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Loss Measurement in Power Conditioning Module for Power-line Magnetic Noise Energy Harvesting Device

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The purpose of our research is to develop an energy harvesting device for a power-line magnetic field of 60 Hz. This device consists of an energy harvesting module and a power conditioning module. The harvesting module can provide 25 mW to an optimum load of 1 kΩ from a field of 45.3 μT. To use the harvested energy as a battery, a power conditioning module consisting of a rectifier circuit and a DC-DC converter is required. We prepared two full-wave rectifier circuits with different Schottky diodes, and an ultralow voltage step-up converter for an output of 5 V. The efficiency of the rectifier circuit was greater than 80 %. It was found that the efficiency of the DC-DC converter depended on the input voltage and the dummy load. From experiments, we successfully demonstrated that our developed harvesting device can provide an output voltage of 5 V. To use this device as a battery, loss in the power conditioning module was also discussed.

Keywords: energy harvesting, power-line magnetic noise, rectifier circuit, DC-DC converter.
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1. Introduction

In recent years, we have focused on techniques for harnessing environmental energy. We can easily observe the existence of light, vibration, and thermal energies in our living environment. Energy harvesting is a key technology for small, self-sufficient devices, which use environmental energy as a power source. The advantages of energy harvesting are that it is no battery and maintenance free. Previously, applications of harvested energy were restricted to devices such as watches, calculator, etc. However, in recent years, because of the emergence of developed wireless sensors operate at few mW, environmental energy has been considered useful for these devices [1]. Table1 shows the typical power consumption in mobile devices [2].

Because power-lines are a life-line in our modern life, we live in undesirable power-line magnetic noise. From the view point of the effect on humans, an acceptable level in a public space is 200 μT at power-line frequency (50 Hz or 60 Hz) [3]. Considering these the reasons, we have newly focused on this magnetic field as a source of energy harvesting. The purpose of this study was to develop an energy harvesting device for power-line magnetic noise. In our previous report [4], we demonstrated energy harvesting of 6.32 mW from a magnetic field of 21.2 μT at 60 Hz. It should be noted that the harvested energy was proportional to the square of the magnetic flux density. Thus, if there was magnetic flux density of 200 μT at 60 Hz, the estimated harvesting energy became 562 mW. This power is sufficient to operate 110 MP3 players, or provide half of the required power for a smartphone.

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However, this harvesting module cannot provide constant voltage at a few volts, and the harvested power depends on the magnetic environment condition. To use the harvested energy as a battery, a power conditioning module consisting of a rectifier circuit and a DC-DC converter is required. The input-output characteristics and the energy losses in these components should be considered.

In this paper, we developed an energy harvesting device consisting of a harvesting module, rectifier circuit, and DC-DC converter for an output of 5 V. If the output is 5 V for a load of 1 kΩ, the consuming energy in the load becomes 25 mW. First, we confirmed the harvested energy of the harvesting module from a uniform magnetic field of up to 45.3 μT. According to our estimation, this amplitude is sufficient to harvest 25 mW. We prepared two full-wave rectifier circuits with different Schottky diodes. From the experimental results, we evaluated the energy losses and required conditions for providing the output voltage of 5 V with several load conditions.

2. Experimental Set Up

2.1 Model

2.1.1 Energy Harvesting Module

Fig. 1 shows the equivalent circuit of the energy harvesting module. We chose a Brooks coil for the shape of the air-core coil. A Brooks coil is a circular coil with a square cross section, and the ratio of the coil length, inner diameter, and outer diameter is 1:2:4 [5]. This coil shape is suitable for development of a resonance circuit because it can achieve the maximum inductance for a given length of winding wire. The values of inductance L (H) and resistance R (Ω) were estimated as

$$L = P_0 a n^2 \text{ (H)}, \quad (1)$$

$$R = 2\pi a n \rho / s \text{ (Ω)}. \quad (2)$$

Where, $P_0 = 1.6994 \times 10^{-6}$ (H/m) is the coil constant for the Brooks coil, a (m) is the mean radius, n is the number of turns, ρ (Ω•m) is the resistivity of copper at room temperature, and s (m^2) is the cross sectional area of the winding. The measured values were in good agreement with the estimated values within ±3 % relative error [6]. To provide a resonance frequency at 60 Hz, we chose the resonant capacitor C (F) from

$$f = 1/2\pi(LC)^{1/2} \text{ (Hz)}. \quad (3)$$

Using the maximum power transfer theorem, we chose load R_L (Ω) to be the same as the coil resistance and used the voltage drop as the output voltage V_{out} (V) for calculating the harvesting energy W (W) with

$$W = V_{out}^{\ 2} / R \text{ (W)}. \quad (4)$$

From Faraday's law of induction and Thévenin's theorem, the amplitude of the voltage source V_{in} (V) can be expressed by

$$V_{in} = 2\pi^2 f n a^2 B \text{ (V)}. \quad (5)$$

Where, f (Hz) is the frequency and B (T) is the mean flux density crossed with the mean cross section of the coil. Table 2 shows the specifications of the energy harvesting module. It consists of an air-core coil, a resonant capacitor, and a load. This module can harvest 6.32 mW from a field of 21.2 μT at 60 Hz.

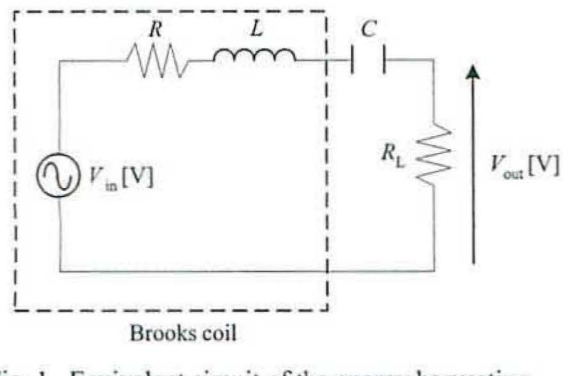


Fig. 1. Equivalent circuit of the energy harvesting module.

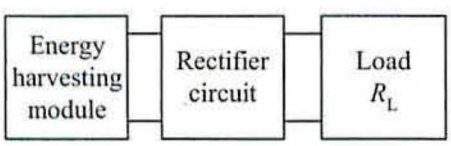


Fig. 2. Block diagram for evaluation of two rectifier circuits.

Table 1 Power consumption in mobile devices. [2]

Device	Power consumption
Smartphone	1 W
MP3 player	50 mW
Wireless sensor node	100 μW
Quartz watch	5 μW

Table 2 Specifications of the energy harvesting module.

Property	Value
Coil width, c [mm]	70
Diameter of wire, δ [mm]	0.5
Spacing factor, β	0.938
Number of turns, n	18395
Inductance of coil, L [H]	60.3
Resistance of coil, R [Ω]	1060
Resonant capacitor, C [μF]	0.110
Cutoff frequency, f_c [Hz]	2.8

Table 3 Specifications of our evaluated diodes.

Name	1N5819	BAT43
Maker	ST Microelec-tronics	ST Microelec-tronics
Type	Schottky diode	Schottky diode
Repetitive peak forward voltage [V]	0.55	0.45
Repetitive peak reverse current [μA]	1000	0.500
Average forward current [A]	1	0.2

Table 4 Specifications of LTC3108. [7]

Parameter	Value
Start-up voltage [mV]	20 ~ 400
Output voltage [V]	2.35, 3.30, 4.10, 5.00

2.1.2 Rectifier Circuit

In this experiment, we made a typical full-wave rectifier circuit. To suppress the voltage drop in the circuit, we compared two low-voltage-driving Schottky diodes. Table3 shows the specifications of the diodes given by the company. Because the specifications are typical values, the actual performance depends on the operating conditions. Fig. 2 shows the block diagram for evaluation of our two rectifier circuits.

2.1.3 DC-DC Converter

Table 4 shows the specifications of our used DC-DC converter (LTC3108, Liner Technology). From the data sheet [7], the startup input voltage of this converter is as low as 20 mV, and the limit of input voltage is 400 mV. This converter can select several output voltage conditions. In this paper, we chose the output voltage mode of 5 V.

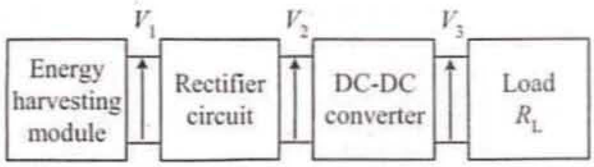


Fig. 3. Block diagram of our energy harvesting device.

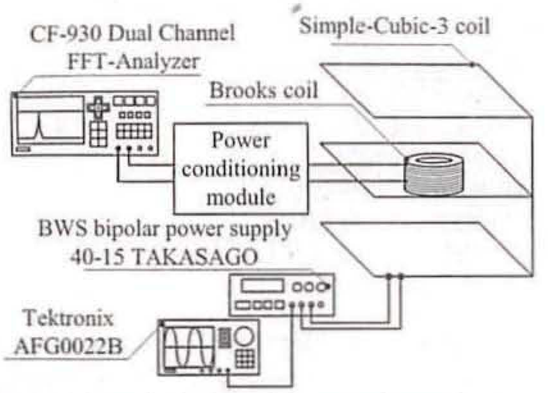


Fig. 4. Schematic design of the experimental set up.

2.2 Evaluation Method

2.2.1 Rectifier

We used our developed Simple-Cubic-3 coil system (SC3) [8] for generating a uniform magnetic field. SC3 was composed of three square coils connected in series, and the distance was the half side length of the coil. The side length was 2 m, and the number of windings was 24:12:24. In an area within a radius of 50 cm from the center, SC3 can generate a uniform magnetic field within ± 1 % deviation [9]. Because the diameter of the modules was 28 cm, we used this area to simulate power line magnetic noise. To evaluate amplitude dependence, the harvested energy was calculated from the measured output voltage. The frequency was 60 Hz, and the amplitude range was from 10 $\mu T_{p\text{-}p}$ to 130 $\mu T_{p\text{-}p}$, with a 10 $\mu T_{p\text{-}p}$ step. The maximum amplitude of the magnetic flux density of 130 $\mu T_{p\text{-}p}$ corresponds to 45.3 μT in rms units.

Using the maximum power transfer theorem, the optimum value of load resistance is 1 kΩ. To provide 5 V to this load, the required energy is 25 mW. First, we confirmed the harvested energy of the harvesting module from a uniform magnetic field of up to 45.3 μT. To evaluate the energy loss in the rectifier circuit, we combined the harvesting module and the rectifier circuit as shown in Fig. 2.

2.2.2 DC-DC Converter

For the preliminary study of our used DC-DC converter, we measured the input-output characteristics with a DC power supply, dummy loads, and a digital multimeter. The range of input voltage provided by the DC power supply was controlled from 20 to 400 mV. The input current was measured by a shunt resistor of 10 Ω for calculating the input power. We selected four dummy loads whose resistances were 1 kΩ, 10 kΩ, 100 kΩ, and 1 MΩ. The output power was calculated from the voltage drop in the loads measured by a digital multimeter.

2.2.3 Energy Harvesting Device

Fig. 3 shows the block diagram of our developed energy harvesting device. It is composed of the energy harvesting module, rectifier circuit, DC-DC converter, and dummy load. We also selected five dummy loads to calculate the output power. Voltages V_1, V_2, and V_3 were measured by an FFT analyzer and a digital multimeter. Fig. 4 shows the schematic design of the experimental setup. The measurement scheme was the same as mentioned in section 2.1.1.

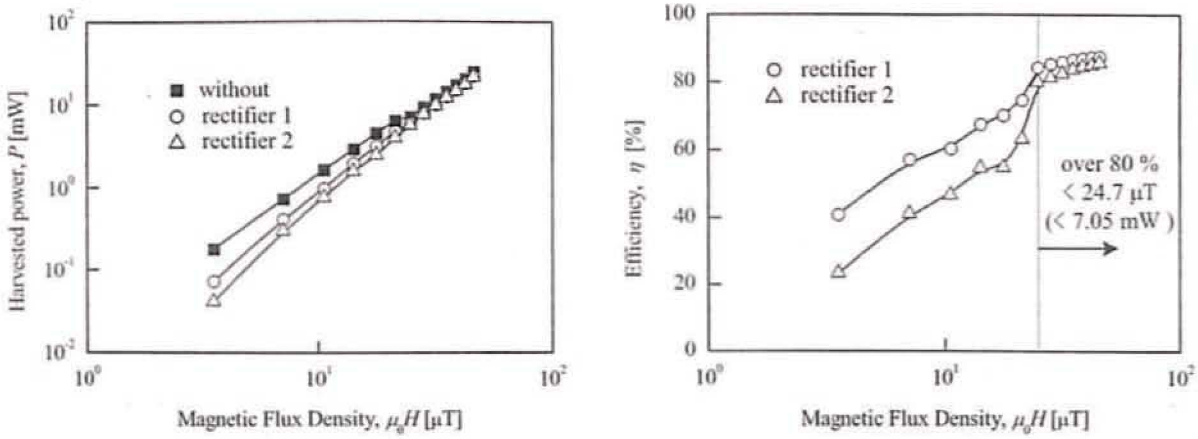
3. Results

3.1 Rectifier

Fig. 5 (a) shows the comparison of harvested power as a function of magnetic flux density, with the installed rectifiers as parameters. The resistance value of the dummy load R_L was 1 kΩ. Without the rectifier, we successfully confirmed that the harvested energy was proportional to the square of the magnetic flux density. The harvested energy was 25 mW from a field of 45.3 μT. If there is no loss in the power conditioning module, it has sufficient power to provide 5 V to a load of 1 kΩ. However, with the installed rectifier circuits, the harvested energy was decreased when the field was low. Compared with the harvested power obtained without a rectifier circuit, the efficiency was also calculated as shown in Fig. 5 (b). The efficiency of rectifier 1 was better than that of the rectifier 2. Thus, we chose the rectifier1 for our harvesting device. It should be noted that the efficiency was greater than 80 % when the magnetic flux density was larger than 24.7 μT. The corresponding input voltage was larger than 2.58 V.

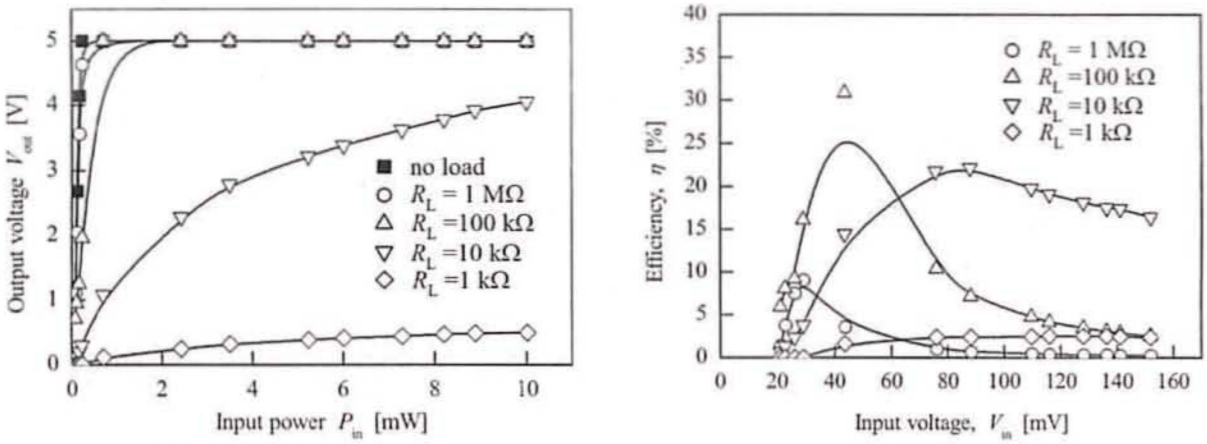
3.2 DC-DC Converter

Fig. 6 (a) shows the input-output characteristics of the DC-DC converter with a DC power supply, dummy loads, and a digital multimeter. If there is no load, the necessary input power was 0.2 mW for providing the output voltage of 5 V. Unfortunately, we could not confirm the output voltage of 5 V if the dummy load was less than 10 kΩ. Compared with the input power, we calculated the efficiency as shown in Fig. 6 (b). We found that there is an optimum condition that depends on the input voltage and the dummy load. The best efficiency of 32 % was achieved when the input voltage and the dummy load were 40 mV and 100 kΩ, respectively.



(a) Harvested power (b)Efficiency

Fig. 5. Comparison of harvested power with and without the installed rectifier circuits.



(a) Input power-output voltage (b) Efficiency

Fig. 6. Input-output characteristics of our used DC-DC converter measured with a DC power supply, dummy loads, and a digital multimeter.

2.2.3 *Energy Harvesting device*

Fig. 7 shows the input-output characteristics of our harvesting device. The input corresponds to the magnetic flux density, and the output corresponds to the voltage drop in the dummy loads. If there is no load, the output voltage reached 5 V with a field of 45.3 μT. However, the output voltage was less than 5 V if the dummy loads were inserted. The maximum output voltages were 4.35 V, 1.75 V, and 261 mV when the inserted dummy loads were 1 MΩ, 100 kΩ, and 10 kΩ, respectively. If there was no power conditioning module, the harvested energy from 45.3 μT was 25 mW. Unfortunately, the maximum harvested energy of the device was 0.019 mW, 0.031 mW, and 0.007 mW with dummy loads of 1 MΩ, 100 kΩ, and 10 kΩ, respectively.

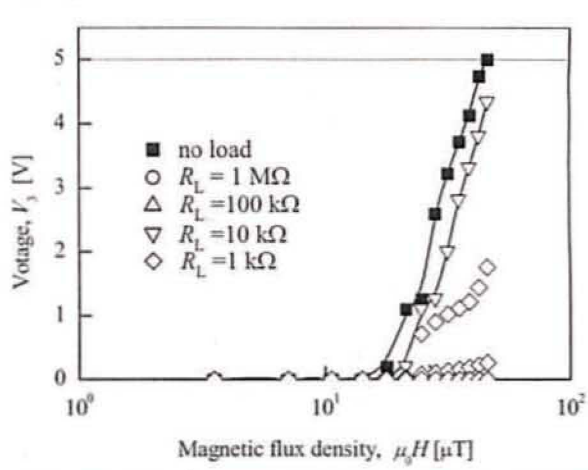


Fig. 7. Input-output characteristics of our harvesting device.

4. Discussion

4.1 Power conditioning module

To determine the required input power for providing an output voltage of 5 V, we measured the input-output characteristics of the power conditioning module. The range of input sinusoidal voltage of 60 Hz was provided by a function generator with an output impedance of 50 Ω. The input current was measured by a shunt resistor of 10 Ω for the calculation of the input power. We selected five dummy loads whose resistances were 1 kΩ, 10kΩ, 100 kΩ, and 1 MΩ.

Fig. 8 shows the results. If there was no load, the required input power was larger than 4 mW. For the dummy load of 100 kΩ, the value was 10 mW. If the dummy load was optimum, the harvesting module could provide 25 mW from the field of 45.3 μT. Therefore, 25 mW was not sufficient to provide an output voltage of 5 V when the dummy loads were less than 10 kΩ.

4.2 Voltage analysis

It has been already mentioned that the efficiencies of the rectifier circuit and the DC-DC converter depend on the input power and load conditions. To analyze the operation of the harvesting device, we checked the input and output voltage in each part.

Fig. 9 (a) shows the characteristics of the harvesting module part. The measured voltage without the power conditioning module was also plotted. If the power conditioning module was installed, the value of V_1 was suppressed and did not depend on the load condition. We have already confirmed the efficiency of the rectifier circuit as shown in Fig. 5 (b). The loss in the rectifier circuit was given by the voltage drop in the used diodes. This result showed that the equivalent input resistance of the DC-DC converter defined the characteristics.

Fig. 9 (b) shows the characteristics of the rectifier circuit part. The measured voltage without the DC-DC converter was also plotted. Because the maximum value of V_1 was less than 477 mV, the maximum value of V_2 was less than 28.9 mV. From our measurements, the corresponding maximum efficiency of the rectifier was less than 57.1 %.

Fig. 9 (c) shows the characteristics of the DC-DC converter part. If there was no load, the required input voltage for providing output voltage of 5 V was 30 mV. When the value of V_2 was larger than 20 mV, the values of V_3 were increased as a function of V_2. From our estimation, the magnetic flux density required to provide the output voltage of 5 V was 53 μT for the dummy load of 1 MΩ and 132 μT for the load of 100 kΩ. The corresponding efficiencies of the DC-DC converter with loads of 1 MΩ and 100 kΩ were 9.06 % and 16.1 %, respectively. However, the maximum output energy was 0.25 mW even if the load was 100 kΩ.

To improve the efficiency and the maximum output power, a suitable DC-DC converter should be chosen, with equivalent input impedance close to the optimum load resistance of 1 kΩ.

5. Conclusion

In this paper, we have made an energy harvesting device for power-line magnetic noise. This device consists of a harvesting module, rectifier circuit, and DC-DC converter. In conclusion, we have obtained the following from experiments:

(1) From the magnetic flux density of 45.3 μT, the harvesting module can provide 25 mW to an optimum load of 1 kΩ

(2) The efficiency of the rectifier circuit was greater than 80 % if the magnetic flux density was larger than 24.7 μT.

(3) The efficiency of the DC-DC converter depended on the input voltage and the dummy load.

(4) We successfully confirmed that our developed device can provide an output voltage of 5 V.

(5) In order to use this device as a battery, a suitable DC-DC converter should be selected.

In this device, the equivalent input impedance and the load dependency of the DC-DC converter is important. To the best of the authors' knowledge, it is not easy to find a suitable ultralow step-up voltage converter, although many DC-DC converters have been developed. Because our rectifier circuit demonstrated relatively good performance, we will try to find another solution without this converter in near future.

Acknowledgment

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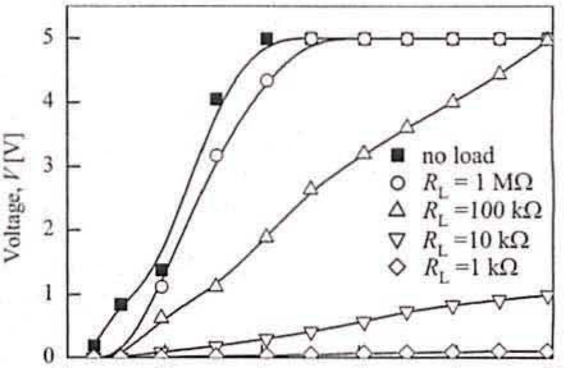
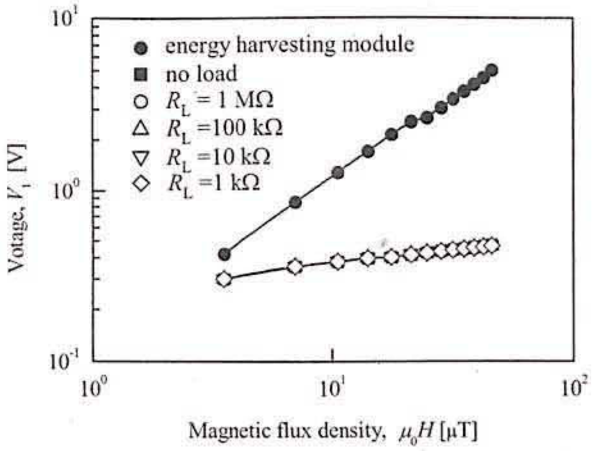
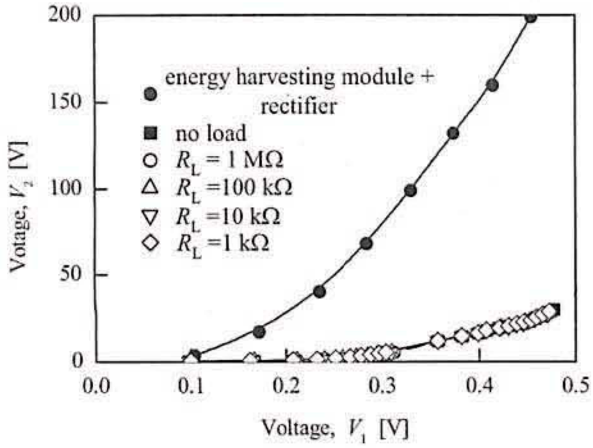


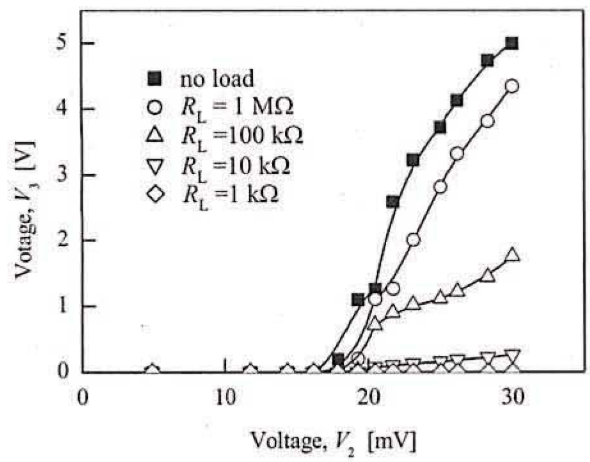
Fig. 8. Input-output characteristics of our power conditioning module measured with a function generator, dummy loads, and a digital multimeter.



(a) Harvesting module part



(b) Rectifier circuit part



(c) DC-DC converter part

Fig. 9. Input-output characteristics of parts in the energy harvesting device.

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