A Comparison of Terahertz Power Measurements at Sub-microwatt Levels

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***Abstract*— In this paper, we compare absolute power measurements obtained at 1 THz using a newly proposed terahertz (THz) calorimeter and a commercial power meter. The experimental measurement was performed at a sub-microwatt level using a photomixer as the THz source. Using the calorimeter, we obtained highly sensitive measurement results with good accuracy at room temperature of 23°C, and there was good agreement with the result from the commercial power meter.**

I. INTRODUCTION

THE quantitative evaluation of absolute power is very important to guarantee the reliability and safety of terahertz (THz) technology. Recently, many types of THz sources and power sensors have been implemented; however, technical improvements in metrological standards and calibration are still being realized. In general, THz sources can generate only a very small power compared with sources in the range of microwaves and light waves. Therefore, it is essential to precisely measure the power range from the sub-microwatt to watt levels. To meet this demand, we have developed a highly sensitive THz calorimeter that can determine the absolute power at the sub-microwatt level at room temperature [1], [2]. In this paper, we report on a comparison of absolute power measurements obtained below 1 μW at 1 THz using the calorimeters and a commercially available power meter.

II. RESULTS

In this experiment, we compared the calorimeter based on an isothermal temperature-control technique and a commercially available power meter. A detailed structure and principle of operation of the calorimeter are described in [1]. The power meter that was employed is a thermal sensor that uses a volume absorber, and its minimum power range is 15 μW according to the manufacturer's specifications. Fig. 1 shows the experimental setup for the comparison. An ultra-low noise nanovolt amplifier (EM Electronics, N5) was used as a preamplifier to improve the SNR for the calorimeter measurement. For the THz source, we used a photomixer that is driven by two distributed feedback lasers that have different wavelengths in the 1.5 μm band at 1 THz. The THz wave was focused using off-axis parabolic mirrors and inputted into the calorimeter and power meter. A mechanical shutter set in the optical path controls the THz irradiation. To prevent infrared leakage from the photomixer, infrared cut filters were inserted into the path. The system was then covered by thermal insulation jackets to prevent problems that are due to the environmental temperature changes. The responses of the calorimeter and the power meter to the THz wave irradiation are shown in Fig. 2 (a) and (b), respectively. The vertical axis in Fig. 2 (a) represents the DC heater power of the calorimeter. The incident power is determined as follows [1]:

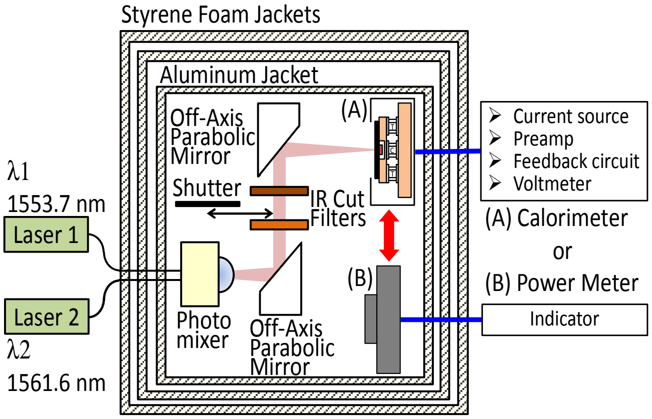

Fig. 1. Brief overview of the experimental setup.

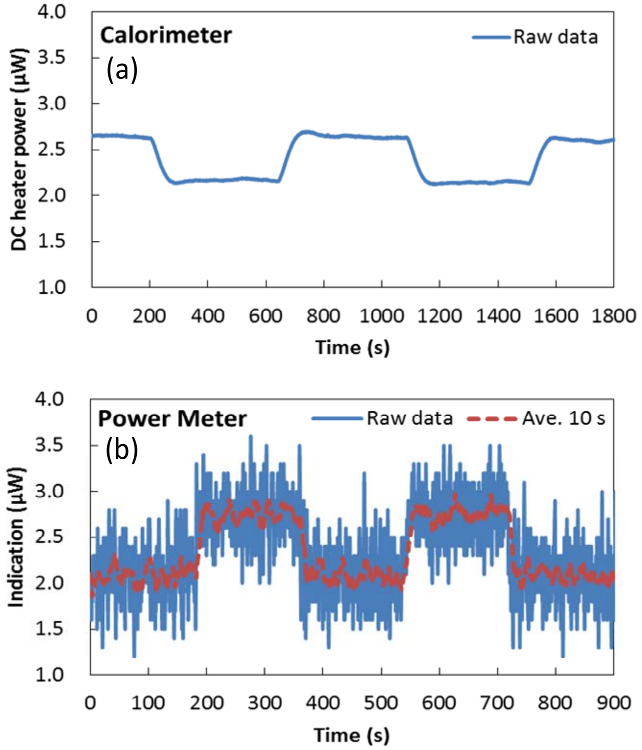

Fig. 2. Response for THz irradiation. (a) calorimeter, (b) power meter.

$$P_i = \frac{K\left(P_{h1} - P_{h2}\right)}{1-R} \qquad (1)$$

where K is a constant that denotes the equivalence of the THz power and the heater power, and it is assumed to be unity in this calorimeter [3]. P_{h1}, P_{h2}, and R represent the heater power when the THz wave is unirradiated, the heater power when it enters the absorber, and the reflectance of the absorber, respectively. The indication in Fig. 2 (b) represents the incident power to the power meter. The solid and dashed lines in Fig. 2 (b) show raw data and a 10-s moving average. Although the measured power was much smaller than the manufacturer's specification, the power meter detected the THz power at the sub-microwatt level by ensuring a thermally quiet measurement environment.

TABLE I
MEASUREMENTS OF THE INCIDENT POWER BY THE CALORIMETER AND THE POWER METER AT 1 THz

N	Incident Power (µW)	
	Calorimeter	Power Meter
1	0.579	0.694
2	0.583	0.659
3	0.590	0.654
4	0.596	0.685
5	0.584	0.676
Average	0.586	0.674
Stdev	0.007	0.017

In Table I, we present five measurements obtained for the incident power. The average power values measured by the calorimeter and the power meter were 0.59 µW and 0.67 µW with standard deviations of 0.007 µW and 0.017 µW, respectively. In addition, we estimated the uncertainties of both measurements based on [4]. The uncertainty budget for the calorimeter and the power meter are shown in Tables II and III, respectively. For the calorimeter measurement, the dominant components of the type B uncertainty are due to the absorber and the equivalence between the THz and DC powers. Because the standard uncertainty of reflectance of the absorber (Schott, NG1) can usually be estimated as 4% [5], in this experiment, we assumed that $R = 0.174 \pm 0.007$ at 1 THz. Then, the standard uncertainty due to the absorber is estimated to be 0.9% based on equation (1). The uncertainty of the equivalence K was estimated by a thermal simulator based on the finite element method [3]. The uncertainty for the power-meter measurement was estimated from the manufacturer's specifications. The dominant sources of uncertainty are due to the calibration accuracy and the display resolution. The calibration accuracy of the power meter used was reported to be ±15% ($k = 2$). Further, the resolution of the digital reading of the power meter was 0.1 µW. Therefore, by assuming a rectangular probability distribution, the contribution of this uncertainty was estimated to be 4.3% to 0.67 µW. Finally, the measurements obtained by the calorimeter and the power meter were 0.59 µW and 0.67 µW with expanded uncertainties of 0.02 µW and 0.12 µW (k = 2), respectively.

TABLE II
UNCERTAINTY BUDGET FOR THE CALORIMETER MEASUREMENT

Source of uncertainty	Type	Probability distribution	Uncertainty contribution (%)
Absorber reflectance	B	Rectangular	0.9
THz/DC equivalence	B	Rectangular	0.4
Uniformity	B	Rectangular	0.2
DC measurement	B	Rectangular	0.1
Random	A	Normal	0.6
Combined standard uncertainty			1.2
Expanded uncertainty (k=2)			2.4

TABLE III
UNCERTAINTY BUDGET FOR THE POWER METER MEASUREMENT

Source of uncertainty	Type	Probability distribution	Uncertainty contribution (%)
Power accuracy	B	Normal	7.5
Linearity	B	Rectangular	0.9
Display resolution	B	Rectangular	4.3
Random	A	Normal	1.1
Combined standard uncertainty			8.8
Expanded uncertainty (k=2)			17.5

III. SUMMARY

In this study, we compared absolute THz power measurements obtained at the sub-microwatt level using our proposed calorimeter and a commercially available power meter at room temperature of 23°C. The results obtained are in good agreement with their expanded uncertainties.

ACKNOWLEDGEMENT

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