

# Energy Calorimeter for Pulsed Laser Radiometry

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## Abstract.

We have developed an energy calorimeter that can determine absolute energy of single-shot laser pulses. The calorimeter is composed of a U-shaped absorption cavity and semiconductor-based thermocouples. The energy sensitivity is calibrated by inducing energy to an electrical heater on the cavity. To reduce a standard deviation, an optimal filtering method was used for the sensitivity calibration. As a result, we obtained that the energy sensitivity is 9.42 mV/J for 10 mJ energy with the low relative standard deviation of 0.02 %.

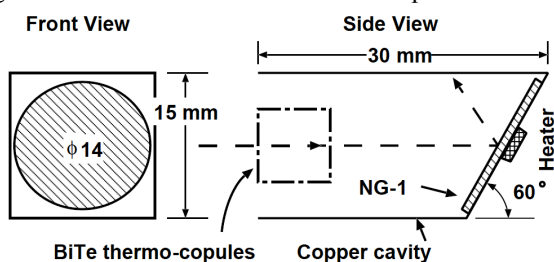
## Introduction

The pulsed laser sources are now widely used in industry, and its precise determination of the laser energy is more important. In 2005, National Metrology Institute of Japan will start an energy sensitivity calibration service for laser energy meters as a special test. To realize this, we have developed a laser energy calorimeter. This abstract describes some characteristics of the energy calorimeter and a calibration method of the energy sensitivity.

## Configuration

Figure 1 shows the absorption cavity of the laser energy calorimeter. The cavity is fabricated with free oxygen copper with a thickness of 0.2 mm. A bottom of the cavity is sloped with an angle of 60 degrees, on which a glass volume absorber of NG-1 (shott glass) with a thickness of 0.5 mm is attached. A single shot laser pulse is irradiated through an entrance, and the most of energy is absorbed in the glass volume. Some energy, which is reflected at the glass surface, is absorbed at the cavity wall by multiple reflections. The inside of the cavity is painted with velvet Nextel coating to increase the absorptance of the cavity. In this configuration, the total reflectance of the cavity for 633 nm is less than 0.02 %, which is measured by an integrating sphere.

The resulting temperature increase from the energy absorption is detected with bismuth telluride thermocouples of seventy-two pairs at the front region of the cavity. The temperature sensitivity of the thermocouple per pair is approximately 200  $\mu\text{V/K}$ , which is seven times larger than that of metal-based thermocouples.



**Figure 1.** Schematic drawings of the absorption cavity of the energy calorimeter. Left is the front view and right is the side view. Pulsed laser enters like an arrow of broken line.

## Sensitivity calibration

The sensitivity of the calorimeter is calibrated with an electrical heater on the absorption cavity. A rectangular electrical pulse of the pulse width  $\Delta t$  is generated with a constant voltage source and a gate switching circuit, and it is induced to the heater, as shown in fig. 2. The electrical energy  $E$  produced by Joule heating is written as

$$E = V^2 \Delta t / R,$$

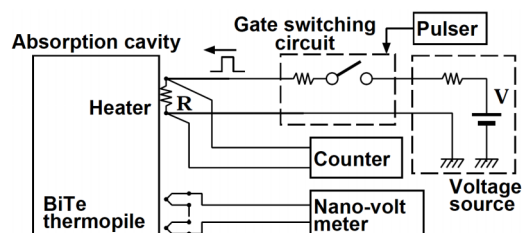
where  $V$  is the voltage of the source and  $R$  is the resistance of the heater. The time-dependent temperature change of the cavity is recorded with a nanovoltmeter as the output voltage of the thermocouples.

To derive the energy sensitivity from the time-dependent output voltage signals, a theory that is based on the First Law of Thermodynamics by West is frequently used. In the theory, the output signals are divided into some regions; an initial rating period, a relaxation period, and a final rating period. The sensitivity is determined with the induced energy and a corrected voltage rise that is calculated with time integration and the voltage difference during these periods. More detail process is given by Zhang. This theory is very useful to determine the sensitivity of the calorimeter, however, intrinsically noise characteristics of the calorimeter are not considered in the theory. Thus, we tried to improve the theory by combining the optimal filtering method. In our method, a noise property of the calorimeter is considered, that would be expected to greatly reduce the standard deviation of the energy sensitivity.

In the present method, we firstly prepare a model signal waveform and a voltage noise spectrum of the calorimeter. We define these Fourier transformations as  $M(f)$  and  $N(f)$ , respectively. Then a relative pulse height  $PH$  for measured waveform  $D(t)$ , which is a signal for each single energy shot, is calculated using a least square method at a frequency region as the following formula.

$$PH = \int \frac{D(f) |M(f)|^2}{M(f) |N(f)|} df / \int \frac{|M(f)|^2}{|N(f)|} df$$

Finally, the corrected voltage rise for  $D(t)$  is obtained by multiplying  $PH$  by the corrected voltage rise for the model waveform  $M(t)$ . More detailed methods are described by



Szymkowiak and Fukuda.

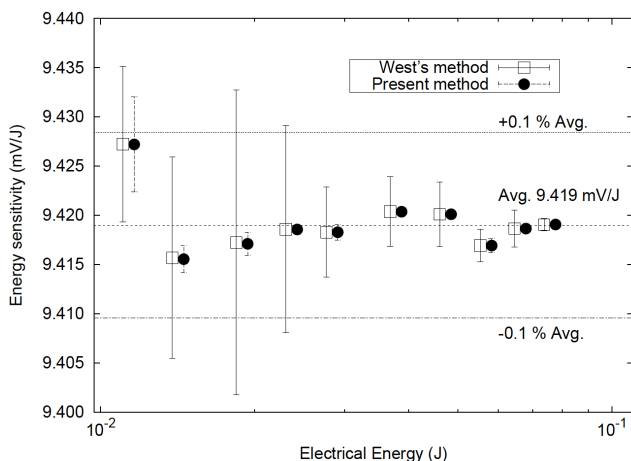
**Figure 2.** Experimental setup for energy sensitivity determination. Rectangular-shape electrical pulses are generated, and are induced the heater. The resulting temperature rise is

measured with BiTe thermopiles.

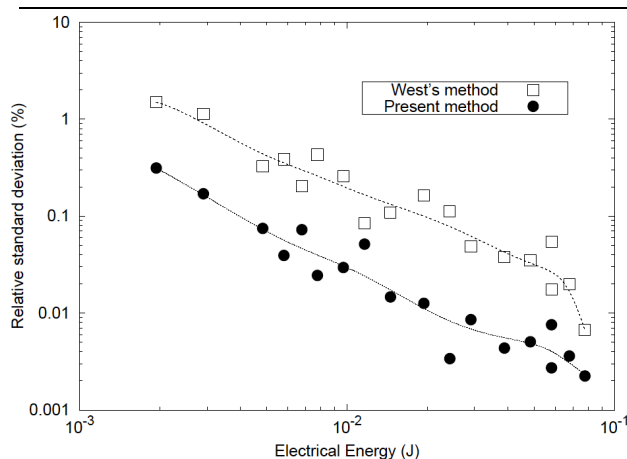
## Experimental Results

We calibrated the energy sensitivity of the calorimeter for the electrically induced energy from 1 mJ to 100 mJ using the method mentioned above. At each energy stage, we obtained five waveforms of  $D(t)$  which has 1024 data points with the sampling time  $\Delta t$  of 0.6 s. A fall time constant of the calorimeter is 55 s, thus the calorimeter will completely return to an equilibrium state after an energy shot during the waveform measurement. As to the calculation process of the corrected voltage rise, we set the relaxation period and the final rating period to 18 s and 39 s, respectively.

The energy sensitivity obtained by our method was 9.42 mV/J, and was well agreed with the value obtained by West's method, as shown in fig. 3. For the measured energy range, the nonlinearity of the sensitivity is less than 0.1 %, which is very useful for the laser energy calibration. Figure 4 shows the relative standard deviation of the energy sensitivity for each electrical energy point obtained by both methods. In the presents method the deviation decreased by ten percents, which is very desirable for precise energy determination.



**Figure 3.** Measurement results for energy sensitivity of the calorimeter obtained by West's method and present method. Bars indicate the standard deviation ( $1\sigma$ ) for five measurements.



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**Figure 4.** Relative standard deviations of the energy sensitivity. The deviations increased at lower energy, however, the deviations for the present method improved by ten percents in this energy range.

## Conclusion

We developed a laser energy calorimeter that is intended as a primary standard for the calibration of the laser energy meters. The sensitivity of the calorimeter was well defined using the optimal filtering method and was found to be 9.42 mV/J. The standard deviation by our method was reduced by ten percents compared to West's method. The nonlinearity of the energy sensitivity was less than 0.1 % in the energy range from 10 mJ to 100 mJ. These performances are very desirable to calibrate laser energy meters with a low measurement uncertainty.

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