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REFERENCES

[1] D. Gabor, "A new microscopic principle," *Nature*, vol. 161, pp. 177–178, May 1948; "Microscopy by reconstructed wave-fronts," *Proc. Roy. Soc. (London)*, vol. A 197, pp. 454–487, July 1949.
[2] E. Leith and J. Upatnieks, "Reconstructed wavefronts and communication theory," *J. Opt. Soc. Am.*, vol. 52, pp. 1123–1130, October 1962.
[3] ——, "Wavefront reconstruction with continuous objects," *J. Opt. Soc. Am.*, vol. 53, pp. 1377–1381, December 1963.
[4] ——, "Wavefront reconstruction with diffused illumination and three-dimensional objects," *J. Opt. Soc. Am.*, vol. 54, pp. 1295–1301, November 1964.
[5] M. H. Horman, "An application of wavefront reconstruction to interferometry," *Appl. Optics*, vol. 5, pp. 333–336, March 1966.
[6] B. P. Hildebrand and K. A. Haines, "Interferometric measurements using wavefront reconstruction technique," *Appl. Optics*, vol. 5, pp. 172–173, January 1966.
[7] J. M. Burch, "The application of lasers in production engineering" (1965 Viscount Nufield Memorial Paper), *Prod. Engrg.*, vol. 44, pp. 431–442, September 1965.
[8] R. L. Powell and K. A. Stetson, "Interferometric vibration analysis by wavefront reconstruction," *J. Opt. Soc. Am.*, vol. 55, pp. 1593–1598, December 1965.
[9] K. A. Haines and B. P. Hildebrand, "Surface-deformation measurement using the wavefront reconstruction technique," *Appl. Optics*, vol. 5, pp. 595–602, April 1966.
[10] L. Mertz and N. O. Young, "Fresnel transformations of images," in *Proc. 1961 Conf. on Optical Instruments and Techniques*. New York: Wiley, 1962, pp. 305–312.
[11] G. Cochran, "New method of making Fresnel transformations with incoherent light," *J. Opt. Soc. Am.*, vol. 55, pp. 615, Map 1965. (Abstract.)
[12] A. Kozma and N. Massey, "Bias level reduction of incoherent holograms," *J. Opt. Soc. Am. (Abstract)*, vol. 56, pp. 537–538, April 1966.
[13] E. N. Leith et al., "Holographic data storage in three-dimensional media," *Appl. Optics*, vol. 5, pp. 1303–1311, August 1966.
[14] M. Born and E. Wolf, *Principles of Optics*. New York: Pergamon, 1959, p. 417.
[15] P. Theocaris, *Appl. Mech. Review*, vol. 15, May 1962.
[16] J. Dalley and W. Riley, "Experimental stress analysis with the moire fringe method," *Prod. Engrg.*, vol. 36, pp. 41–48, May 24, 1965.
[17] P. Theocaris and A. Koutsabessis, *J. Sci. Instr. (London)*, vol. 42, August 1965.
[18] K. Haines and B. P. Hildebrand, "Contour generation by wavefront reconstruction," *Phys. Letters (Netherlands)*, vol. 19, pp. 10–11, September 1965.
[19] B. P. Hildebrand and K. A. Haines, *Phys. Letters (Netherlands)*, vol. 21, June 1966.

Calorimetric Measurement of Pulsed Laser Output Energy

D. A. JENNINGS

***Abstract*—There are several methods by which one may measure the energy output of the pulsed laser. However, the technique which seems to be most promising as far as accuracy and precision are concerned is the calorimetric method. We have designed, built, and calibrated calorimeters for measuring the output energy of the pulsed ruby laser (6943Å). The heart of the calorimeter is a small absorption cell containing an aqueous solution of $CuSO_4$. The temperature of the absorption cell, as measured by a thermocouple, indicates the energy absorbed by the calorimeter. The calorimeter was calibrated in two different ways: 1) the known heat capacity of the absorption cell and the thermocouple sensitivity calibration gives a calorimeter calibration, which agrees within 0.3 percent of 2) an electrical energy substitution calibration which is obtained via a heater wire contained in the absorption cell solution. A method has been devised by which two calorimeters may be intercompared. Calorimeters which we have built and calibrated agree with each other to about 0.7 percent. This specific calorimeter has been designed to measure energies up to 30 J and will take peak powers of up to 200 MW/cm^2.**

INTRODUCTION

ONE OF THE IMPORTANT parameters of pulsed laser systems is their output energy. The application of pulsedl asers requires knowing this energy with varying degrees of accuracy, depending on the application. There are several methods by which one may measure the energy output of the laser [1]–[7]. In this paper we would like to describe an optical calorimeter for measuring the output energy of a pulsed laser. The calorimetric technique seems very promising as far as accuracy and precision are concerned. The calorimeter which is described in this paper was designed to measure 0.1- to 30-J laser pulses in the 5000 to 10 000-Å range.

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The author is with the National Bureau of Standards, Boulder, Colo.

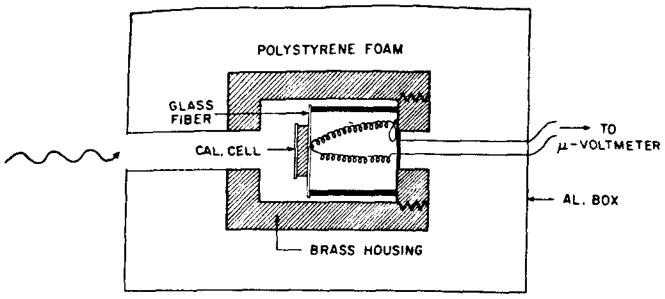

Fig. 1. Cross-sectional diagram of the calorimeter, showing layout of components, method of supporting calorimeter absorption cell, and position of the thermocouple.

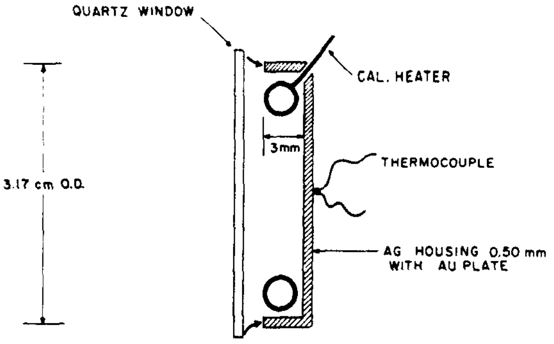

Fig. 2. Cross-sectional diagram of the calorimeter absorption cell showing the approximate size of components and the position of the heater wire.

General Description

The basis of the calorimetric system is the calorimeter proper, which is shown in Fig. 1. The calorimeter absorption cell, filled with an absorbing solution, was supported in a massive brass housing (heat sink) by means of small glass fibers. The brass housing was placed in polystyrene foam insulation and the entire system enclosed in an aluminum box. One junction of a Cu-constantan thermocouple was attached to the absorption cell, and the other junction was attached to the brass housing. When a pulsed laser was fired into the absorption cell, the cell rose in temperature and the thermocouple generated a voltage proportional to the temperature difference between the absorption cell and the brass housing. The output voltage of the thermocouple was then a measure of the energy in the laser beam. The voltage generated by the thermocouple was measured with a microvoltmeter whose output was fed into a strip-chart recorder.

The Absorption Cell

Since the heart of the system is the absorption cell, we shall describe it in detail. Figure 2 shows a cross-sectional view of the absorption cell. The absorption cell was made of silver, so as to give a fast thermal equalization to the cell. The silver cell was then electroplated with 2.5×10^{-4} cm of gold in order that the tarnish problem be kept to a minimum. The cell diameter was 3.17 cm and the depth was 3.0 mm. The wall thickness was 0.50 mm. The silver cell had three small holes near the edge. One hole was utilized for filling, and the other two were for a heater wire. The heater wire we shall describe later. The entrance window was made of quartz. Eopoxy was used to bond the quartz to the silver cell and also to seal the fill and heater-wire holes. The cell was filled with a one molar solution of $CuSO_4 \cdot 5H_2O$. The addition of 2 drops of Bendix purple ink per 10 cc of solution extends the useful range to 5000 Å, as opposed to only 6500 Å with $CuSO_4$ solution alone. An absorption curve of this solution is shown in Fig. 3. The absorption coefficient α is defined by the equation

$$I = I_0 C^{-\alpha x}$$

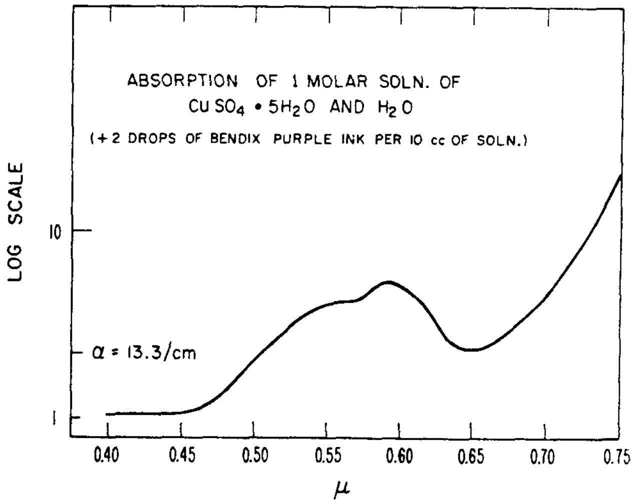

Fig. 3. Absorption spectrum of the solution used in the calorimeter absorption cell. The calibration of the arbitrary log scale is shown and was measured at 6943 Å.

where I is the laser beam intensity at a distance x in the absorbing liquid, I_0 is the initial laser beam intensity, and x is the distance into the liquid as measured from the surface. The absorption coefficient α was measured using a low intensity incoherent light source at 6943 Å, and checked using the high intensity Q-switched ruby laser. The cell filled with this solution will absorb 99.9 percent of the laser beam, not counting the Fresnel losses of the window.

A cell of this description gave about 0.1°C temperature rise for a 1-J input.

Calibration of the Calorimeter System

Great care must be taken in the calibration of the calorimeter since the accuracy is no better than the calibration. Two independent methods of calibration were used. One calibration was based on the heat capacity of the absorption cell and the thermocouple calibration, and the second calibration was based on an electrical energy substitution via the heater wire.

The heat capacity calibration consisted of weighing all the component parts of the absorption cell and then using the best obtainable values for the specific heats to calculate the heat capacity of the absorption cell. All components of the absorption were accurately weighed. The thermocouple sensitivity was calibrated using standard techniques. The heat capacity calibration factor for this particular calorimeter was calculated to be $3.102 \pm .024\ \mu\text{V/J}$. The uncertainty was obtained by taking into account the errors in the specific heats, weighing, and thermocouple sensitivity. This calibration factor has also been adjusted to correct for Fresnel reflection losses of the entrance window. The error here was very small, since the correction was only on the order of 4 percent. The true calibration was obtained by use of the following equation

$$\text{SHC}_t = \text{SHC}(1 - R)$$

where SHC is the specific heat calibration, SHC_t is the adjusted specific heat calibration, and R is the reflection as calculated from the Fresnel equations.

The electrical energy substitution calibration was accomplished by passing a known dc current through the heater wire for a known length of time. The heater wire was Teflon coated and had a resistance of 16 ohms per foot and a total resistance of 110 ohms.

The dissipation of heat outside the cell from the leads to the heater was small and corrected for in the calibration.

Prior to making the electrical energy substitution calibration, all instruments were calibrated to an accuracy of 0.2 percent.

The electrical energy calibration proceeded in the following manner. The gate output from a preset scaler, counting the line frequency (60 hertz), was used to turn on a transistor switch. The transistor was powered by a constant current source (constant to 0.01 percent), and the absorption cell heater wire was in the collector circuit of the transistor. The voltage drop V across the heater wire was measured via the calibrated strip-chart recorder. Since the voltage V and the heater-wire resistance R and the time t are known, the energy J, put into the absorption cell, can be calculated from

$$J = \frac{V^2}{R} t.$$

A typical calibration trace obtained from the strip-chart recorder is shown in Fig. 4. The overshoot at the beginning of the trace was due to the close proximity of the heater wire to the silver housing of the absorption cell. The error, introduced because the silver housing was warmer during the overshoot than when in an isothermal condition, was small enough to be neglected. An estimation of this error from both convection and radiation cooling shows it to be less than 0.25 percent. Other losses, such as conduction of heat along the wire leads and quartz mounting fiber, were less than 0.1 percent over the entire measurement (20–30 minutes).

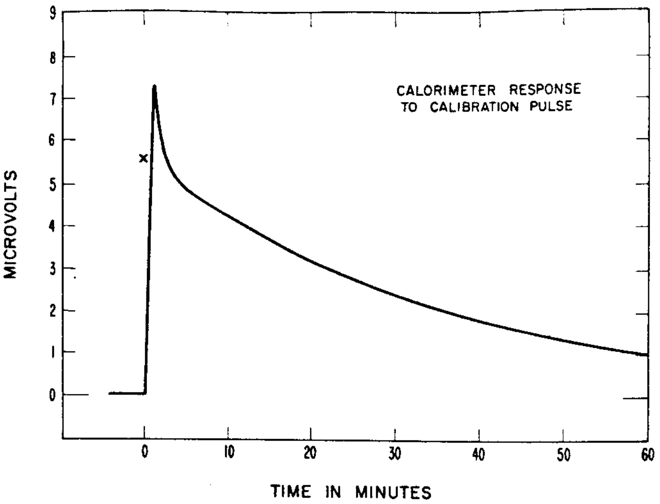

Fig. 4. Typical chart trace of the calorimeter system response to a calibration. Note the overshoot due to the close proximity of heater wire to the silver housing. The total energy input to the calorimeter here was 1.55 J.

The electrical energy substitution calibration was finally obtained by making an exponential extrapolation of the thermal decay back to time $= 0$, as shown by the x on the chart (Fig. 4).

The precision of the calorimeter system was determined by the reproducibility of the electrical energy substitution calibration. The electrical energy substitution calibration factor for this calorimeter system was $3.092\ \mu\text{V/J}$. This factor was the average of 13 calibration runs. The data had a standard deviation of 0.009. The two calibrations, specific heat and electrical energy substitution, compare very favorably with each other. From this we assume that the accuracy and precision is good to at least ± 1 percent.

Results and Intercomparisons of Calorimeters

A typical output of the calorimeter system for a normal ruby laser is shown in Fig. 5. Notice here that there was no overshoot as compared with the electrical calibration. The output energy of the laser was found by making the exponential extrapolation to time $= 0$, indicated by the x on the chart, and then dividing the deflection at time $= 0$ by the calibration factor.

Two calorimeter systems of the same basic design were intercompared with a setup as shown in Fig. 6. The technique was to measure the reflectivity R of the beam splitter. This position of calorimeter, as shown in Fig. 6, was the A position and the reflectivity of the beam splitter was R_A. Then the calorimeters were interchanged to position B, and R_B measured. Now if calorimeter No. 1 was assumed to be correct, and calorimeter No. 2 was in error by a fractional amount Δ

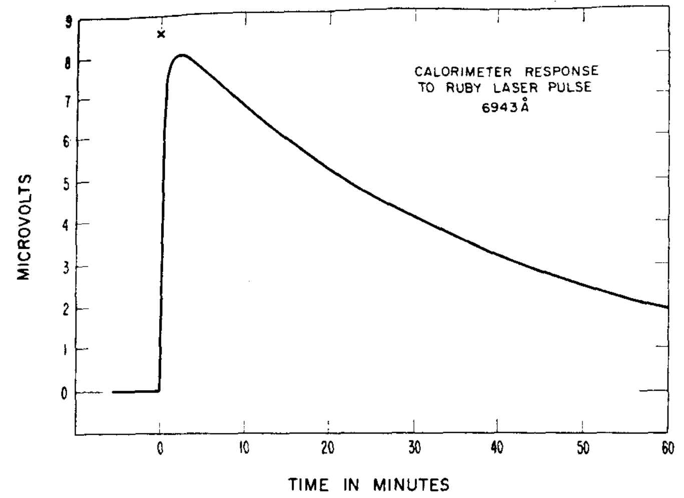

Fig. 5. Typical chart trace of the calorimeter system response to normal ruby laser pulse. Note here that there is no overshoot at the beginning of the trace. The energy in the laser pulse for this shot was 2.77 J.

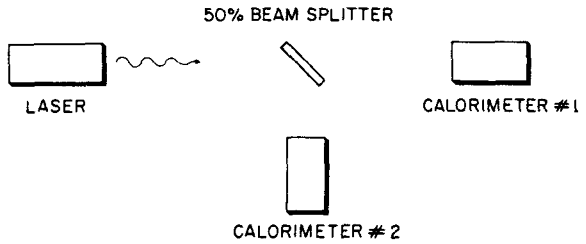

Fig. 6. Block diagram of apparatus arrangement used in the intercomparison of two calorimeters.

where

$$\Delta = \frac{E_2{}^1 - E_2}{E_2{}^1}$$

where $E_2{}^1$ is the true incident on calorimeter No. 2, and E_2 is the apparent energy, then Δ can be shown to be equal to

$$\Delta = \frac{R_A}{R_B} - 1.$$

For lasers which have a polarized output, i.e. 90° or 60°-oriented ruby laser rods, the laser rod must be oriented properly, relative to the beam splitter. This was easily done to ±1°, and represented an error of no more than ±0.1 percent.

Using this technique, we find a Δ for our calorimeter systems of 0.007. This result was from an average of 10 comparison runs. The data had a standard deviation of 0.002.

DISCUSSION

We have made several calorimeters modeled after the same basic design with modifications to include cone shaped absorption cells, a different absorbing liquid ($CuCl_2 + H_2O$), and Brewster's angle input. We have tested the calorimeters with laser energies up to 15 J (normal laser) and powers up to 150–200 megawatts (Q-switched), and found no anomalies in the calorimeters. It would seem possible to scale the calorimeter components to make calorimeter systems that would measure very high energies, say 10^4 J with one percent accuracy and precision, by using a large aperature, large volume calorimeter so as not to exceed a certain energy density, in order to avoid a change in state of the absorbing fluid.

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REFERENCES

[1] T. H. Maiman, R. H. Hoskins, I. J. D'Haenens, C. K. Asawa, and V. Evtuhov, "Stimulated optical emission in fluorescent solids. II. Spectroscopy and stimulated emission in ruby," *Phys. Rev.*, vol. 123, p. 1151,–1157, August 15, 1961.

[2] S. Koozekanani, P. P. Debye, A. Krutchkoff and M. Ciftan, "Measurements of the laser output," *Proc. IRE* (*Correspondence*), vol. 50, p. 207, February 1962.

[3] T. Li and S. D. Sems, "A calorimeter for energy measurement of optical masers," *Appl. Optics*, vol. 1, pp. 325–328; May 1962.

[4] A. L. Glick, "A method for calibration of laser energy output," *Proc. IRE* (*Correspondence*), vol. 50, p. 1835, August 1962.

[5] R. C. C. Leite and S. P. S. Porto, "A simple method for calibration of ruby laser output," *Proc. IRE* (*Correspondence*), vol. 51, pp. 606–607, April 1963.

[6] J. A. Calviello, "An optical calorimeter for laser energy measurements," *Proc. IRE* (*Correspondence*), vol. 51, pp. 611–612, April 1963.

[7] M. Stimler, "Ballistic torsional pendulum," U. S. Gov. Res. Rept. AD-420, p. 469, October 1963.