NBS TECHNICAL NOTE

418

Radiometric Methods for Measuring Laser Output

U.S. DEPARTMENT OF COMMERCE
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D. A. McSparron, C. A. Douglas,
and H. L. Badger

Metrology Division
Institute for Basic Standards
National Bureau of Standards
Washington, D.C. 20234

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RADIOMETRIC METHODS FOR MEASURING LASER OUTPUT

D. A. McSparron, C. A. Douglas, and H. L. Badger

The output of pulsed lasers may be measured with reasonable accuracy by modifications of established radiometric methods. The receiver, thermopile or phototube, is used ballistically. It is calibrated by an incandescent-lamp standard of spectral irradiance. The laser beam is attenuated to make its irradiation on the receiver comparable to that from the calibrating source. Attenuation is accomplished by intercepting the entire laser beam on a diffusely reflecting surface. The attenuation factor is determined from direct measurement of the reflectance of this diffusing surface and the geometric constants of the system. The accuracy of the measurement of laser output is dependent upon the accuracy of calibration of the standard of spectral irradiance and the accuracy with which the spectral sensitivity of the receiver, the spectral transmittance of the band-pass filters, and the reflectance of the diffuser can be determined. Measurements made with different photoelectric receivers agree to about 1.5% using a 1/4-joule pulsed ruby laser as a source. Total uncertainty is estimated to be about 5%. Measurements made using these radiometric methods have been compared with calorimetric measurements and a discrepancy of 9% was observed.

Key Words: Laser, radiometry, laser energy measurement, radiometric calibration, photoelectric photometry, optical attenuator.

1. Introduction

The rapid development of laser technology has left workers in the field without recognized methods of measuring the parameters of interest. The situation is particularly bad in the measurement of the energy emitted from pulsed lasers. Discrepancies of 25% or more have been common. Two widely differing approaches to the problem have been popular, namely, radiometric and calorimetric. A common calorimetric approach entails the absorption of the entire laser beam in a liquid. The temperature rise of the liquid is then a measure of the total energy contained in the pulse. Calorimetric measurements are difficult to perform because of the low signal levels obtained from low energy pulsed lasers, usually a few microvolts, and because of the long recycling times, thirty minutes or more. In addition, no information can be obtained from calorimetric measurements on the peak power levels of the pulse. The work described in this paper employs a radiometric approach. In addition to the advantages of relatively high signal levels and fast recycling times, a radiometric method can provide information about the peak power levels in the pulse through the display of the receiver output on an oscilloscope. Although the work to date has involved only a relatively low powered, approximately 1/4-joule, conventional ruby laser operated at 694.3 nm, the measurement techniques and procedures should be readily applicable to a wide range of energies and wavelengths.

A pulsed laser beam differs from conventional sources in that it is highly monochromatic, extremely intense, of short time duration, and in some cases polarized. These properties require modification of conventional radiometric measurement techniques if existing standards are to be used for the calibration. Such receivers as vacuum phototubes, photomultipliers and thermopiles can tolerate maximum incident power levels only of the order of milliwatts/cm^2 for conventional tubes or at most watts/cm^2 for present biplanar photodiodes. Beyond these levels physical damage occurs. Since instantaneous power levels in laser beams run to megawatts/cm^2 and higher, some attenuation device is necessary. An ideal attenuator should be simple, rugged, and readily standardized through existing techniques. Attenuation factors that range from 10^{-4} to 10^{-8} are necessary. A diffusing surface of high reflectance meets these requirements.

2. Experimental Setup

The experimental setup used is shown in Figure 1. Energy from the laser is incident normally on a pressed block of USP grade magnesium carbonate. Receivers are placed at a distance d from the diffuser, in tracks that form a 20° angle with the incident beam. The attenuation factor, α, is given by:

$$\alpha = \frac{\beta a \cos 20^\circ}{\pi d^2} \tag{1}$$

where a is the area of the receiver, β is the 0°:20° (incidence angle: reflectance angle) reflectance factor [1/] of the $MgCO_3$ and d is the distance from the $MgCO_3$ to the receiver. $MgCO_3$ was chosen for the diffusely reflecting surface and has proved satisfactory for the wavelength and energy used as will be discussed later.[2/] An angle of 20° was chosen to be sufficiently far from the normal that the effects of specular components of the reflected beam are negligible and yet to be sufficiently small so that cos θ is not a rapidly varying function. The β of this equation was measured at 20° on a goniophotometer with substantially monochromatic light of the same wavelength as the ruby laser used in this work. Thus, no assumptions about the diffuse reflection properties of $MgCO_3$ have been made. For typical values, a one-centimeter-radius receiver and a receiving distance of 100 cm, α is approximately 10^{-4}. Increased attenuation may be obtained by increasing d or, if necessary, by introducing a second diffuser.

Two types of receivers have been used in this work. The first is a type PJ14B vacuum phototube. These phototubes have very low dark currents and an S-7 response which is relatively flat at the ruby wavelength. This tube is no longer being manufactured. It was originally developed for use in the Hardy (General Electric) recording spectrophotometer. The second type of receiver, so far used for preliminary investigations only, is a Moll large-surface thermopile. It has 80 constantan-manganin junctions placed in a circular array one centimeter in radius with a platinum black surface.

3. Calibration

3.1 General Considerations

Typically in radiometry employing a photoelectric or thermoelectric receiver, the primary problem is not the measurement of the electrical output of the receiver to the desired degree of accuracy and precision. Instead the primary problem is the calibration of the receiver in terms of electrical output per unit of incident energy (or power). The problem is particularly acute when the sensitivity of the receiver is not constant but varies with the wavelength of the incident energy as does the sensitivity of a phototube, and a calibrating source having a spectral energy distribution identical with that of the source to be measured is not available. The calibration procedure is as follows.

1/ Reflectance factor is the ratio of the reflected flux to that reflected by a perfect diffuser identically irradiated.

2/ Although $MgCO_3$ was the chosen material other diffusers of high reflectance such as MgO and $BaSO_4$ should also prove satisfactory. These materials would be more stable chemically when irradiated by high-energy laser pulses. $MgCO_3$ was chosen mainly because of the ready availability of pressed blocks with large surface areas.

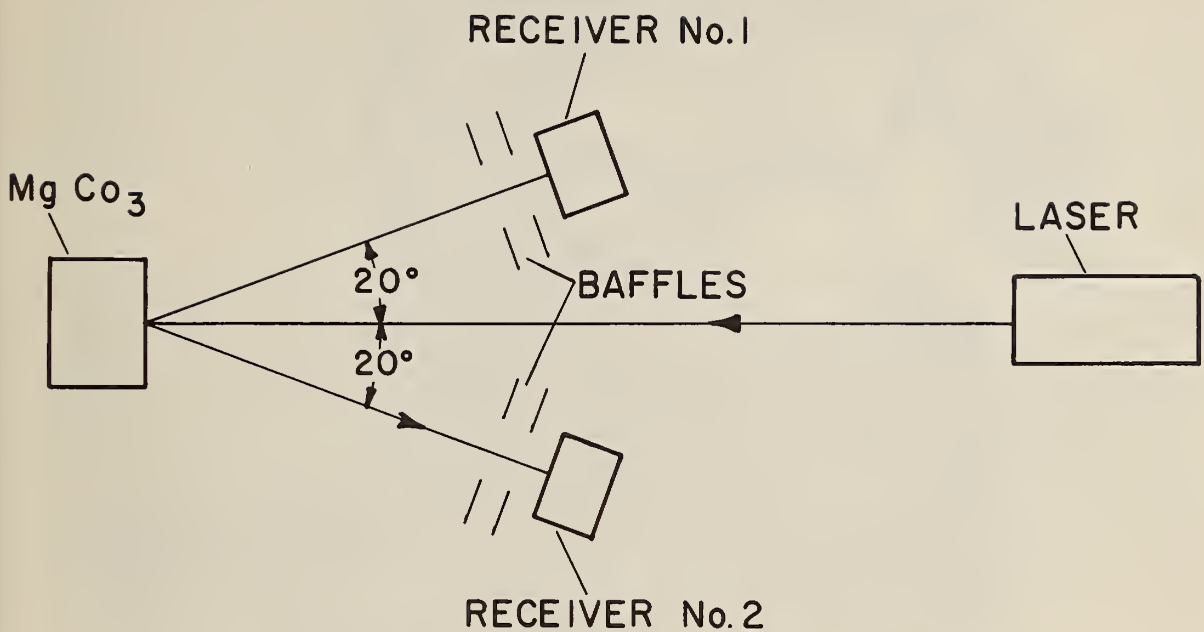

Figure 1. Experimental Setup for Measuring Laser Energy

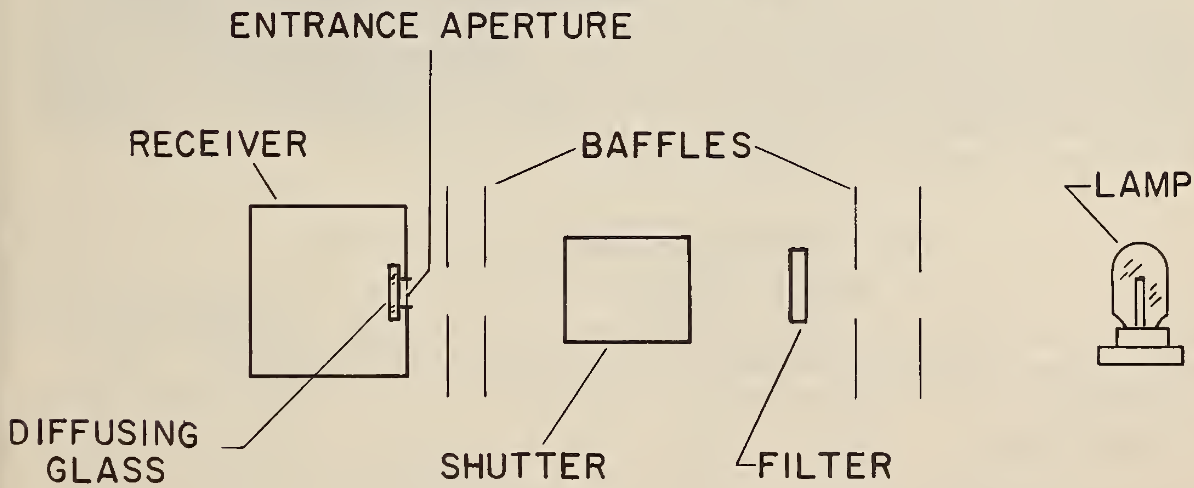

Figure 2. Experimental Setup for Calibrating Receivers

The receivers were calibrated in a separate experiment. The calibration setup is shown in Figure 2. A lamp calibrated for spectral irradiance is used as an energy source. Energy from this lamp is passed through a filter, then a shutter and finally on to the receiver. The filter is introduced in order to spectrally limit the output of the lamp. A special two-part shutter was used. The first part consists of a 60-r/min. synchronous motor which drives a sector disk through a multiple-speed reduction gear-head. The disk is thus rotated at various known slow speeds to provide series of light pulses of accurately known time durations. The second part is a simple open-close shutter that allows selection of a single pulse from the series of pulses provided by the sector disk. The combination thus simulates the pulsed characteristic of the laser beam except that the pulse lengths are longer.

Care was taken to fully and uniformly irradiate the sensitive surface of the receiver because receivers might exhibit large sensitivity variations across the receiving surface. [1,2]* The requirement for uniform irradiance was met by using source-to-receiver distances which were large in comparison to the size of the source and the receiver aperture. In addition, since the available energy and phototube sensitivity allowed it, a diffusely transmitting glass was incorporated as part of each phototube receiver as shown in Figure 3. The baffling shown in Figures 1 and 2 is required to eliminate the effects of stray light and interreflections. The laser head emits stray light in two ways, namely flashtube light escaping through the vent holes and light emitted through the rod which has not undergone laser action. In contrast to the laser beam proper, the flux incident on the $MgCO_3$ diffuser from these sources of stray light obeys the inverse-square-law and hence, can be reduced to any degree desired by the use of large laser-head-to-diffuser distances. In this work a distance of five meters was used.

3.2 Phototube Calibration

Figure 4 is a block circuit diagram of the measuring circuit used with the phototubes. The photocurrent charges a capacitor, C. An electrometer-amplifier is used to determine the voltage to which the capacitor is charged and the result is displayed on a chart recorder.

At a wavelength λ, a steady-burning lamp with a spectral radiant intensity, I_λ,[3/] and at a distance, d, from the receiver aperture, will produce a spectral irradiance, E_λ, on the receiver aperture where $E_\lambda = I_\lambda/d^2$. If an interference filter of spectral transmittance, $\tau(\lambda)$, is placed between the lamp and the phototube and if the phototube has a relative spectral response, $R(\lambda)$, the phototube output will be proportional to the triple product: $E_\lambda \tau(\lambda) R(\lambda)$. In the calibration setup (Figure 2) the shutter allows irradiation of the phototube receiving surface for a measured time, T. Hence, the voltage to which the capacitor is charged, V_P, is given by:

$$V_P = K_{PT} a T \int_{\lambda_1}^{\lambda_2} E_\lambda \, \tau(\lambda) R(\lambda) d\lambda \qquad (2a)$$

where a is the area of the receiver aperture, K_{PT} is the receiver calibration factor, and λ_1 and λ_2 are the lower and upper limits of the pass band of the filter. Thus:

*Numbers in [] refer to similarly numbered references at the end of the paper.

3/ In this paper quantities which are restricted to a narrow wavelength band are indicated by adding the word spectral. The corresponding symbols are indicated by a subscript, e.g., E_λ, for a spectral concentration or a λ in parenthesis, e.g., $\tau(\lambda)$, for a function of wavelength. This usage is in accord with the recommendations of ISO, IEC, CIE, and SUN Commission of IUPAP and in forthcoming American Standard Y10.6.

Figure 3. Photoelectric Receiver

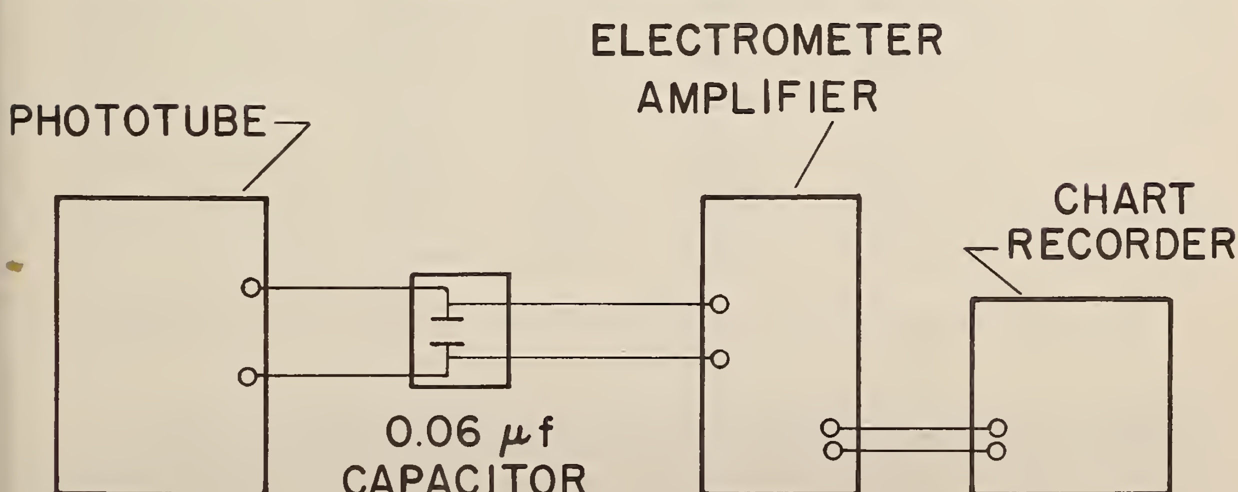

Figure 4. Block Circuit Diagram of the Phototube Measuring Circuit

$$K_{PT} = \frac{V_P}{aT\int_{\lambda_1}^{\lambda_2} E_\lambda \tau(\lambda) R(\lambda) d\lambda} \tag{2b}$$

This factor is a function of the transmittance of the diffusing glass, the size of the capacitor, and the absolute sensitivity of the phototube at the wavelength at which $R(\lambda)$ is unity.

In the laser-measuring setup (Figure 1), the voltage, V_L, developed on the capacitor as the result of a laser shot will be:

$$V_L = K_{PT}\, \alpha\, R_{(694.3)} Q \tag{3}$$

where α is the attenuation factor given by Equation 1, and $R_{(694.3)}$ is the relative spectral response of the phototube at 694.3 nm. Hence, the laser energy is:

$$Q = \frac{V_L}{K_{PT}\, \alpha\, R_{(694.3)}} \tag{4}$$

4. Laser Measurements with the Phototubes

In order to establish the validity of the phototube calibrations, a complete factorial calibration experiment was performed. Systematically, all combinations of three phototubes, two interference filters, two exposure times, two lamps, and two receiver housings with diffusers were used to determine six calibration factors, one each for each phototube-housing combination. The results are shown in Table I.

Table I: Phototube Calibrations

Phototube	Receiver Housing	Average K_{PT}[a] (Volts/Joule)[b]	S.D. of a Single Measurement (%)	S.D. of Avg.[c] (%)
2134	B	9,528	2.44	0.85
	A	6,982	0.91	.32
2136	B	8,049	2.41	.85
	A	5,893	2.59	.92
2138	B	12,493	2.11	.75
	A	8,892	1.47	.53
		Average	1.99	0.70

[a] Based upon the relative response of the phototube at 694.3 nm ($R_{694.3}$) = 1.00

[b] Volts per joule incident on the receiver aperture.

[c] Based on 8 independent determinations of K_{PT}.

Each calibration factor, K_{PT}, shown in Table I is an average of eight different combinations of lamp, filter, and exposure time. The standard deviations quoted are indicative of the precision with which the various measured parameters, V_p, $R(\lambda)$, $\tau(\lambda)$, and E_λ can be determined. Analysis of the data shows no systematic variation with filter, exposure time, or receiver housing. A shift of 1.3% was traceable to the standard lamp used. However, the direction and magnitude of this shift are such as to be explained by the fact that one of the lamps has functioned as a working standard while the other has been held as a reference standard.

In order to check the consistency of the calibration factors thus determined, an additional experiment was performed. Laser energy was measured by using the arrangement shown in Figure 1. Each phototube-housing combination was used in each of the 2 positions shown to measure the energy of three laser shots. Since only two phototube-housing combinations could be used at one time, an experimental design involving a total of 36 laser shots was employed. This design allowed separation of the effects due to varying laser energy from those due to calibration uncertainties. The data from these two experiments were analyzed statistically. The results for the various factors involved in the calibration experiment were as stated above. Two additional effects were found. Measurements made with one of the phototubes, Number 2136, appear to differ from the other two by about 1%. The exact cause has not been traced as yet. The second effect was a 4% shift depending only on whether the receiver was located at position 1 or position 2 of Figure 1. This effect was traced to interreflected energy reaching the receiver at one position and not the other, emphasizing again the need for adequate shielding of the equipment. Table II shows the experimental design and the results of the energy measurements. (All results obtained by measurements at receiver position 1 have been corrected by subtracting 4% from the measured value.)

Table II: Laser Energy Measurements

Phototube (Position 1)	Receiver Housing	Laser Output Joules[a]	Phototube (Position 2)	Receiver Housing	Laser Output Joules[a]	Difference (Pos. 1 - Pos. 2) (%)
2134	A	.2245	2138	B	.2190	2.3
2136	A	.2157	2138	B	.2189	-1.4
2136	A	.2199	2134	B	.2264	-2.7
2138	A	.2249	2134	B	.2279	-1.3
2138	A	.2322	2136	B	.2300	0.9
2134	A	.2339	2136	B	.2346	-0.4
2136	B	.2328	2134	A	.2353	-1.7
2138	B	.2327	2134	A	.2381	-2.1
2138	B	.2316	2136	A	.2204	4.9
2134	B	.2305	2136	A	.2157	6.8
2134	B	.2227	2138	A	.2312	-3.5
2136	B	.2269	2138	A	.2312	-1.8

[a]The energies reported are in each case the average of three separate firings of the laser.

The results of this statistical analysis show that the physical parameters, exposure time, lamp energy, relative spectral response of the receivers, and particularly notable, interference filter transmittances, have been evaluated and combined in a mutually consistent manner. The experimental parameters, such as receiver housing and receiver position, are also under adequate control. Hence, a set of mutually consistent measurements has been achieved under widely varied conditions.

Several experiments were run to check on possible sources of systematic error. An investigation was made to determine if the phototubes were saturating under the high power density produced by the laser. The usual aperture was replaced with a larger aperture (area ratio 11.6) and the supply voltage across the phototube was varied. A second phototube was used to monitor the laser output. Table III indicates that phototube saturation was not biasing the experiments.

Table III: Phototube Saturation Experiment

Supply Voltage[a] (Volts)	Test Phototube Output (Volts)	Monitor Output (Volts)	Ratio (Test/Monitor)
520	2.06	0.189	10.90
270	2.08	.193	10.78
180	2.02	.188	10.74
100	1.81	.177	10.22
100[b]	1.82	.188	9.68

[a]The normal supply voltage on the phototube was 220 volts.

[b]This measurement was made with the test phototube 12 cm closer to the $MgCO_3$ block than the previous ones. The inverse-square law has been applied to put this measurement on the same basis as the others.

In order to check for possible polarization effects, a linear polarizer was placed in front of one of the two receivers. No change in the measured values was observed as the plane of polarization was rotated.

Several experiments were run to check on the stability and suitability of $MgCO_3$ for the diffusing surface. The reflectance factor, β of Equation 1, was remeasured one year after the original measurement. The measurements agreed to within 1/2%, the precision of the gonioreflectometer. A converging lens was introduced into the laser beam in order to focus the beam on the $MgCO_3$ block. Although the energy density was concentrated by a factor of 10^3, no effects were observed either in the measured energy or in the physical condition of the block. Finally the usual measuring angle of 20° was varied and the phototube responses noted. Although the angle was varied from 15° to 45° no anamalous effects were observed.

5. Thermopile Calibration

A block circuit diagram of the thermopile measuring circuit is shown in Figure 5. The circuit is one that allows for calibration against an external emf and thus obviates the necessity of relying on amplifier or recorder stability. The output of the thermopile is stated in terms of the microvolts developed at the amplifier input terminals.

For a thermopile, $R(\lambda)$ in Equation 2b is 1.00 and hence no significant error is introduced by the relative spectral sensitivity parameter. However, in contrast with the PJ14B phototubes whose spectral sensitivity is negligible beyond one micron, thermopiles respond to energy far into the infrared. Since the spectral irradiance values, E_λ, of the standard lamps become uncertain beyond 2.5 microns, it is necessary to introduce a filter to absorb long-wavelength energy. A "heat-absorbing" glass with a transmittance of 1% or less for wavelengths beyond 1.1 microns was used. However, even when the filter is used, 16% of the transmitted energy from the standard lamps is contained in the region beyond 1.1 microns.

With the modification that $R(\lambda) = 1.00$ the calibration procedure described for the phototubes is applicable. When this was tried experimentally, difficulties were encountered. The lamp energies available during calibration were such that exposure times in the range 1/2 to 3 seconds were required to keep the thermopile response far enough above the noise level for accurate measurements. Experiments showed that the thermopile had a 1/e time constant of about 3 seconds. The amplifier-recorder system also had a response time on the order of seconds. The effects due to the thermopile and those due to the measuring system proved inseparable and new equipment having a faster response time is being obtained. It is expected that when this equipment is put in operation thermopile measurements of the laser energy will be possible.

Although accurate calibration of a thermopile is uncertain at this time, the short time duration of the laser pulse allows self-consistent measurements. This experiment was performed by placing a phototube at one of the receiver positions shown in Figure 1 and the thermopile at the other one. The ratio of their readings should be constant. Experimentally the standard deviation of a single measurement was 2.8%. A similar experiment performed with two phototubes gave a standard deviation of a single measurement of 0.77%. This internal consistency of thermopile energy measurements indicates that future work with the thermopile will be profitable.

6. Comparison with Calorimeter

A check of the accuracy of the calibrations was made by making a limited comparison of results with a calorimeter built at the NBS Boulder Laboratory. [3] Since the calorimeter accepts the entire laser beam, an auxiliary monitoring system is required. Figure 6 shows the arrangement employed. The monitor was first calibrated relative to the phototubes by removing the calorimeter and allowing the laser beam to impinge on the $MgCO_3$ block as in Figure 1. The calorimeter was then put in place and a transfer comparison obtained. In placing the calorimeter, care was taken <u>not</u> to align it with its entrance window perpendicular to the incoming laser beam. The calorimeter was canted with respect to the laser beam enough to insure that the energy reflected from the entrance windows did not proceed back along the beam track to the laser head. A simple calculation (assuming 16% reflectance from the calorimeter windows, 90% transmittance and 8% surface reflectance at the beam splitter) shows that an additional energy increment amounting to 12% of the calibrating energy can reach the monitor if this procedure is not observed.

When the transfer comparison between the calorimeter and the phototubes was carried out, a discrepancy of about 9% was observed. The calorimeter indicated lower energies than the phototubes.

7. Discussion of Possible Sources of Error

In view of the discrepancies observed between data on laser energies obtained with the phototubes and with the calorimeter, consideration has been given to possible systematic errors in the calibration of the photoelectric receivers.

The estimated uncertainty of the E_λ values is 3% in the spectral region of interest, 650 to 750 nm. Since the laser wavelength, 694.3 nm, lies in the visible region a check on the irradiance values of the standard lamps was possible through a measurement of luminous intensity and color temperature. [4] The irradiance values thus obtained checked those obtained directly within 1/2% and 3% for the two lamps.

The transmittance values, $\tau(\lambda)$, of the interference filters used to approximate the monochromaticity of the laser beam were measured at NBS on a Cary 14 recording spectrophotometer. Since filters having narrow pass bands centering approximately on the laser wavelength were used, the calibration procedure is spectrally a substitution method. The narrower of the two interference filters employed has a half-band width of 1.1 nm. The spectrophotometer has a maximum resolution of 0.2 nm and thus will not completely resolve this filter spectrally. Instead the readout will be an average transmittance value for a 0.2-nm bandwidth.

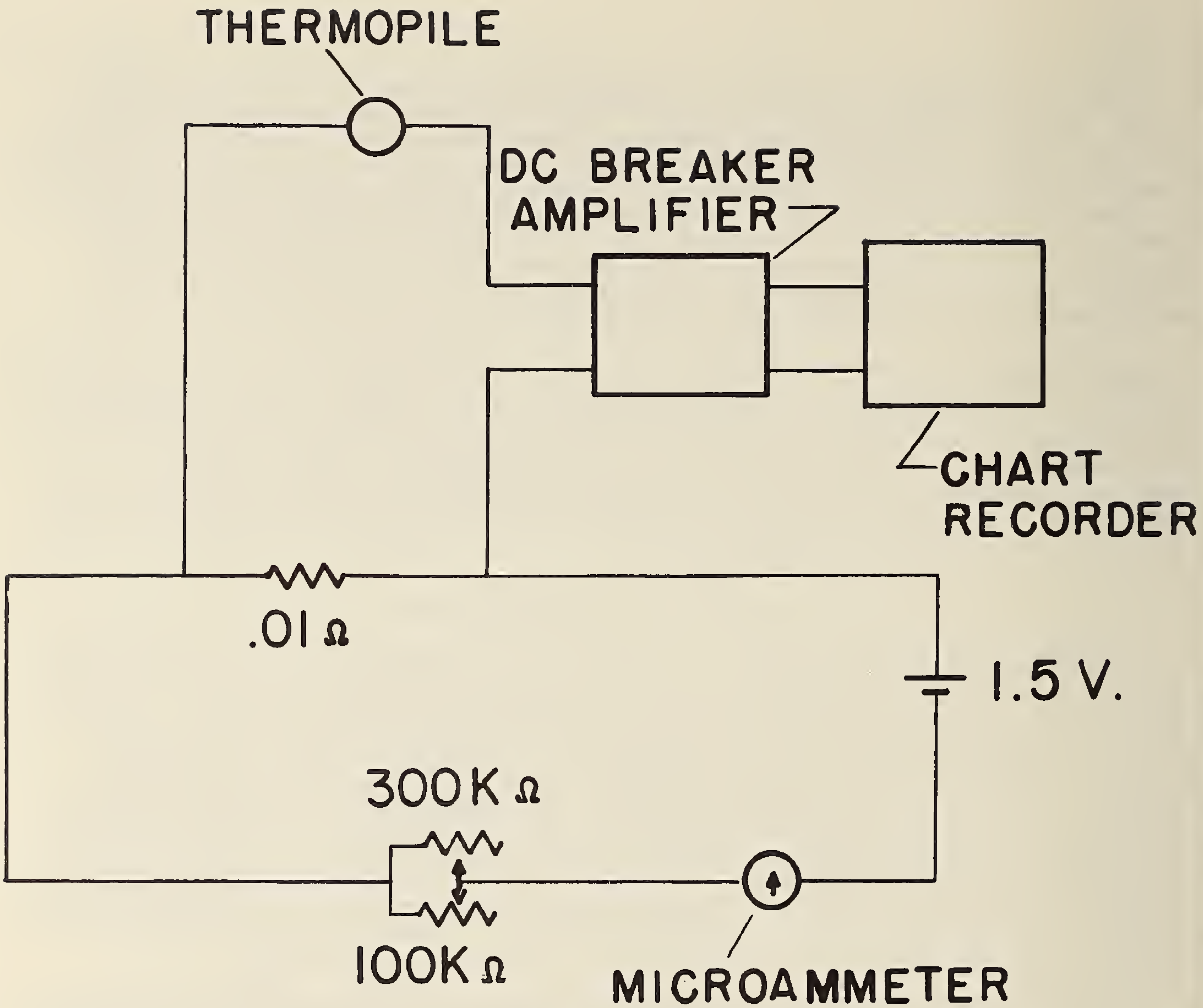

Figure 5. Block Circuit Diagram of the Thermopile Measuring Circuit

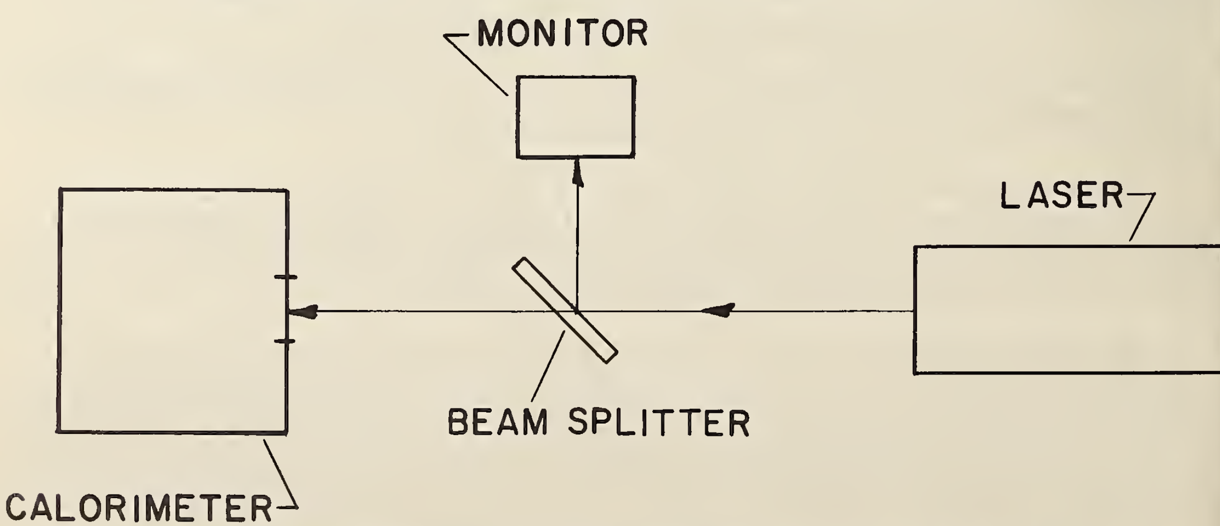

Figure 6. Experimental Setup for Measuring Laser Energy with a Calorimeter

Although the measured spectral transmittance values at any given wavelength will be in error, the area under the transmission curve should be constant for a wide range of resolutions. Further, since E_λ and $R(\lambda)$ are slowly varying functions across the pass band of the filter, the energy reaching the phototube as computed in the integral in Equation 2b should be very nearly correct because of the self-compensating nature of this error in the $\tau(\lambda)$ values. Hickey's experiments confirm this directly. [5]

The relative spectral response, $R(\lambda)$, of the phototube-diffusing-glass combinations was measured on a detector-spectrum recorder. This instrument consists of an electronically-controlled incandescent lamp which, together with a single-grating monochromator, gives a constant spectral radiant flux with a band width of approximately 10 nm. The instrument is similar to the one described by Mitsuhashi and Nakayama. [6] Measurements made on this instrument are believed to be uncertain by no more than ±5% for the slope of the $R(\lambda)$ curve in the spectral region of interest. Note that since the laser wavelength lies within the narrow band passed by the interference filter it is the slope of $R(\lambda)$ within the pass band of the interference filter that affects the accuracy of the calibration rather than the values of $R(\lambda)$.

The narrow pass band interference filters were used to insure that the shape of the $\tau(\lambda)$ curve would be the dominant factor in the integral in Equation 2b since $\tau(\lambda)$ can be measured with higher accuracy than $R(\lambda)$ or E_λ. Both the E_λ and the $R(\lambda)$ functions are slowly varying in the narrow spectral region of the pass band of the interference filters. Analytic studies show the dominance of $\tau(\lambda)$ over E_λ and $R(\lambda)$ on the calibration accuracy. For example, a 5% shift in the slope of the $R(\lambda)$ curve makes only a 1/2% change in the value of the integral.

Systematic errors in $\tau(\lambda)$, $R(\lambda)$ and the exposure times would have been detected immediately in the course of the analysis of the factorial calibration experiment. Systematic errors in the reflectance factor, β (Equation 1), or the irradiance, E_λ (Equation 2b) could still be present and would not necessarily have been so detected. As indicated above, experience and direct measurement indicate that E_λ is known to within 3%. Past experience indicates that reflectance factor measurements should be in error by no more than 1%. As indicated previously interreflections can be a source of error. However, the magnitude of the residual interreflections, after correction for the positional effect, is believed to be much too small to account for the difference between the phototube and calorimeter calibrations. Lack of experimental precision is not likely to be the cause. The 3-sigma limit for the agreement of two independent and simultaneous measurements of laser output based on the difference column of Table II is 4.5%. Since the average of 12 sets of 3 measurements each with the photoelectric receivers was used in the comparison with the calorimeter, the 3-sigma limit for the mean of the photoelectric measurements is insignificant in comparison to the possible systematic errors. Thus the discrepancy between the phototubes and calorimeter is difficult to explain.

8. Conclusions

The output of low energy, ruby lasers has been measured using photoelectric radiometers. Attenuation of the laser beam was accomplished by intercepting the entire laser beam on a diffusely reflecting surface and viewing this surface from a distance with the photoelectric receiver. Measurements made with different photoelectric receivers agree to about 1.5%. Total uncertainty is estimated to be about 5%. Measurements made using this radiometric method have been compared with calorimetric methods and a discrepancy of 9% was observed.

Future plans call for continued research to eliminate the discrepancy between the calorimeter and phototube measuring systems. Comparisons with a thermopile calibration and measuring system are also planned. The results reported above have been obtained with a relatively low-powered, conventional ruby laser. Present plans call for applying these measurement techniques to lasers of higher energy, to Q-switched lasers, and to lasers operating at wavelengths other than 694.3 nm. Once agreement is established among the various measuring systems, transfer calibrations similar to the one described for the monitor used in the calorimeter work can be used to calibrate any number of additional measuring systems.

The authors wish to express their thanks to Mr. R. P. Teele, [7] whose preliminary studies led to the present work, and to Mr. Hsien Ku of the NBS Statistical Engineering Section for his help in analyzing the results of the calibration and laser-measuring experiments. In addition, the authors wish to thank their other colleagues, too numerous to mention individually, for their valuable assistance.

9. References

[1] R. Stair, W. E. Schneider, W. R. Waters, and J. K. Jackson, Some Factors Affecting the Sensitivity and Spectral Response of Thermoelectric (Radiometric) Detectors, Applied Optics, Vol. 4, pp. 703-710 (June 1965).

[2] R. Stair, W. E. Schneider, W. R. Waters, J. K. Jackson, and R. E. Brown, Some Developments in Improved Methods for the Measurement of the Spectral Irradiances of Solar Simulators, NASA CR-201.

[3] D. A. Jennings, Calorimetric Measurement of Pulsed Laser Output Energy, IEEE Transactions on Instrumentation and Measurement, Vol. IM-15, No. 4, pp. 161-164 (Dec. 1966).

[4] L. E. Barbrow, Memorandum on a Procedure for Obtaining Spectral Radiant Intensities of Tungsten-Filament Lamps, 400-700 mμ, Journal of the Optical Society of America, Vol. 49, p. 1122 (Nov. 1959).

[5] J. R. Hickey, Correlation of Monochromator and Filter Radiometry Determinations of the Spectral Distribution in Large Solar Simulators (The Eppley Laboratory, Inc., Reprint Series No. 26), Institute of Environmental Sciences and American Society for Testing and Materials International Symposium on Solar Radiation Proceedings, pp. 95-105.

[6] H. Mitsuhashi and T. Nakayama, Apparatus for the Study of Spectral Response of Photoelectric Surface, Journal of the Physical Society of Japan, Vol. 11, pp. 308-311 (March 1956).

[7] R. P. Teele, Measurement of Pulsed Laser Output, presented at the 1965 Spring Meetings, Optical Society of America, Dallas, Texas, Paper TE12, 31 March - 2 April 1965.

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