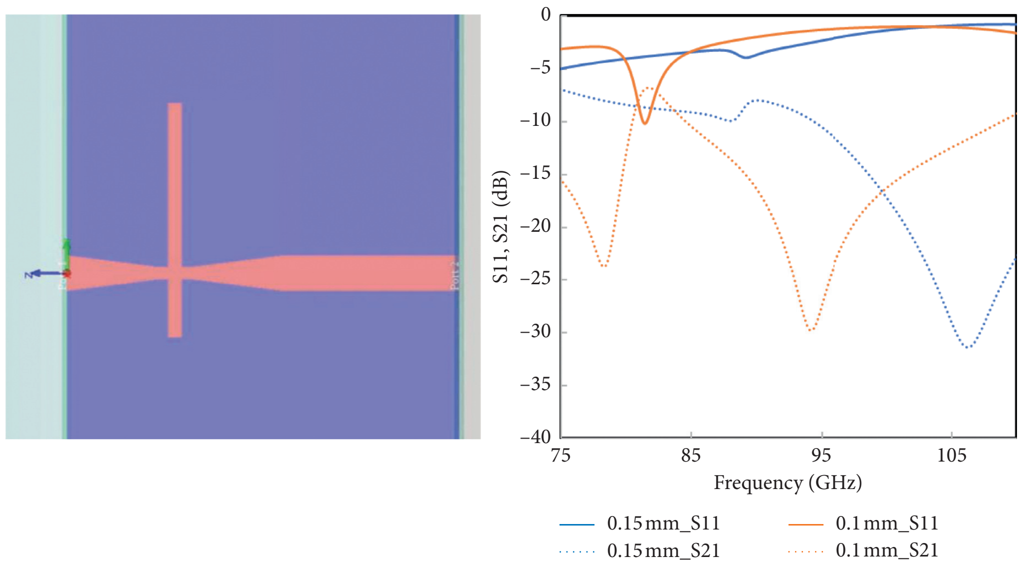


Figure 3: Configuration of the simulated part of the filter 2 in EMPro (a). Simulated result of S-parameter (b). The widths are 0.1 mm and 0.15 mm. Based on the result, the 0.1 mm-width filter shows a better notch filter property at 94 GHz.

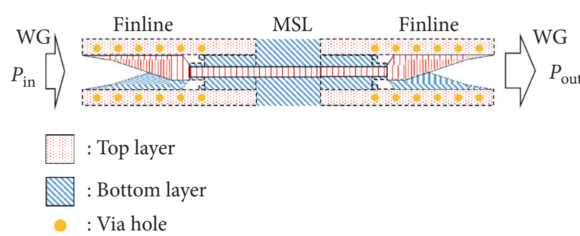


Figure 4: Configuration of a FMF sample. This sample is used for finline transmission measurements because the MSL part cannot be connected to the WG port of VNA. By changing the MSL part length and comparing them, the MSL loss per unit length is obtained. By removing the contribution of MSL, pure finline efficiency is obtainable.

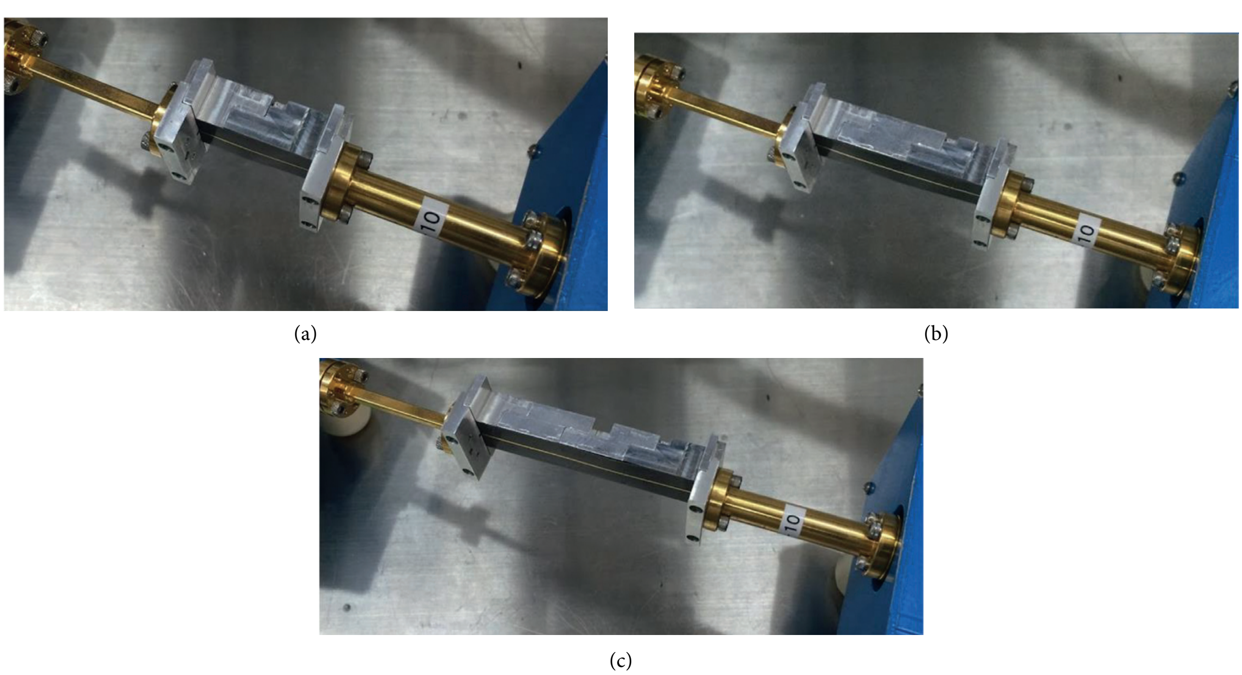


Figure 5: Measurement configuration of FMF samples. Using a vector network analyzer, the transmission efficiency can be measured: 40 mm (a), 61 mm (b), and 82 mm (c). By changing the MSL part length and comparing their transmission efficiencies, the MSL loss per unit length can be calculated.

TABLE 3: Measurement result of FMF sample transmission efficiency and calculated result of $\eta_{\mathrm{MSL}}$ and $\eta_{\mathrm{fin}}$.

| Transmission efficiency (dB) | | | MSL loss (dB/mm) | MSL loss $\alpha$ ($L = 40$ mm) (dB) | $\eta_{\mathrm{MSL}} = 1 - \alpha$ | $\eta_{\mathrm{fin}}$ |
|---|---|---|---|---|---|---|
| $L = 40$ mm | $L = 61$ mm | $L = 82$ mm | | | | |
| −3.50 | −4.90 | −6.23 | 0.065 | 2.08 | 0.62 | 0.85 |

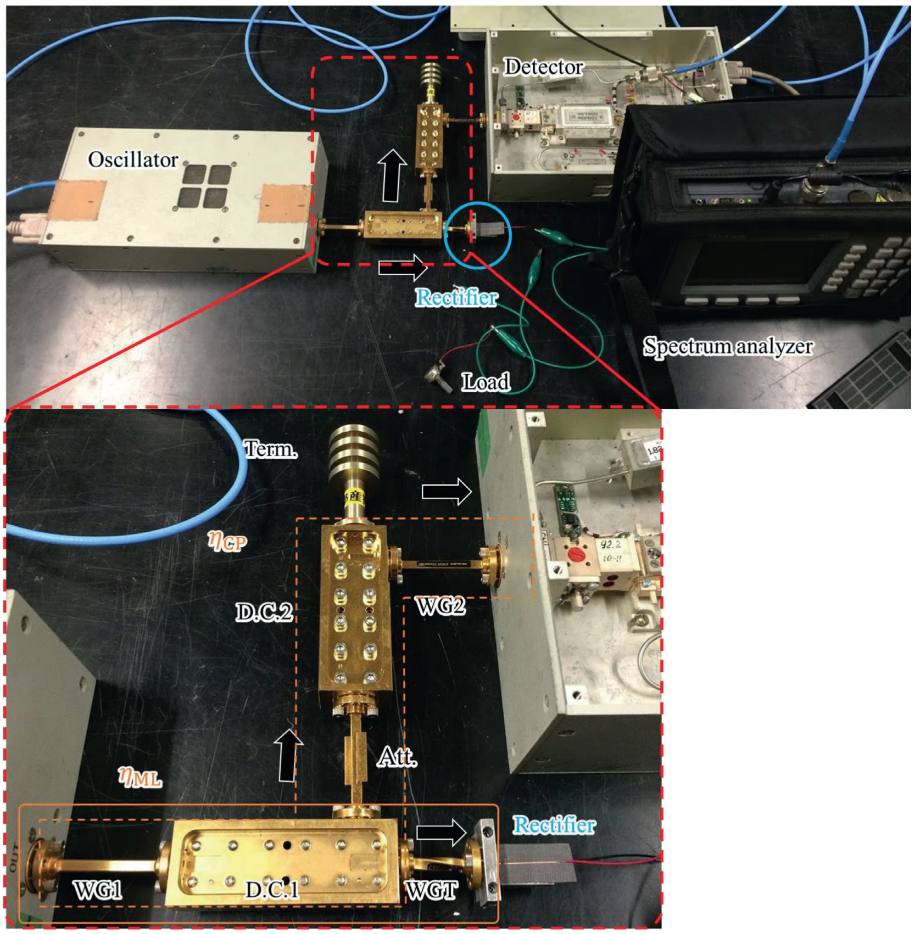


FIGURE 6: Rectifier measurement configuration. Power from the oscillator is divided at a directional coupler (D.C.1): one is input to the rectifier through the finline; the other is input to the detector. Voltage across the load is measured using the voltmeter.

eliminate the loss effect in MSL, we fabricated three FMF samples with different MSL lengths (40 mm, 61 mm, and 82 mm) and compared their transmission efficiencies. Results show that the MSL loss per unit length was calculated. The pure finline transmission efficiency was evaluated using equation (3).

Photographs of the FMF samples are presented in Figure 5. A W-band VNA (PNA-X N5247; Keysight Technologies Inc.) is used for FMF sample efficiency measurements. A support made of duralumin is used to connect the sample to the WG port of the VNA. To compensate the MSL length effect, the support is designed to change its length merely by inserting a joint with a length of 21 mm. The result is presented in Table 3. The measured finline transmission efficiency was 85%. This efficiency is used in rectifier efficiency measurements as described in the next section.

$$\eta_{\mathrm{fin}} = \sqrt{\frac{P_{\mathrm{out}}}{\eta_{\mathrm{MSL}} P_{\mathrm{in}}}}. \tag{3}$$

*3.2. Rectifying Efficiency of a Rectifier.* Figure 6 shows the measurement configuration. A 94 GHz/400 mW oscillator and a heterodyne detector (TR-10/94/x ELVA-1) are used for this measurement. The input power and the voltage at the end of the rectifier circuit are visible simultaneously using a directional coupler (D.C.1), which divides the power before input to the rectifier circuit. Another directional coupler (D.C.2) and an attenuator (Att.) are used to attenuate the power from the oscillator and to meet the upper limit of input to the detector. The main direction of D.C.2 is terminated to eliminate the effect of the open end. Output power from the oscillator is input to the circuit through the

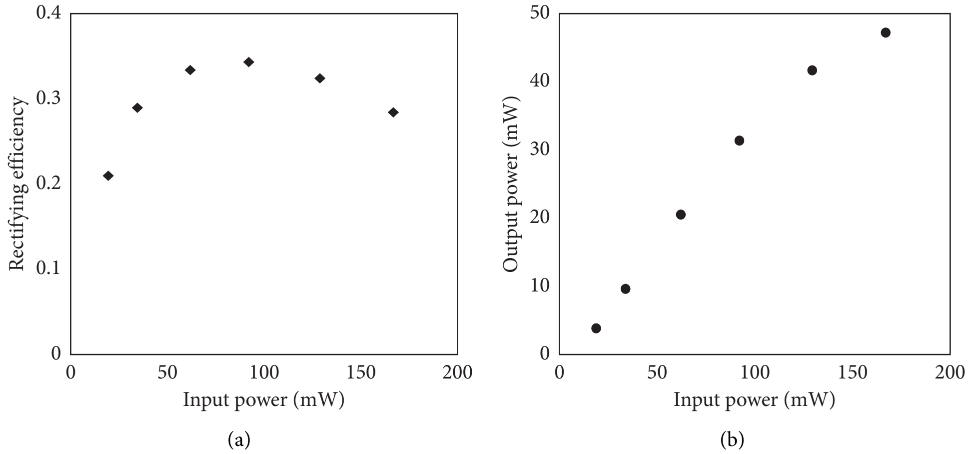


Figure 7: Measured rectification results at the optimum output impedance conditions: rectifying efficiency vs. input power (a) and output power vs. input power (b). At input power of 128 mW, the rectifying efficiency and output power are, respectively, 41.7 mW and 32.5%. We use this point as indicating high performance.

Table 4: Comparison with earlier works examining 94 GHz rectifiers.

| | [13] | [18] | [17] | [14] | This work |
|---|---|---|---|---|---|
| Rectification method | CMOS Schottky diode | Mott diode (IPM RAS) | GaAs Schottky diode (VDI) | Diode-connected transistor | GaAs Schottky diode (MACOM) |
| Technology | 130 nm CMOS | 0.254 mm PTFE | 0.254 mm alumina | 65 nm CMOS | 0.127 mm PTFE |
| Transmission line | FGCPW | MSL | CPW | Slotline | MSL |
| Power supply to a rectifier | Dual-band LTSA | Four-element MSA | Bow-tie slot | Half-wave horizontal dipole | Finline |
| Input RF power | 2.27 mW | 73 mW | 3.16 mW | 2.82 mW | 128 mW |
| DC output power | 0.84 mW | 15 mW | 1.02 mW | 0.28 mW | 41.7 mW |
| Rectifying efficiency ($\eta_{rec}$) | 37% | 20.5 | 32.3% | 10% | 32.5% |

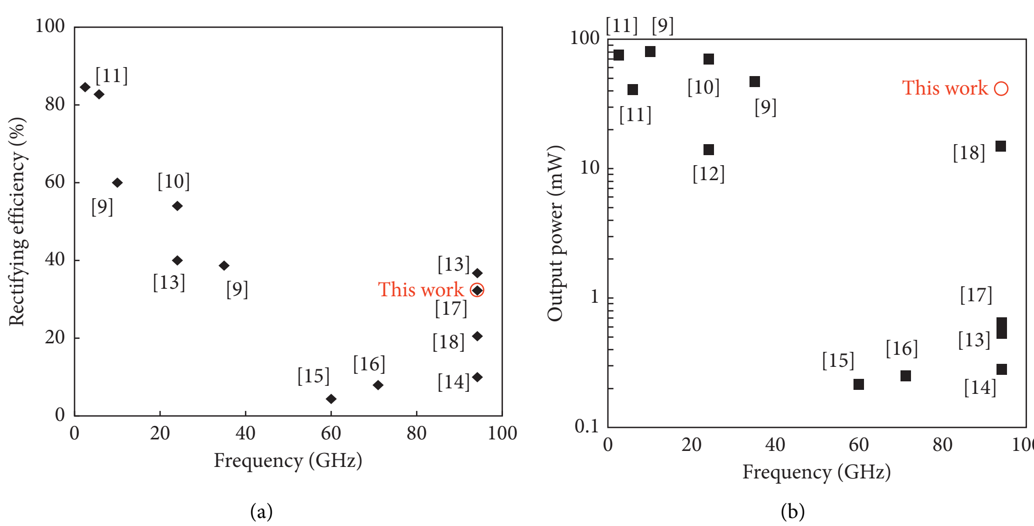


Figure 8: Comparison with other works from 2.45 GHz to 94 GHz: maximum rectifying efficiency vs. frequency (a); output DC power vs. maximum rectifying efficiency (b).

finline, which has transmission efficiency of 85% from measurements. Variable resistance is used as the load resistance. The output DC voltage across the resistance is measured using a voltmeter. Using equation (4), the rectifying efficiency ($\eta_{rec}$) can be calculated. The measured DC voltage ($V_{out}$), load resistance ($R_{load}$), measured power at the detector ($P_{det}$), finline transmission efficiency ($\eta_{fin}$), transmission efficiency of main direction ($\eta_{ML}$), and transmission efficiency of coupled direction ($\eta_{CP}$) are included in equation (4). In addition, $\eta_{ML}$ and $\eta_{CP}$ are measured by VNA in advance, as measured in the earlier part. Figure 7 shows $\eta_{rec}$ and $P_{DC}$ vs. $P_{in}$. When the load resistance is 150 Ω at input power of 128 mW, the rectifying efficiency was obtained as 32.5%. Under this condition, the output DC power was 41.7 mW. This value is approximately equal to the result obtained for the rectenna in an earlier study [19], which is 27.4%. Therefore, measurement of 94 GHz rectifiers under high power input becomes more accurate through this study.

Results obtained from this study are presented in Table 4 along with those of earlier studies that have examined this subject. At the same frequency, the efficiency was the second highest in the world; the output was found to be the highest value ever reported. Actually, the wavelength at 94 GHz is short, which can facilitate the production of small circuits. Furthermore, our highest output can engender great benefits for application to MAVs. Comparison of this work with other studies of lower frequency indicates that 94 GHz rectifiers show lower performance because of the large loss at the diode and the transmission line (Figure 8):

$$\eta_{rec} = \frac{P_{DC}}{P_{in}} = \frac{V_{DC}^2}{P_{in} R_{load}} = \frac{V_{DC}^2}{\eta_{ML}\eta_{fin} P_o R_{load}} = \frac{\eta_{CP} V_{DC}^2}{\eta_{ML}\eta_{fin} P_{det} R_{load}}. \quad (4)$$

## 4. Conclusions

We developed a 100 mW-class 94 GHz single-series rectifier aimed at MAV application using MMW. Its rectifying efficiency was evaluated before integration by fabricating FMF samples using a finline, for which the transmission efficiency was inferred as 85%. When the input RF power was 128 mW, the output DC power and rectifying efficiency of the rectifier ($\eta_{rec}$) were obtained respectively as 41.7 mW and 32.5%. The output power was the world's highest value reported to date: 94 GHz. Comparison of results of this study to an earlier study revealed that the measurement of 94 GHz rectifiers under high power input gives better accuracy.

## Data Availability

Data will be available on Open Access Repository with DOI after the review process.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

This work was supported by a JSPS Grant-in-Aid for Scientific Research (Grant no. JP15H05770), Nippon Pillar Packing, and "Nanotechnology Platform Japan" of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), in the Takeda clean room with the help of the Nanofabrication Platform Center of the VLSI Design and Education Center (VDEC), the University of Tokyo.

## References

[1] G. W. Jull, "Summary report on SHARP (stationary high-altitude relay platform) part A—technical feasibility of microwave-powered airplanes," CRC Report No. 1393, Communications Research Centre, Ottawa, Canada, 1985.

[2] H. Matsumoto, N. Kaya, M. Fujita, T. Fujiwara, and T. Sato, "Microwave lifted airplane experiment with active phased array antennas," MILAX Report, Kyoto University, Kyoto, Japan, 1995.

[3] S. Komatsu, K. Katsunaga, R. Ozawa, K. Komurasaki, and Y. Arakawa, "Power transmission to a micro aerial vehicle," in *Proceedings of the 45th AIAA Aerospace Sciences Meeting and Exhibit (AIAA-Paper 2007-1003)*, Reno, Nevada, January 2007.

[4] S. Nako, K. Okuda, K. Miyashiro, K. Komurasaki, and H. Koizumi, "Wireless power transfer to a microaerial vehicle with a microwave active phased array," *International Journal of Antennas and Propagation*, vol. 2014, Article ID 374543, 5 pages, 2014.

[5] N. Shinohara, "Beam efficiency of wireless power transmission via radio waves from short range to long range," *Journal of Electromagnetic Engineering and Science*, vol. 10, no. 4, pp. 224–230, 2010.

[6] K. Shimamura, H. Sawahara, A. Oda et al., "Feasibility study of microwave wireless powered flight for micro air vehicles," *Wireless Power Transfer*, vol. 4, no. 2, pp. 146–159, 2017.

[7] C.-J. Peng, S.-F. Yang, A.-C. Huang, T.-H. Huang, P.-J. Chung, and F.-M. Wu, "Harmonic enhanced location detection technique for energy harvesting receiver with resonator coupling design," in *Proceedings of the IEEE Wireless Power Transfer Conference (WPTC)*, pp. 1–3, Taipei, Taiwan, May 2017.

[8] H. Zhang, Y.-X. Guo, S.-P. Gao, and W. Wu, "Wireless power transfer antenna alignment using third harmonic," *IEEE Microwave and Wireless Components Letters*, vol. 28, no. 6, pp. 536–538, 2018.

[9] T.-W. Yoo and K. Chang, "Theoretical and experimental development of 10 and 35 GHz rectennas," *IEEE Transactions on Microwave Theory and Techniques*, vol. 40, no. 6, pp. 1259–1266, 1992.

[10] K. Hatano, "Development of 24 GHz-band MMIC rectenna,"vol. 50, pp. 199–201, in *Proceedings of the Radio And Wireless Symposium (RWS)*, vol. 50, pp. 199–201, IEEE, Austin, TX, USA, January 2013.

[11] Y. H. Suh and K. Chang, "A high efficiency dual-frequency rectenna for 2.45- and 5.8-GHz wireless power transmission," *IEEE Transactions on Microwave Theory and Techniques*, vol. 50, no. 7, pp. 1784–1789, 2002.

[12] S. Ladan, S. Hemour, and K. Wu, "Towards millimeter-wave high-efficiency rectification for wireless energy harvesting," in *Proceedings of the 2013 IEEE International Wireless Symposium (IWS)*, pp. 7–10, Beijing, China, April 2013.

[13] H.-K. Chiou and I.-S. Chen, "High efficiency dual-band on-chip rectenna for 35- and 94-GHz wireless power transmission in 0.13-μm CMOS technology," *IEEE Transactions on Microwave Theory and Techniques*, vol. 58, no. 12, pp. 3598–3606, 2010.

[14] N. Weissman, S. Jameson, and E. Socher, "W-band CMOS on-chip energy harvester and rectenna," in *Proceedings of the 2014 IEEE MTT-S International Microwave Symposium (IMS 2014)*, pp. 1–3, Tampa, FL, USA, June 2014.

[15] H. Gao, U. Johannsen, M. K. Matters-Kammerer et al., "A 60-GHz rectenna for monolithic wireless sensor tags," in

*Proceedings of the 2013 IEEE International Symposium on Circuits and Systems (ISCAS 2013)*, pp. 2796–2799, Beijing, China, May 2013.

[16] H. Gao, M. K. Matters-Kamrnerer, P. Harpe et al., "A 71 GHz RF energy harvesting tag with 8% efficiency for wireless temperature sensors in 65 nm CMOS," in *Proceedings of the 2013 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*, pp. 403–406, Seattle, WA, USA, June 2013.

[17] S. Hemour, C. H. P. Lorenz, and K. Wu, "Small-footprint wideband 94 GHz rectifier for swarm micro-robotics," in *Proceedings of the 2015 IEEE MTT-S International Microwave Symposium*, pp. 5–8, Phoenix, AZ, USA, May 2015.

[18] A. Etinger, M. Pilossof, B. Litvak et al., "Characterization of a Schottky diode rectenna for millimeter wave power beaming using high power radiation sources," in *Proceedings of the 12th Symposium of Magnetic Measurements and Modeling SMMM' 2016*, Częstochowa-Siewierz, Poland, October 2016.

[19] K. Matsui, K. Fujiwara, Y. Okamoto et al., "Development of 94 GHz microstrip line rectenna," in *Proceedings of the 2018 IEEE Wireless Power Transfer Conference (WPTC)*, pp. 1–4, Montreal, Canada, June 2018.

[20] K. Hatano, N. Shinohara, and T. Mitani, "Improvement of 24 GHz-band class-F load rectennas," in *Proceedings of the 2012 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications*, pp. 7–10, Kyoto, Japan, May 2012.

[21] J. H. C. van Heuven, "A new integrated waveguide-microstrip transition (short papers)," *IEEE Transactions on Microwave Theory and Techniques*, vol. 24, no. 3, pp. 144–147, 1976.

[22] K. Fujiwara and T. Kobayashi, "Low-cost W-band frequency converter with broad-band waveguide-to-microstrip transducer," in *Proceedings of the 2016 Global Symposium on Millimeter Waves (GSMM) & ESA Workshop on Millimetre Wave Technology and Applications*, pp. 1–4, Espoo, Finland, June 2016.

[23] Japanese Patent Application No. 2016243600.