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A Laser Power Meter for Large Beams*

D. A. JENNINGS AND E. D. WEST

Radio Standards Physics Division, National Bureau of Standards, Boulder, Colorado 80302

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A power meter is described in detail for large or divergent laser beams, either cw or repetitively pulsed. The meter measures the flow of heat generated by the beam and is calibrated with an electrical heater wound just behind the absorbing surface. The meter is capable of power measurements of 1 to 30 W accurate to ±2.5%.

INTRODUCTION

THE measurement of average cw laser power is often a routine operation, especially if the laser beam is well collimated and less than 1 cm in cross section. The measurement is not so simple when the beam is large in diameter, say 5 to 10 cm, or not well collimated, as in diode lasers or laser beams which have been made to diverge.

We would like to describe a simple device, which allows the measurement, on an absolute basis, of the average power of lasers of large diameter and/or divergent beams. The device is also useful for the measurement of average power of repetitively pulsed lasers.

The instrument is designed to measure average power from 1.0 to 30.0 W; however, there seems to be no reason why the device cannot be scaled to higher or lower powers. In what follows we shall describe in detail, the construction of the instrument, its calibration, and operating characteristics.

THE INSTRUMENT

The entire instrument, which we will call a disk calorimeter (DC), is constructed of aluminum alloy 6061 with a vapor blasted, black anodized finish. In Fig. 1 we show a cross section of the DC, which has cylindrical symmetry about a horizontal axis. The main parts of the DC are the disk, which absorbs the radiation and converts it to heat; the conducting tube, which carries the heat to the sink; the thermopile, which measures the temperature gradient in the tube; and a calibrating electric heater. The absorbing disk is 0.5 mm thick and the conducting tube has a wall thickness of 0.5 mm and is 1.2 cm long. In order to avoid the thermal resistances of mechanical connections, the disk, the conducting tube, and heat sink with its vertical cooling fins are machined from a solid block of aluminum. The front surface of the disk is painted with a special flat black paint.[1] The characteristics of this surface, are discussed later.

The principle of operation is as follows: The laser beam of interest is made to fall on the disk where it is converted into heat. This heat raises the temperature of the disk and causes a temperature difference ΔT to be established along the tube connecting the disk with the heat sink. The heat is then dissipated into the air via the cooling fins. The ΔT, which is generated along the tube, is measured by a four-junction series connected copper–constantan thermopile of 0.13 mm wire (No. 36 gauge). Since the anodized finish forms an insulating layer, the thermocouple junctions are placed in contact with the cylinder and epoxyed in place, the hot junction near the disk and the cold junction near the heat sink. The junctions are distributed symmetrically about the cylinder.

On the back side of the disk, at a 3 mm distance from the cylinder, is a ledge on which is wound a heater wire of 0.13 mm manganese wire (No. 36 gauge). It has a resistance of approximately 90 Ω and is connected to feedthroughs by 18 gauge copper wire. This heater allows one to electrically calibrate the DC by Joule heating.

CALIBRATION AND TEST

The calibration is effected by determining the sensitivity to electrical heating S_{el} of the meter in the following manner: The output voltage of the thermocouples is amplified by a suitable microvoltmeter and then recorded on a strip chart. A known amount of power is supplied to the DC by applying a known voltage to the heater and the output in microvolts is read from the chart recorder. The S_{el} is then

$$S_{el}=\mu V/W.$$

The data for a typical calibration run are shown in Table I.

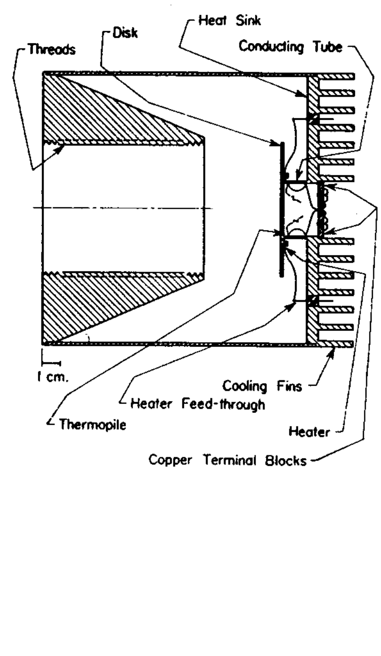

FIG. 1. Cross section of the disk calorimeter. A laser beam incident on the disk is converted to heat which sets up a temperature gradient in the conducting tube. The gradient is sensed by the thermopile.

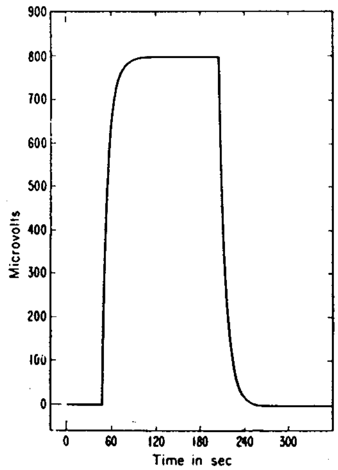

FIG. 2. A trace of a typical output from the disk calorimeter in response to a constant electrical power. The power was turned on at 50 sec and off at 210 sec.

The calibration is over the power range 1–20 W. The zero drift was measured over several hours and was less than 0.5 μV. Zero stability is required for accurate calibration and power measurement. If the flat black paint absorbed all of the incident laser beams then the calibration would be complete, but as one might expect, it does not. We have measured this particular paint and found it to be flat from 400 to 1060 nm and at 10.6 μ. The total reflection r from the surface was measured to be 4.0%. The damage threshold for the black paint, as measured by a CO_2 laser, is 500 W/cm^2. The sensitivity to laser input S_l is obtained from S_{el} by correcting for this reflection

$$S_l = S_{el}(1-r)^{-1}.$$

This calibration has been compared with other methods developed at NBS and we find agreement to 3%.[2]

The instrument requires 50 sec to reach 99% of its ultimate reading. A calibration trace is shown in Fig. 2. We have compared the time development of the response of the DC to both laser power and Joule heating and find no difference; however, this point is strictly relevant only to the time required to make a measurement, since the DC is used in the steady state mode.

ACCURACY

Since one may know the voltage and resistance better than 0.1% and the absorption of the surface better than 1.0%, it would seem that the accuracy is limited by other quantities not so easily measurable, such as thermal emf, a constant rate of change in ambient temperature, linearity of the readout electronics, and changes in ambient lighting conditions during a power measurement. In some power measurements one may need to be concerned with pump lamp light and electrical noise from the laser electronics. In various versions of the apparatus we have fabricated the DC of copper and have used different thermocouple material and different calibrated microvoltmeters and chart recorders. The various versions behave in essentially the same way. The DC fabricated of copper behaves essentially as the aluminum DC, with the exception of response time which is twice as fast.

TABLE I. Electrical calibration data for the disk calorimeter.

Power v^2/R	Response	Sensitivity S_{el}
1.005 W	83.20 μV	82.76 μV/W
4.914	405.2	82.46
9.930	811.2	81.69
14.94	1212.	81.11
19.71	1598.	81.08

The largest source of error is geometrical variation of response over the surface of the disk. In order to ascertain the magnitude of this error, we used a laser beam of 5 W to probe the response. The laser power level was held to $\pm 1\%$ during the measurements. Beams of three different diameters were used, 5.5, 4.0, and 2.0 cm. Table II shows the results of this test. We feel that the 4 cm beam reads very close to the true power. The 2 cm beam, which exaggerates the nonuniformity, read different by only 3%.

For accurate measurements the small variation of S_{el} with power (Table I) should be taken into account. We feel that this nonlinearity is due to convection cooling of the disk; however, this can be calibrated out by performing the calibration at the power level for which the DC is to be used.

With the foregoing in mind, we can now see how the errors propagate through the calibration. The sensitivity to a laser beam in terms of its factors is

$$S_l = (R/v^2)D(1-r)^{-1}G,$$

where R is the resistance of the heater, v is the voltage applied to the heater, D is the deflection in microvolts as read from the chart recorder, r is the total reflection from the disk, and G is the geometrical response factor. The

TABLE II. Power indicated by the disk calorimeter as a function of beam size with a 5 W input beam.

Beam size	Power
5.5 cm	4.96 W
4.0	5.0
2.0	5.16

fractional error in S_l is then given by the expression

$$\frac{dS_l}{S_l}=\frac{dR}{R}+\frac{2dv}{v}+\frac{dD}{D}+\frac{dr}{(1-r)}+\frac{dG}{G}.$$

In our work we estimate dR/R 0.1%, $2\ dv/v < 0.2\%$, $dD/D < 0.1\%$, $dr/(1-r) < 1\%$, and $dG/G < 1\%$ for beams 4 to 5 cm in diameter, ranging up to 3% for beams 2 cm in diameter. The corresponding error in S_l ranges from ± 2.4 to $\pm 4.4\%$. We feel then that if the disk is completely filled, the DC gives the true power to $\pm 2.4\%$ and in the worst case of small beams $\pm 4.4\%$.

ACKNOWLEDGMENT

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[1] The particular paint seal was Nextel velvet coating 101–C10 black made by 3M Co.

[2] D. A. Jennings, E. D. West, K. M. Evenson, A. L. Rasmussen, and W. R. Simmons, Technical Note No. 382, National Bureau of Standards, Boulder, Colo., Oct. 1969.