



Fundamental Study on Wireless Power Transfer for Sensing Tools in Turning Operations

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We are developing a sensing tool to monitor machining conditions during turning operations. Current sensing tools are powered by batteries, which pose operational challenges such as battery replacement managing. This study aims to power the sensing tool using wireless power transfer instead of batteries. We designed and evaluated a rectenna operating in the 5.7 GHz band, integrated into an aluminum housing that simulates a cutting tool. In an experiment conducted with a transmission power of 30 W and a transmission distance of 1,000 mm, the rectenna yielded a DC output power of 0.45 W, confirming that it is sufficient to operate the sensing tool.

Keywords: wireless power transfer, rectenna, battery-free, cutting tool, sensing tool

1. Introduction

In recent years, digital transformation (DX) has been progressing across all industries, increasing the demand for automation and unmanned operations. On machining shop floors, systems for monitoring machining conditions are being developed by collecting and analyzing data from various sensors and communication devices integrated into machine tools and their peripheral equipment. Because turning tools are located closest to the machining point, embedding sensors in them enables highly accurate monitoring of machining conditions.

Our company has developed a sensing tool (sensor-embedded cutting tool) that measures cutting forces during machining by embedding strain sensors near the cutting edge closest to the machining point and wirelessly transmits the collected data to a receiver outside the machine tool (Fig. 1).^{(1),(2)} Specifically, as shown in Fig. 2, the sensing tool is mounted on the turret*¹ inside the machine tool, and a receiver is installed on the window outside the machine tool to monitor cutting forces. However, because this sensing tool is powered by a battery, it requires periodic replacement, resulting in significant time and cost penalties. Furthermore, machining lines must be stopped during battery replacement, which poses a major problem by significantly reducing production efficiency. To address this issue, we are investigating wireless power transfer (WPT) as an alternative power source for the sensing tool.

Microwave-based WPT enables power delivery over relatively long distances, but transmission efficiency remains a challenge.⁽³⁾ Improving efficiency requires a high-gain transmitting antenna and a highly efficient rectenna.*² Numerous prior studies have reported highly efficient rectennas that suppress circuit losses by directly matching the antenna with the rectifier.⁽⁴⁾⁻⁽⁷⁾ In particular, rectennas composed of a patch antenna and a rectifier^{(6),(7)} exhibit little performance degradation even when mounted on metal surfaces because they incorporate a ground plane. Therefore, they are suitable for installation inside metal cutting-tool housings.

In this study, as a proof-of-concept (PoC) for driving the sensing tool via WPT, we designed and evaluated a rectenna integrated into an aluminum housing that simulates a cutting tool.

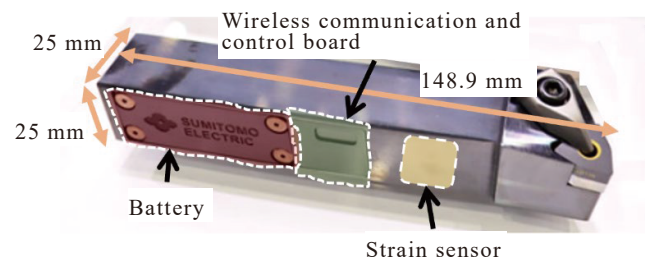


Fig. 1. Current sensing tool for cutting tools

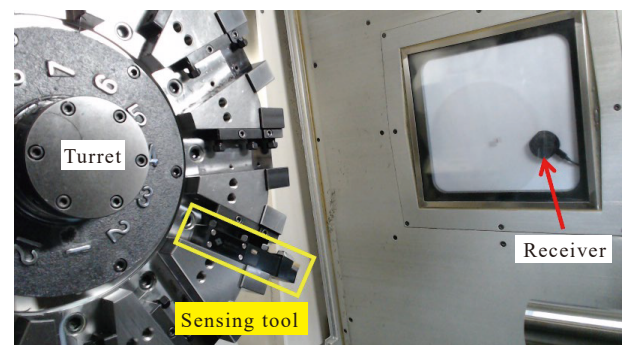


Fig. 2. Sensing tool integrated into a machine tool

2. Required Performance of WPT

The configuration of the WPT system⁽⁸⁾ examined in this study is shown in Fig. 3. A transmitter is installed on the window of the machine tool, and a rectenna is mounted

inside the battery box of the sensing tool to supply power wirelessly to the sensor and the wireless communication and control board. The distance between the transmitter and the rectenna is approximately 1,000 mm. Since the rectenna must be housed in the existing battery box, it must be designed to be no larger than 17.5 mm × 41 mm. In addition, an output power of at least 0.1 W is required from the rectenna to operate the sensing tool.

For beam-type WPT, three frequency bands are permitted for use: 920 MHz, 2.4 GHz, and 5.7 GHz.⁽³⁾ In this study, the 5.7 GHz band was selected because it offers higher transmission power and is the most advantageous for antenna minimization due to its high frequency. Based on these considerations, the target specifications of the rectenna in this study are summarized in Table 1.

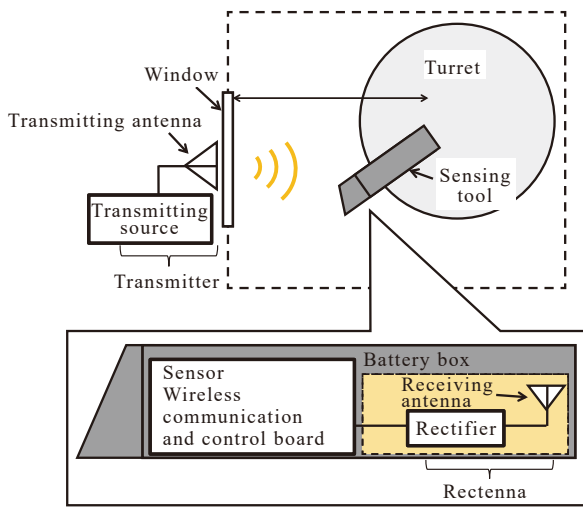


Fig. 3. Configuration of the WPT system

Table 1. Target specifications

Rectenna	Dimensions	17.5 mm × 41 mm or less
	Output	0.1 W or higher

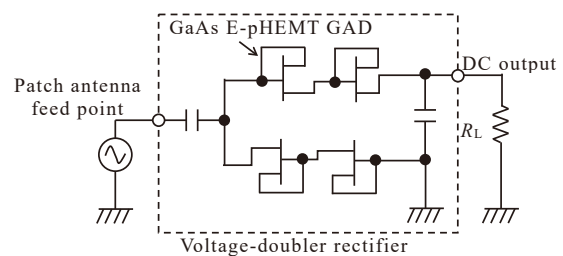
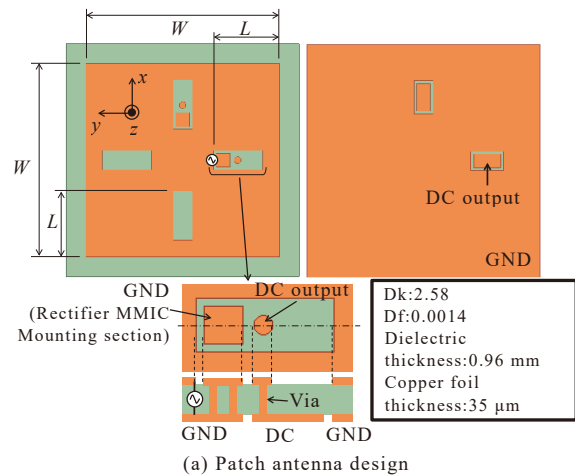
3. Rectenna

Prior studies^{(6),(7)} proposed a rectenna composed of a patch antenna and a voltage-doubler rectifier monolithic microwave integrated circuit (MMIC).^{*3} Direct matching between the antenna and the rectifier achieved high efficiency, yielding an output power of 0.32 W (rectification efficiency: 76%) with an input power of 26.2 dBm (approx. 0.42 W) to the rectifier. This performance is well-suited for the WPT system under consideration in this study. Based on these results, this study adopts the rectenna configuration proposed in these prior studies,^{(6),(7)} which consists of a patch antenna and a voltage-doubler rectifier MMIC.

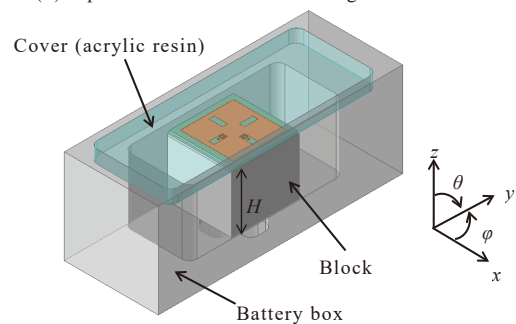
3-1 Rectenna configuration

Figure 4 shows the rectenna configuration.⁽⁸⁾ The antenna is fabricated on an NPC-F260A substrate manufactured by PILLAR Corporation, and the rectifier employs a 0.5 μm GaAs enhancement-type pseudomorphic high elec-

tron mobility transistor (E-pHEMT)^{*4} Gated Anode Diode (GAD)^{*5} (PD50-10, WIN Semiconductors Corp.). Figure 4 (a) illustrates the antenna design, which features a square patch antenna formed by a copper-foil pattern on the substrate surface, with a feed point located inside the patch antenna. The feed point features a notch for mounting the rectifier MMIC (Fig. 4 (b)). This MMIC is mounted on the top-surface GND plane, which is connected to the bottom-surface GND plane through thermal vias. To maintain a symmetrical current distribution across the patch antenna, an additional notch is placed at the geometrically opposite position. While a single feed point is used here for single-polarization, the structure is designed to accommodate future expansion to dual-polarization operation. Direct matching between the rectifier MMIC and the patch antenna eliminates the need for a matching circuit, thereby reducing circuit losses. A rectenna with the above configuration is installed inside an aluminum housing that simulates the battery box in the cutting tool, as shown in Fig. 4 (c). Impedance matching between the antenna and the



(b) Equivalent circuit of the voltage-doubler rectifier



(c) Patch antenna integrated into the cutting tool

Fig. 4. Rectenna configuration

rectifier is achieved by adjusting the height H of an aluminum block placed on the back side of the antenna. Additionally, an acrylic cover is attached to protect the rectenna from chips, coolant, and oil during turning operations.

3-2 Antenna design

To directly match the antenna to the rectifier, it is necessary to determine the optimal antenna impedance. Figure 5 shows the calculation model used to derive the design conditions for the antenna impedance. The patch antenna is modeled as a parallel circuit consisting of a resistance R_{ant} and an inductance L_{ant} , which is connected to the voltage-doubler rectifier through a bonding wire with an inductance L_{bw} . A load resistance R_L is connected to the output of the rectifier. The value of L_{bw} was calculated as 0.2 nH based on the diameter and length of the bonding wire. Table 2 lists the parameters of the GaAs E-pHEMT GAD (gate width $W_g = 0.6$ mm).^{(6),(8)} Using this model, the optimal antenna impedance is derived by searching for R_{ant} , L_{ant} , P_{in} , and R_L that maximize the rectification efficiency η_{rec} , which is defined as $\eta_{rec} = P_{out} / P_{in}$. Figure 6 shows the analysis results obtained using the circuit simulator ADS (Advanced Design System), where R_L and P_{in} were optimized to 1.5 k Ω and 26.7 dBm, respectively. Figure 6 presents a contour plot of η_{rec} at 5.8 GHz, indicating that the rectification efficiency is maximized when $R_{ant} = 200$ Ω

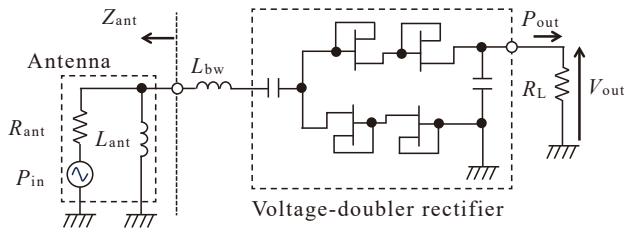


Fig. 5. Antenna impedance calculation model

Table 2. Parameters of GaAs E-pHEMT GAD ($W_g = 0.6$ mm)

Parameter	Symbol	Unit	Value
Saturation current	I_s	nA	7.1
Ideality factor	n		1.2
Series resistance	R_s	Ω	3.0
Breakdown voltage at 80 μ A	V_{br}	V	13.7
Junction capacitance at 0 V	C_{j0}	pF	0.21
Parasitic capacitor	C_d	pF	0.13
Series Inductor	L_s	nH	0.16

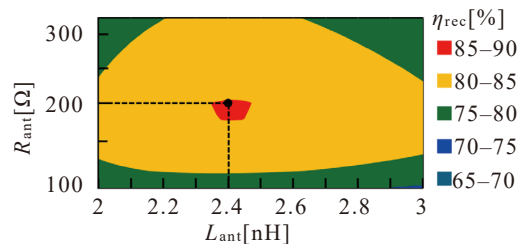


Fig. 6. Rectification efficiency η_{rec} against R_{ant} and L_{ant} at 5.8 GHz

and $L_{ant} = 2.4$ nH. Using these values, the design conditions for the antenna impedance Z_{ant} are determined to be $Z_{ant} = 32 + j73$ Ω .

To satisfy this condition, the patch width W , the notch position L , and the aluminum block height H were adjusted using the electromagnetic field simulator HFSS (high-frequency structure simulator). The locus of Z_{ant} for each parameter variation is shown in Fig. 7. Figure 7 (a) shows that increasing W increases both the resistance and reactance, followed by resonance at a certain value, after which the impedance becomes capacitive. Figure 7 (b) shows that increasing L decreases both the resistance and reactance. Figure 7 (c) shows that increasing H increases both the resistance and reactance. Figure 8 shows the design results for the optimized dimensions $W = 14.1$ mm, $L = 4.75$ mm, and $H = 15$ mm. At a frequency of 5.8 GHz, the antenna impedance Z_{ant} is $34 + j81$ Ω , which is sufficiently close to the target value. The directivity of the antenna under these conditions is shown in Fig. 9. The antenna gain was 6.6 dBi, and the 3-dB beamwidth was 62° on the E-plane and 92° on the H-plane, demonstrating favorable characteristics.

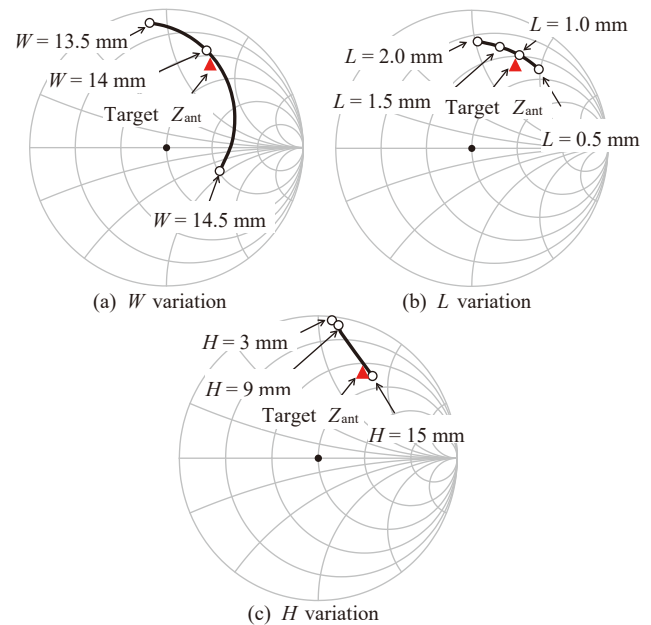


Fig. 7. Antenna impedance locus for each dimension

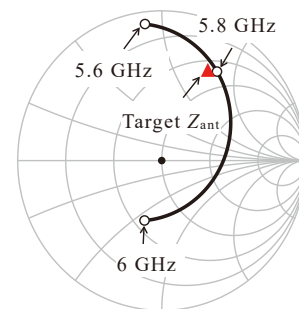


Fig. 8. Antenna impedance after dimension adjustment

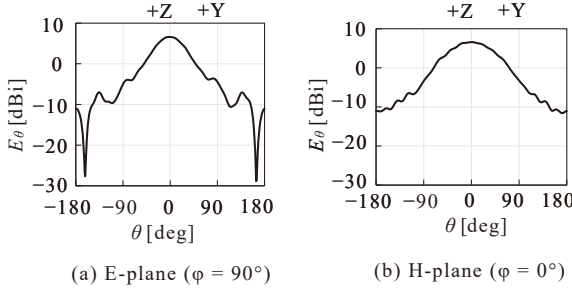


Fig. 9. Directivity of the patch antenna integrated into a cutting tool at 5.8 GHz

3-3 Rectenna performance evaluation

Figure 10 illustrates the prototype rectenna integrated into a cutting tool. Only the battery box in the cutting tool is simulated by the aluminum housing, and its dimensions are identical to those of the actual tool. Additionally, an acrylic cover is attached for dust and waterproofing. The rectenna measures 17 mm × 17 mm, allowing it to fit inside the battery box of the cutting tool. The rectifier MMIC is mounted on the GND plane on the top surface of the substrate, and bonding wires connect the rectifier MMIC, the feed point, and the DC output terminal.

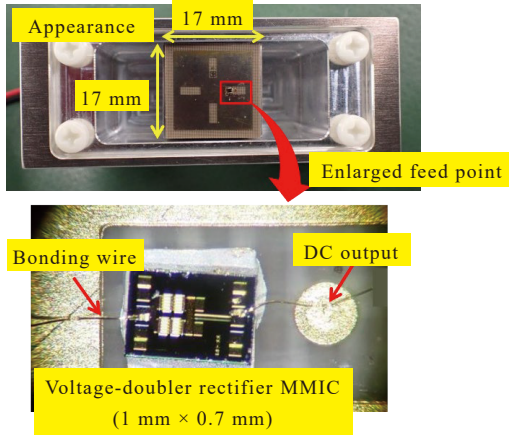


Fig. 10. Prototype rectenna

Next, the evaluation method for the rectenna is described.^{(6),(8)} Figure 11 shows the measurement setup for the rectification efficiency η_{rec} . As shown in Fig. 11 (a), a standard dipole antenna is placed 300 mm away from the transmitting antenna to measure the received power P_{ref} . Then, the standard dipole antenna is replaced with the rectenna to measure the output power P_{out} (Fig. 11 (b)). Under these conditions, the input power to the rectifier, P_{in} , is calculated as $P_{in} = P_{ref} + (G_{ant} - G_{ref})$, where G_{ant} is the simulated antenna gain of the rectenna and G_{ref} is the gain of the standard dipole antenna.

Figure 12 shows the frequency response of the rectenna, and Figure 13 shows its input-output characteristics. The dashed lines represent measured results, and the solid lines represent the ADS simulation results. Since the

peak frequency of the rectification efficiency shifted by approximately 100 MHz between the measurement and simulation, the comparison was made at their respective peak frequencies. At $f = 5.7$ GHz, $P_{in} = 27.8$ dBm, and $R_L = 1.7$ k Ω , the rectenna achieved $\eta_{rec} = 80.9\%$ and $V_{out} = 28.8$ V, which are in good agreement with simulation results.

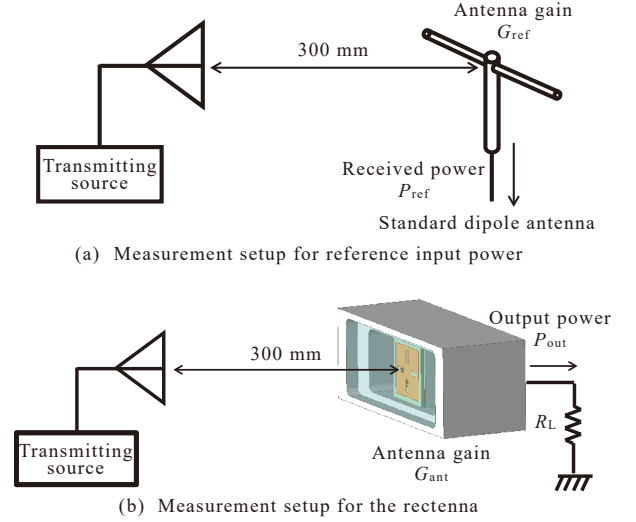
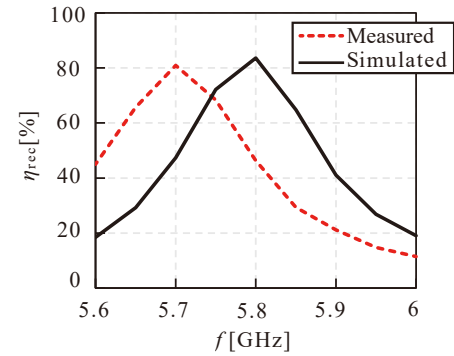
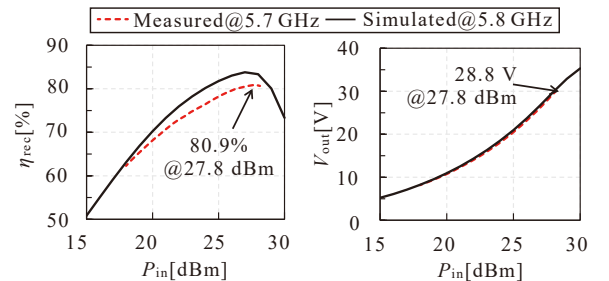
Fig. 11. Measurement setup for rectification efficiency η_{rec} Fig. 12. Rectenna frequency response ($P_{in} = 27.8$ dBm, $R_L = 1.7$ k Ω)

Fig. 13. Rectenna input-output characteristics

4. System-level WPT Evaluation

A system-level WPT evaluation test was conducted using the prototype rectenna. Figure 14 shows the experimental setup. In this evaluation test, an 8 × 8 waveguide

slot array antenna (gain: 23.3 dBi) was used as the transmitting antenna.⁽⁸⁾ Its flat structure allows for easy installation on the window of a machine tool, making it highly suitable for this system. Figure 15 shows the measurement block diagram for this evaluation. RF signals from a signal generator (SG) were fed into the amplifier, and power was supplied to the transmitting antenna while monitoring the transmission power using a power meter through a directional coupler. The distance between the transmitting antenna and the rectenna was 1,000 mm, and the transmission frequency was 5.7 GHz. A load resistance $R_L = 1.7 \text{ k}\Omega$ was connected to the output terminal of the rectenna as a pseudo-load for the sensing tool, and the DC output voltage V_{out} was measured using a multimeter. Figure 16 shows the output power P_{out} of the rectenna and the total system efficiency η_{total} against the input power P_{Tx} to the transmitting antenna. Here, P_{out} and η_{total} are defined as $P_{out} = V_{out}^2 / R_L$ and $\eta_{total} = P_{out} / P_{Tx}$, respectively. When an input power of 30 W was supplied to the transmitting antenna, the rectenna produced a DC output of 0.45 W and an output voltage of 27.6 V, which successfully exceeded the target power of 0.1 W. The total system efficiency at this point was approx-

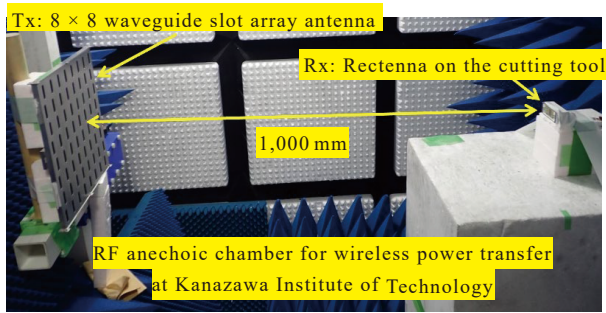


Fig. 14. Evaluation of wireless power transfer

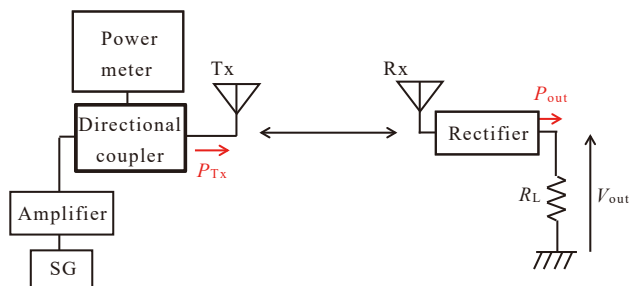


Fig. 15. Measurement block diagram

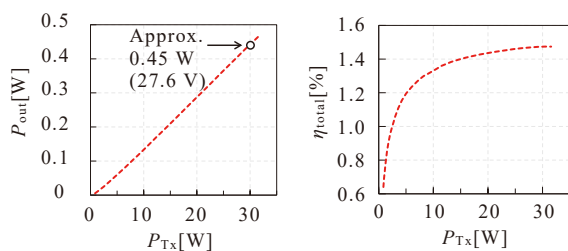


Fig. 16. Output power P_{out} and system efficiency η_{total} against transfer power P_{Tx}

imately 1.5%. Although voltage step-down is required to power the sensing tool, it was confirmed that the available power is sufficient for its operation, even when considering losses in the DC-DC converter.

5. Conclusion

In this study, we conducted a PoC investigation to achieve WPT for driving a sensing tool. A rectenna integrated into an aluminum housing that simulates a machining tool was designed and evaluated. At a transmission distance of 1,000 mm, the system achieved a received DC power of 0.45 W, demonstrating that the proposed WPT system is a feasible power supply method for a sensing tool.

Technical Terms

- *1 Turret: A tool post that holds multiple cutting tools arranged radially.
- *2 Rectenna: The abbreviation for rectifying antenna. A device that converts microwaves and other radio waves into direct current.
- *3 MMIC: An acronym for monolithic microwave integrated circuit. A microwave integrated circuit that integrates transistors, diodes, and other components on a single semiconductor substrate.
- *4 GaAs E-pHEMT: An enhancement-mode pseudomorphic high-electron-mobility transistor (E-pHEMT) based on GaAs semiconductor materials. It offers high-speed operation and is suitable for high-frequency circuits.
- *5 Gated Anode Diode (GAD): A diode formed by connecting the gate and drain terminals of the pHEMT.

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