NBS TECHNICAL NOTE 1010

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

Measurement of Pulsed-Laser Power

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Measurement of Pulsed-Laser Power

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Measurement of Pulsed-Laser Power

M. Young and R. A. Lawton

We describe calibrating several optical-pulse power meters to an accuracy of about 8% or better. The meters are designed for Q-switched neodymium lasers with peak powers in excess of a few megawatts and pulses longer than five or ten nanoseconds. Combined with a fast oscilloscope or a transient digitizer, the meters display the time-domain waveform of the laser emission and thereby allow determination of parameters such as transition duration (risetime, falltime), duration and peak power. We discuss calibrating the meters by both pulsed and cw methods, and show why each method is useful as a check on the other. We treat in some detail the effect of speckle on the use of diffusers as attenuators in power meters such as ours.

Key Words: Attenuators; calibration; laser; neodymium laser; peak power; power meter; pulsed laser; Q-switched; risetime; speckle; waveform.

1. Introduction

In this report, we describe the evaluation and calibration of three pulsed-laser power meters. The meters are designed to display in the time domain the instantaneous power of the pulses emitted by Q-switched YAG lasers; the pulses may be as short as 10 ns or so, with average energy densities up to about 0.5 J cm^{-2}. Knowing the time-domain waveform, we may determine parameters such as the duration and the peak power of the pulse.

The meters employ two reflecting diffusers for attenuation. The attenuated pulse irradiates a fast (0.5-ns duration) silicon photodiode held at a fixed temperature. The output waveform may be displayed on a fast real-time oscilloscope or on a transient digitizer when computer processing of single pulses is required.

In the body of the report, we discuss the absolute calibration of the power meters, by both pulsed and cw methods; the two results agree to within the estimated experimental error. We also discuss in some detail the effect of speckle on the use of diffusers as attenuators.

2. Power Meter Design

For this project, we calibrated several existing power meters; these meters had been designed and constructed by another group at NBS and are described here for completeness.

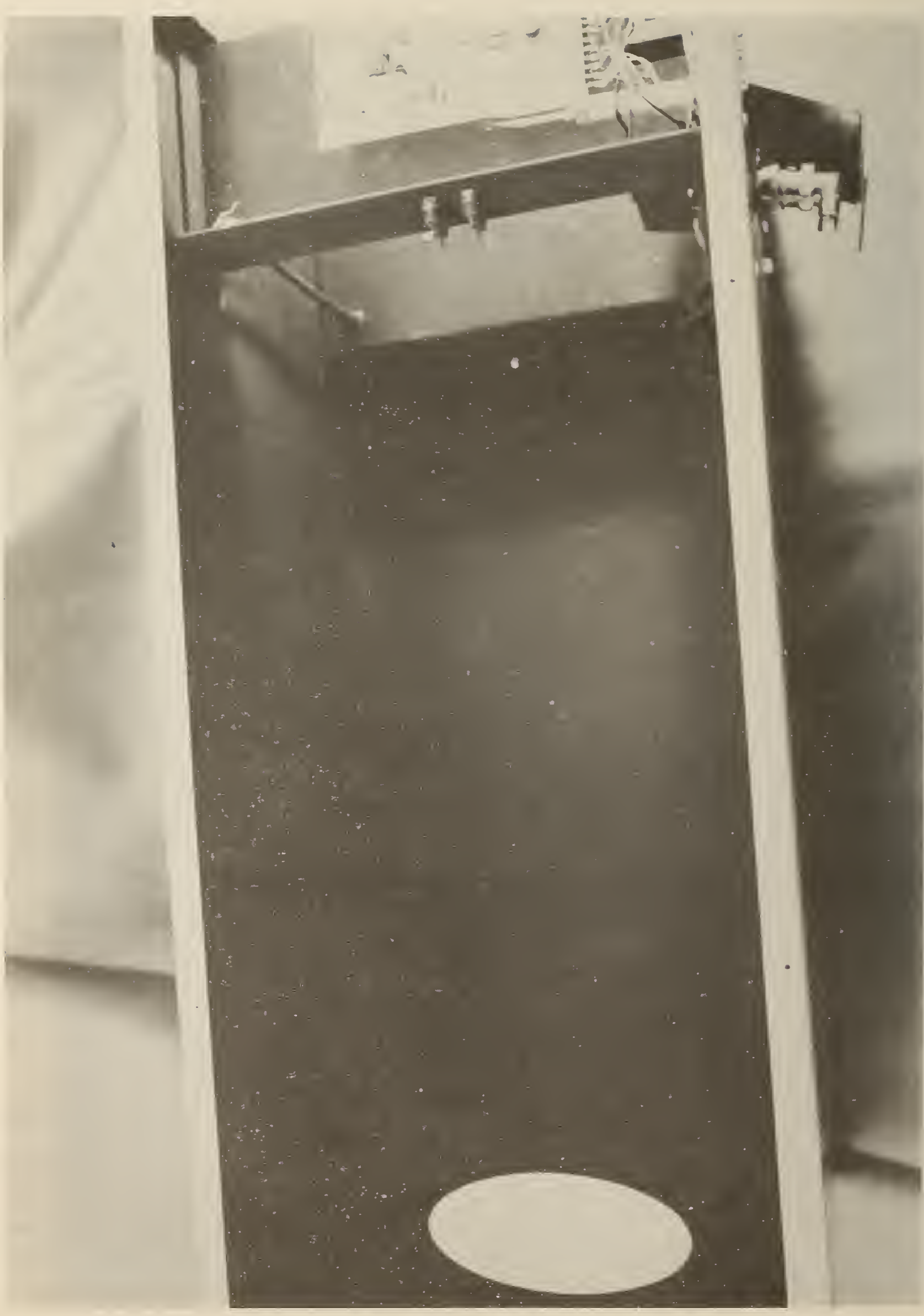
Figure 1 is a photograph of one of the meters. Figure 2 shows the same meter with the top removed. On the left of the figure is a diffuser that is used for attenuation of incident, megawatt pulses; the right side of the figure shows the circuit board for biasing two photodiodes and controlling their temperature. Figure 3 displays the meter with the front panel removed to show the boxes that contain the photodiodes. These boxes contain a second diffuser for additional attenuation, as shown in figure 4.

Figures 5 and 6 are schematics of the power meter and the second-diffuser box. The heavy lines represent a principal ray (which enters through the center of the aperture stop). The first diffuser scatters the beam, and a very small portion of the energy passes through the hole in the second diffuser box and falls on the second diffuser. Some of the light scattered by the second diffuser falls on the active area of the photodiode. The resulting photocurrent is displayed on a transient digitizer, yielding a time-domain representation of the laser power.

The diffusers had been made of Eastman white reflectance coating [1], primarily because of its ready availability in any size. This barium-sulfate paint has a very high, diffuse reflectance and is nearly a Lambertian surface [2]. Therefore, little error will be introduced if the incident laser beam enters the meter at a slight angle; this need not be the case with a weak diffuser, such as ground or etched glass, whose scattered light is strongly peaked in the directions of specular transmission and reflection.

Damage-threshold tests were performed with the 25-ns pulses emitted by a particular Q-switched YAG laser. An audible pop occurred at energy densities in excess of 600 mJ cm^{-2}. We define this energy density as the damage threshold for pulses of this wavelength and duration. Shorter pulses may have lower damage thresholds (measured in terms of energy density) owing to their higher peak powers.

Figure 1. The optical-pulse power meter.



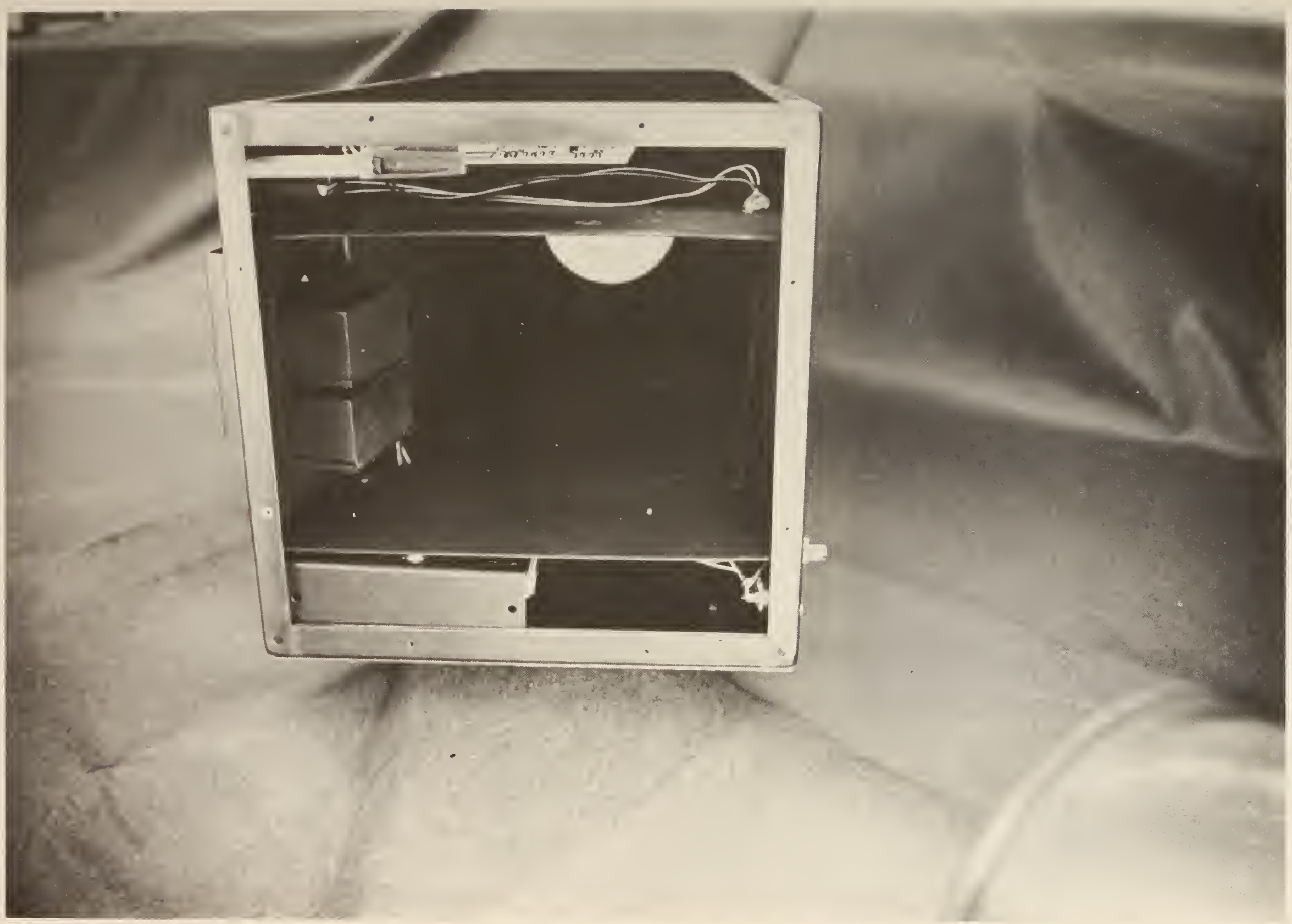


Figure 3. Front view with aperture removed.

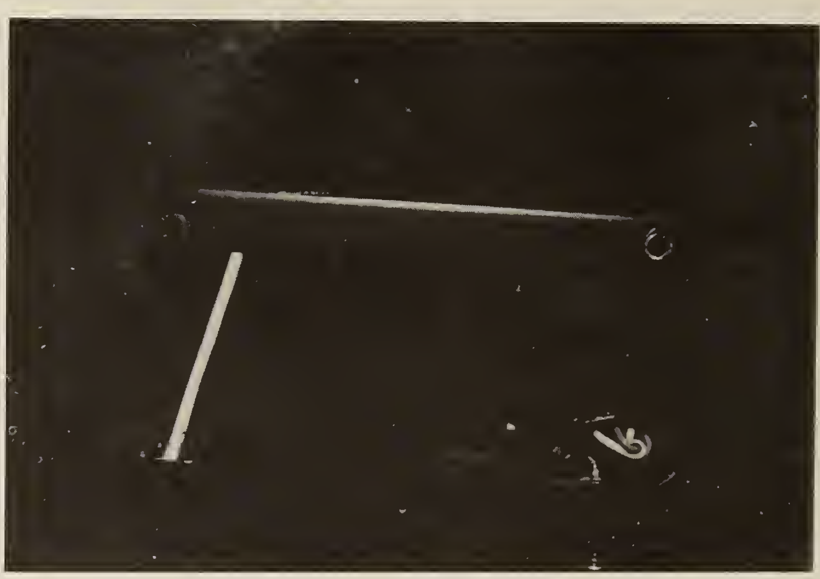


Figure 4. Top view of diffuser box with cover removed.

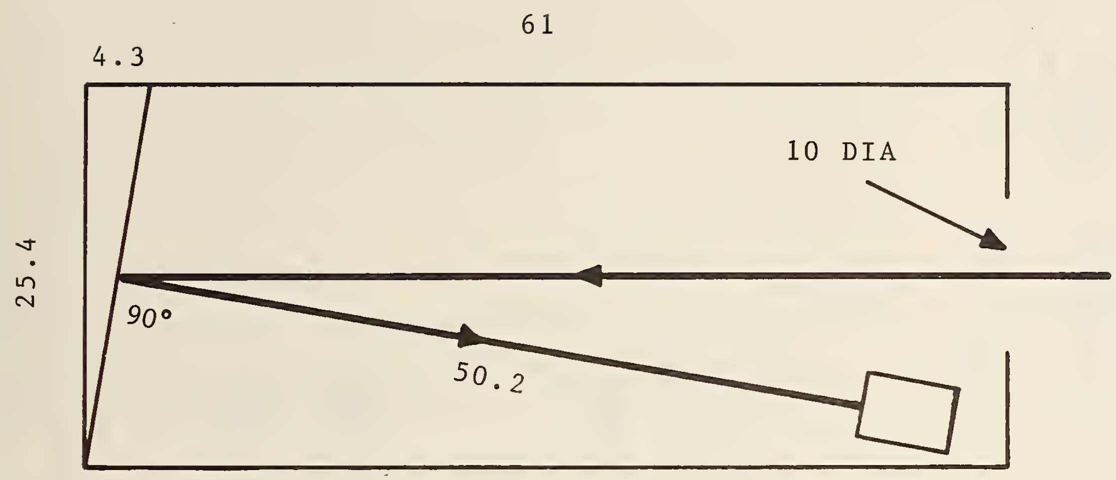


Figure 5. Optical-pulse power meter, showing diffuser and second-diffuser box. All dimensions are in centimeters.

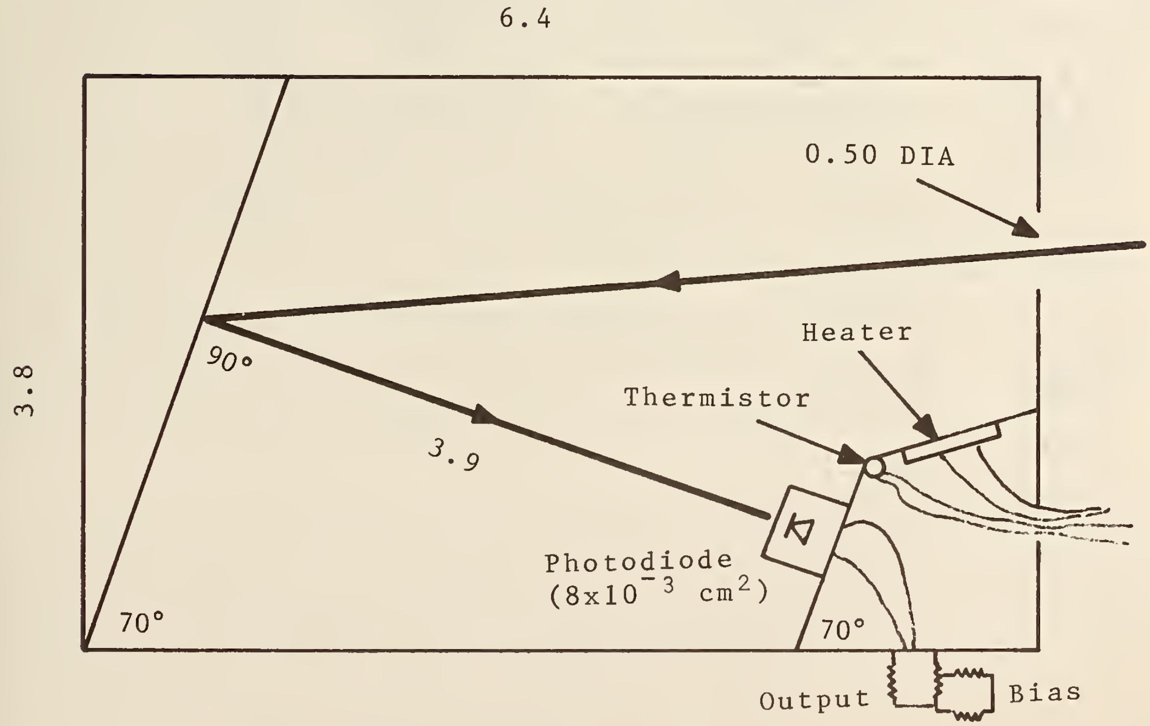


Figure 6. Second-diffuser box.

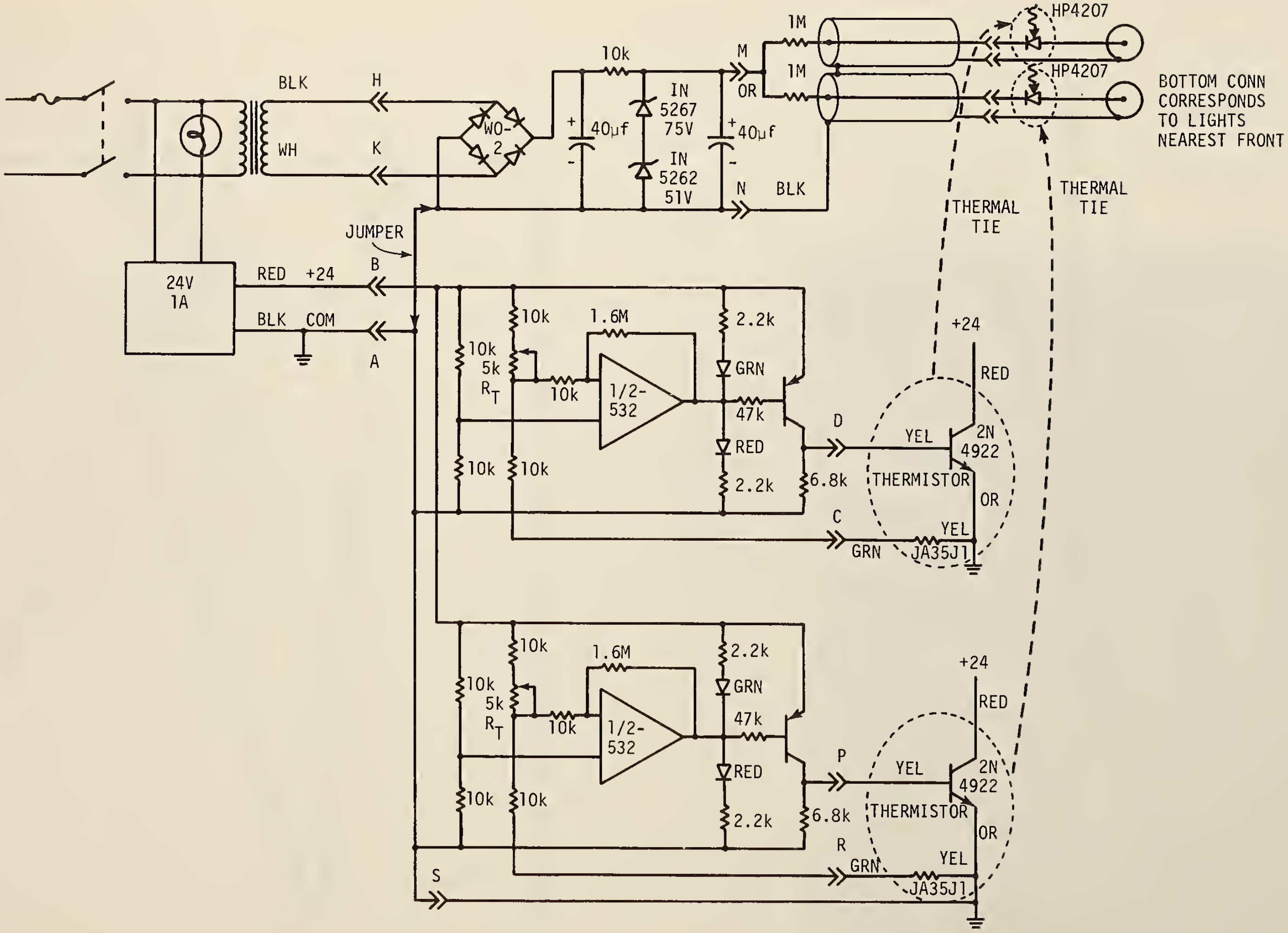


Figure 7. Schematic of temperature controller and photodiode-bias power supply.

The photodiodes are Hewlett-Packard 5082-4207's [3]. Each meter is equipped with two photodiodes in separate diffuser boxes. The temperatures of the boxes are stabilized at about 50°C to ensure that the responsivity of the diodes will not change with changing ambient conditions. Figure 7 is a schematic of the circuit used to control the temperature. A power transistor is used to elevate the temperature of the photodiode; the dashed lines in the figure indicate close thermal contact among the power transistor, the photodiode and the thermistor that is used to monitor the temperature of the box. (The red and green LED's are used for visual indication that the temperature has stabilized; when both LED's remain bright, the meter is ready to use. The LED's are seen through the holes shown in the top of figure 1.)

The impulse response of the power meter is its output waveform when the input is a very short optical pulse (in principle, a delta function). The meter will display an accurate representation of an optical pulse only if the duration of the pulse is long compared with the impulse response of the meter.

Figure 8 shows the impulse response of a typica_ photodiode in series with the transient digitizer. To determine the impulse response, we used a mode-locked YAG laser whose pulse duration was about 50 ps. The duration of the waveform shown in figure 3 is about 1.3 ns, measured between the points at which the photocurrent is 1/e times the peak value. (Because of the high attenuation coefficient of the entire power meter, we could not display the impulse response of the meter itself. A simple calculation shows, however, that the difference in transit times between the principal ray and a marginal ray from an extreme position on the first diffuser is about 40 ps, or one order of magnitude less than the impulse response of the photodiode.)

Because the diffusers are good Lambertian reflectors, we can estimate the attenuation coefficient of the power meter fairly accurately [4]. If a small plane scatterer has apparent radiance L and area dS, then the power $d^2\phi$ radiated at angle θ to the normal and into a solid angle $d\Omega$ is

$$d^2\phi = L\ dS \cos\theta\ d\Omega\ . \tag{1}$$

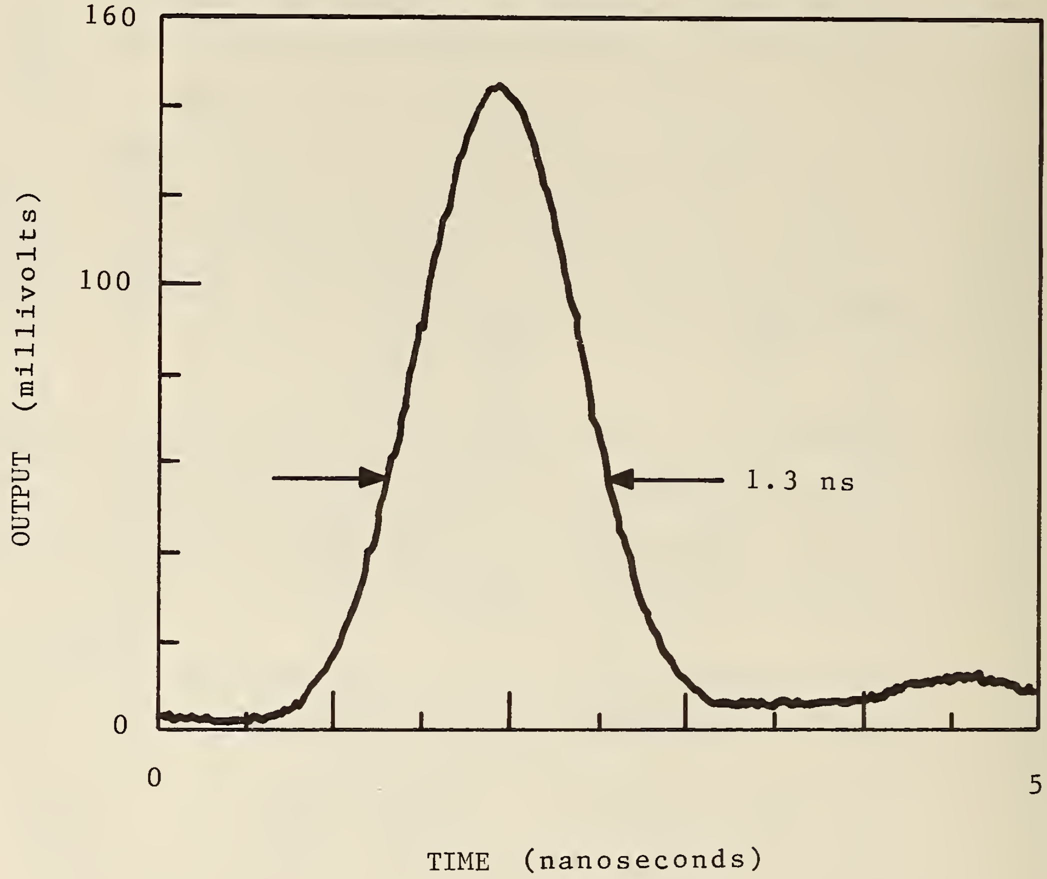


Figure 8. Impulse response of one of the photodiodes, convolved with the impulse response of the transient digitizer.

If the source approximates a Lambert radiator, then L is not a function of θ. The total power radiated into the hemisphere is $\pi L\ dS$. Therefore, the fraction radiated into the solid angle $d\Omega$ is $d^2\phi/\pi L\ dS$, or

$$dA \cos \theta/\pi r^2 \tag{2}$$

where dA is the area of the aperture through which the radiation is detected and r is the distance between the aperture and the scatterer.

For our power meter, θ is zero for both reflections. The diffuse reflectance of the paint is 0.98 at 1.1 μm [2]. Thus, using the dimensions shown in figures 1 and 2, we find that the attenuation coefficient is approximately 4×10^{-9}.

According to the manufacturer's specifications, the responsivity of the photodiodes is about 0.08 A/W at 1.06 μm [3]. Therefore, we expect an overall responsivity of about 3×10^{-10} A/W. The mean value of the measured responsivities of three power meters containing six detectors is about 2.3×10^{-10}; all values fall within 15% of their mean.

3. Speckle

The use of diffusers as attenuators is complicated slightly, when the light is coherent, by the appearance of speckles in the scattered light field. The presence of speckles will contribute to fluctuations in the output of the power meter because the laser-beam profile differs from shot to shot and possibly because successive shots hit slightly different points on the diffuser.

To estimate the effect of speckle, we consider a diffuser illuminated by a laser beam whose radius is r_1; the diffuser scatters the beam through an opening whose radius is r_2. The average size of speckles in the plane of the hole is determined solely by the wavelength of the radiation, the distance of the hole from the diffuser, and the size of the illuminated patch of the diffuser. One of us (Young) has shown that the average speckle size (measured, say, between half-intensity points) is about

$$0.8\ \lambda\ell/r_1, \tag{3}$$

where ℓ is the distance between the diffuser and the observation plane [5]. The average number M of speckles that passes through the hole is therefore

$$M = (r_1 r_2/0.8\ \lambda\ell)^2, \tag{4}$$

assuming that the diffuser and the hole are circular.

If we treat speckles as discrete entities (like balls) and assume that they obey a Poisson distribution, we conclude that the standard deviation σ of a large number of independent measurements is $M^{\frac{1}{2}}$. Expressed as a fraction of M, the standard deviation is

$$\sigma/M = M^{\frac{1}{2}} = 0.8/N, \tag{5}$$

where $N = r_1 r_2/\lambda\ell$ is a sort of Fresnel number.

In an elegant theoretical review, Dainty has shown that the fractional standard deviation of a normal speckle pattern should be about $1/N\pi$, which is in surprisingly good agreement with the simple estimate we have presented [6]. Edwards has very briefly discussed an experimental determination of the standard deviation which seems to be in rough agreement with ours and with Dainty's when N is large [7].

If we wish to keep fluctuations due to speckle noise down to 1 or 2% of the mean, then eq (5) shows that we must allow about 10,000 speckles to pass through the hole in the diffuser box and another 10,000 speckles to fall on the detector. To meet the first requirement, we must illuminate the first diffuser with a beam whose diameter is at least 3 cm. The number of speckles that fall on the detector is determined by the geometry of the diffuser box to be about 6000; the standard deviation is about 1.3% of the mean. Overall, we might expect speckle to contribute to an uncertainty of a few percent.

To measure the effects of speckle and possibly diffuser nonuniformity, we scanned the first diffuser of each of three meters with a continuous, 1-watt

YAG laser. We placed the meter on a table that could be moved by stepping motors in two orthogonal directions. The YAG laser illuminated a spot about 1 cm in diameter on the diffuser.

We chopped the laser beam at the rate of 120 Hz and detected the current with a lock-in amplifier preceded by a current amplifier. We scanned the entire face of the diffuser in 0.25-cm increments covering a 7.5-cm square.

We used digital electronics to record the position of the power meter, the output of the power meter, and the output of a reference detector that accounted for fluctuations in laser power. A minicomputer normalized the power meter output to that of the reference detector and plotted the results as a function of x and y, as shown in figure 9. An additional run was made with the power meter stationary to test for the effect of noise in the detectors.

After scanning the data by eye and eliminating points that were obviously off the edge of the diffuser, we calculated the mean and sample standard deviation s for each diffuser. (In this paper we use s to denote the standard deviation of a sample that contains n observations and σ to denote the standard deviation of the entire population. s and σ are related in that s is used to estimate σ.) Table 1 shows the values of s and of the maximum deviation Δ_{max} from the mean. The results show that the combined effects of speckle and nonuniformity are of the order of 4 to 5%; detector noise accounts for less than 1% of the fluctuation. For most consistent results, the power meters should be illuminated with a spot somewhat larger than 1 cm, as suggested above; the larger the spot, the less the fluctuation due to speckle noise.

Table 1. Results of diffuser nonuniformity scan.

Meter	Sample Standard Deviation s	Maximum Deviation Δ_{max}
NWK 1	4.8%	9%
NWK 2	5.0	12
NWK 3	3.7	10

NWK 1

NWK 2

NWK 3

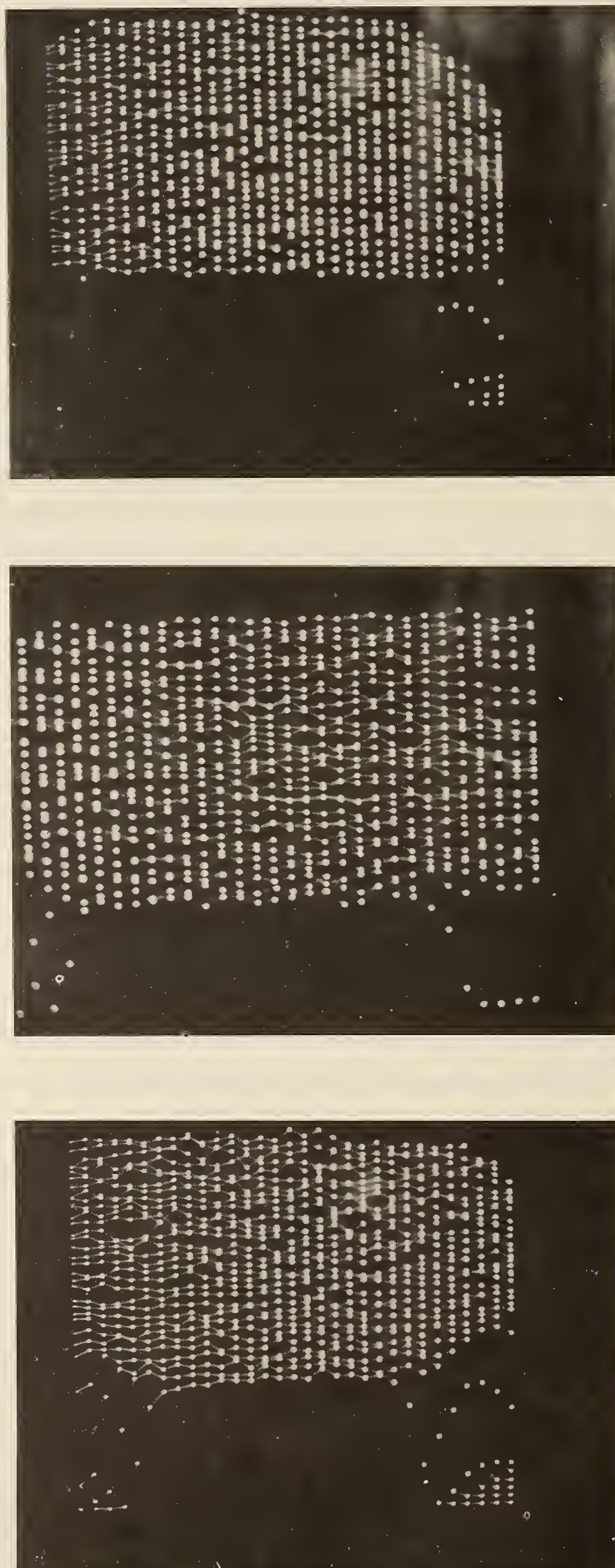


Figure 9. Results of the uniformity scan of three power meters.

4. Absolute Calibration

To determine the relationship between the instantaneous laser power and the power-meter output (as measured by the digitizer), we calibrated three of the power meters with a pulsed YAG laser and a computer processing system. The impulse-response duration of the power meter was much less than the duration of the laser pulse.

We also verified the results by calibrating the meters with a continuous, 1-watt YAG laser and lock-in amplifier techniques.

As yet, there is little calibration history on these meters. We therefore recommend that others who build similar meters use them in conjunction with a calibrated energy meter until sufficient history exists that confidence may be placed in the calibration of the power meters. The main difficulty we can foresee may be in the use of the white paint. Whereas this paint is designed as a reflectance standard for use in colorimetry and spectrophotometry, and for use in integrating spheres, it may be degraded by high-power laser beams.

Pulsed-Laser Calibration. Figure 10 shows the arrangement used for the calibration of the meter with a pulsed laser. The laser beam is split approximately fifty-fifty; one half is directed into the power meter and the other half into a calorimeter. The calorimeter has been calibrated against the National Bureau of Standards C-series calorimeter [8]. The beam splitter, a quarter-wave stack designed for use in a glass laser cavity, is calibrated in place as we discuss below. We shall also discuss measurement errors and systematic errors below.

The laser is operated in a single-shot mode. Each pulse carries about 150 mJ. The output of the power meter is acquired by a transient digitizer and processed by computer. Figure 11 shows the response of the power-meter-and-transient-digitizer combination to a typical pulse. When correctly calibrated, the vertical scale may be used to determine the peak power of the pulse.

We used the computer to integrate the output of the transient digitizer. We monitored the energy of each pulse with the calorimeter and calculated the responsivity R of the power meter (ampere/watt) by using the relation that

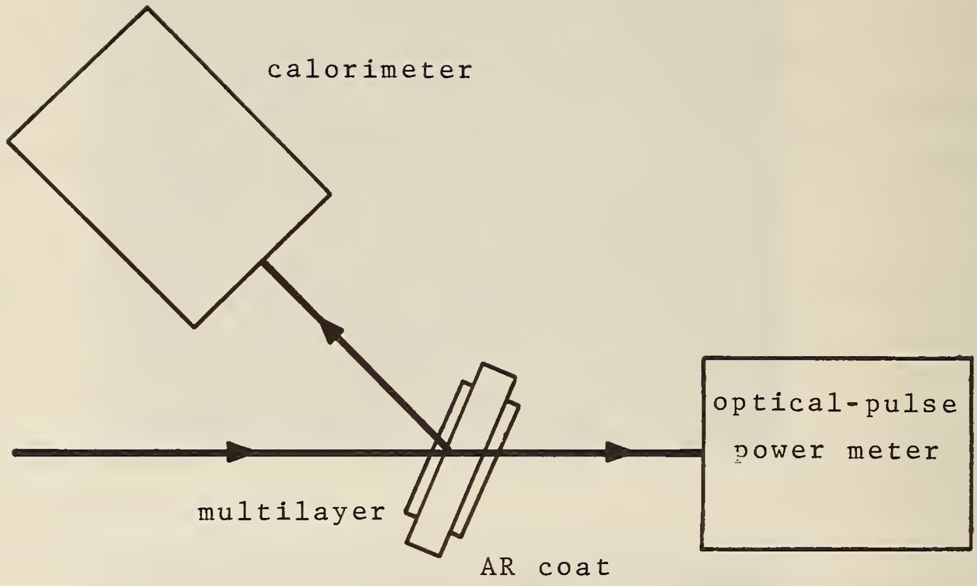


Figure 10. Calibration of the optical-pulse power meter with the pulsed YAG laser.

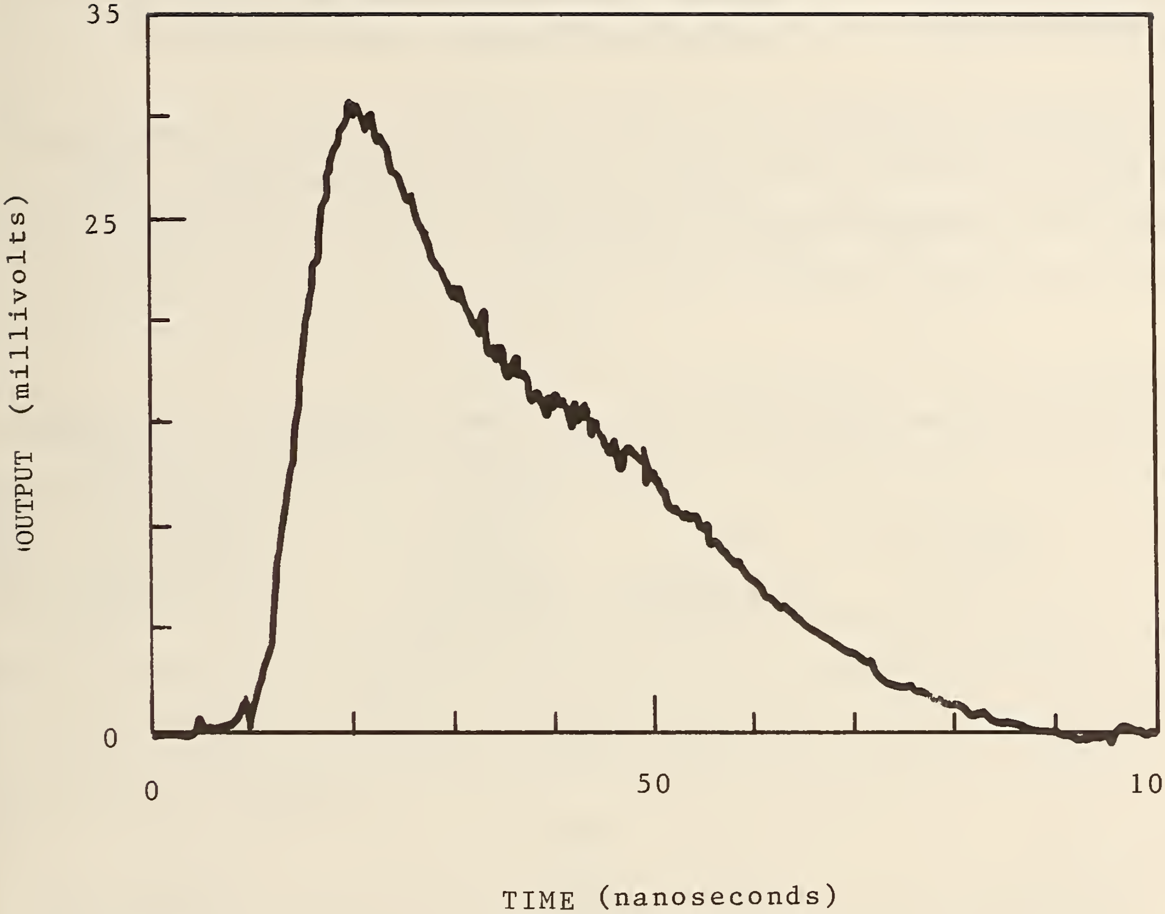


Figure 11. Typical pulse emitted by pulsed YAG laser, displayed by the transient digitizer.

$$R = \frac{\text{integrated output (volt sec)}}{\text{calorimeter output (joule)} \times \text{splitter ratio} \times 50\Omega}, \qquad (6)$$

where the splitter ratio is defined as the ratio of transmitted energy to reflected energy and where the transient digitizer's input impedance is assumed to be precisely 50Ω.

To eliminate the effects of scatter in the laser output, we calculated the responsivity for each of several shots and took the mean value as our best estimate of the responsivity of the instrument. The results are shown in column 2 of table 2.

Table 2. Power meter responsivity and error limits, pulsed-laser measurements.*

	Responsivity R	Number of Samples n	Sample Standard Deviation s	Statistical Limit of Error (SLE)	Total Limit of Error (TLE
NBS 1 U	2.303×10^{-10} A/W	5	0.15×10^{-10} A/W	±7.7%	13%
L	2.099	8	0.08	±3.2	8
NWK 1 U	2.424	10	0.12	±3.6	8
L	2.286	10	0.11	±3.4	8
NWK 4 U	1.880	10	0.08	±2.9	8
L	2.268	10	0.10	±3.3	8
Mean	2.210	--	--	--	--

*U and L refer to the upper and lower detectors in each power meter.

If the power meters were always used with the same transient digitizer (and plug-in), then it would be acceptable to compute the responsivity R' in units of volt/watt, where $R' = 50R$. To calculate R as we have done in eq (6), we must know the input impedance of the digitizer. We have found it to be almost precisely 50Ω at zero frequency, but we experienced difficulty measuring the impedance at higher frequencies because the BNC connectors were not repeatable. The evidence seems to be, nonetheless, that the input impedance may differ by a few ohms at frequencies higher than 100 MHz. The slight impedance mismatch at these frequencies will affect the impulse response of the instrument, and we discuss the effect of finite impulse width below.

Transient-Digitizer Calibration. Because the power meters are not always used with the same instrumentation, we found it necessary to calibrate separately the transient digitizer with its plug-in unit. On the appropriate scale, we found the vertical scale to be inaccurate by about 2.5% over the voltage range that resulted from the photocurrent.

In addition, we found the digitizer to vary from linearity by approximately 1%. To assess the effects of this nonlinearity on the measurement of pulses, we performed the following experiment.

We used an oscillator to generate a 10-MHz sine wave, whose harmonics we measured to be at least 35 dB less than the fundamental. We acquired about two cycles of the sine wave with the transient digitizer and stored the data in the computer. We used this information to calibrate the time base, which we found accurate to about 4%.

We generated a sine function digitally and adjusted its frequency and amplitude to match as accurately as possible the sine wave acquired by the digitizer. To this end, we computed the deviations of the acquired waveform from the true sine function and displayed the deviations as a function of time. We adjusted the computed sine wave until we minimized the deviations throughout the central 8 cm of the 10-cm display, as shown in figure 12. This figure shows that the digitizer nonlinearity is most significant in the first centimeter of the display; therefore, we confine our interest to the central portion of the display, where we estimate the average deviation to be about 1.5%. Likewise, we have taken all our data within the central portion of the display. Thus, digitizer nonlinearity contributes approximately 1.5% to the total limit of error.

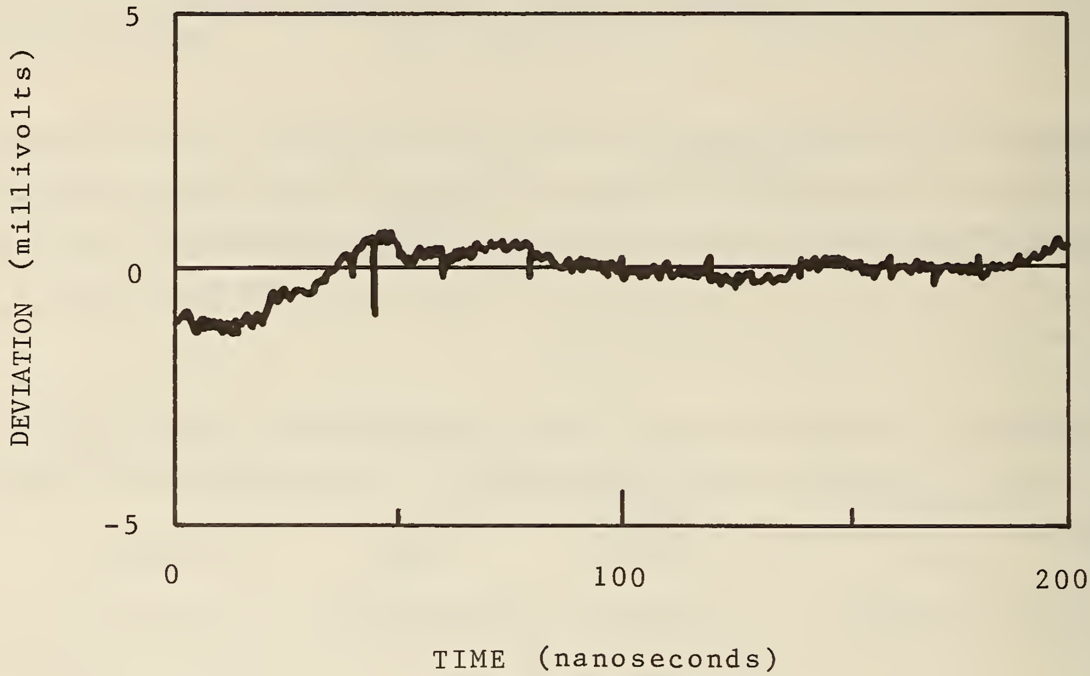


Figure 12. Deviation between acquired sine wave and calculated sine wave.

Beam-Splitter Calibration. We calibrated the beam splitter in place by using two calorimeters and an interchange method [9]. Once the beam splitter was calibrated, neither the laser nor the beam splitter was moved during the duration of our experiments.

Suppose that we have two energy meters (or power meters in the case of a continuous laser) that are known to be linear detectors. They may be completely uncalibrated, and they need not be identical or nearly identical. To calibrate the beam splitter, we arrange the energy meters in the manner shown in figure 13a. If the (possibly unknown) calibration factor of meter M1 is F_1 and that of meter M2 is F_2, then the beam-splitter ratio R_a is precisely

$$R_a = \frac{M_2 \ F_2}{M_1 \ F_1} , \tag{7}$$

where M_1 and M_2 are the uncalibrated meter readings, for example in volts if the meters use thermopiles as detectors. The beam-splitter ratio is not the reflectance, but the ratio of reflected energy to transmitted; in general, it is not possible to derive the reflectance from the splitter ratio.

We now interchange the calorimeters as in figure 13b and measure the splitter ratio again. In this case, R_b is precisely

$$R_b = \frac{M_1' \ F_1}{M_2' \ F_2} , \tag{8}$$

where M_1' and M_2' are again uncalibrated meter readings.

The values of R_a and R_b in the two expressions, though unknown because the R's are unknown, are in principle exactly equal; therefore, it is a tautology to write that

$$R = (R_a \ R_b)^{1/2} \tag{9}$$

or

$$R = \left(\frac{M_2}{M_1} \times \frac{M_1'}{M_2'} \right)^{1/2} = (r_a \ r_b)^{1/2} , \tag{10}$$

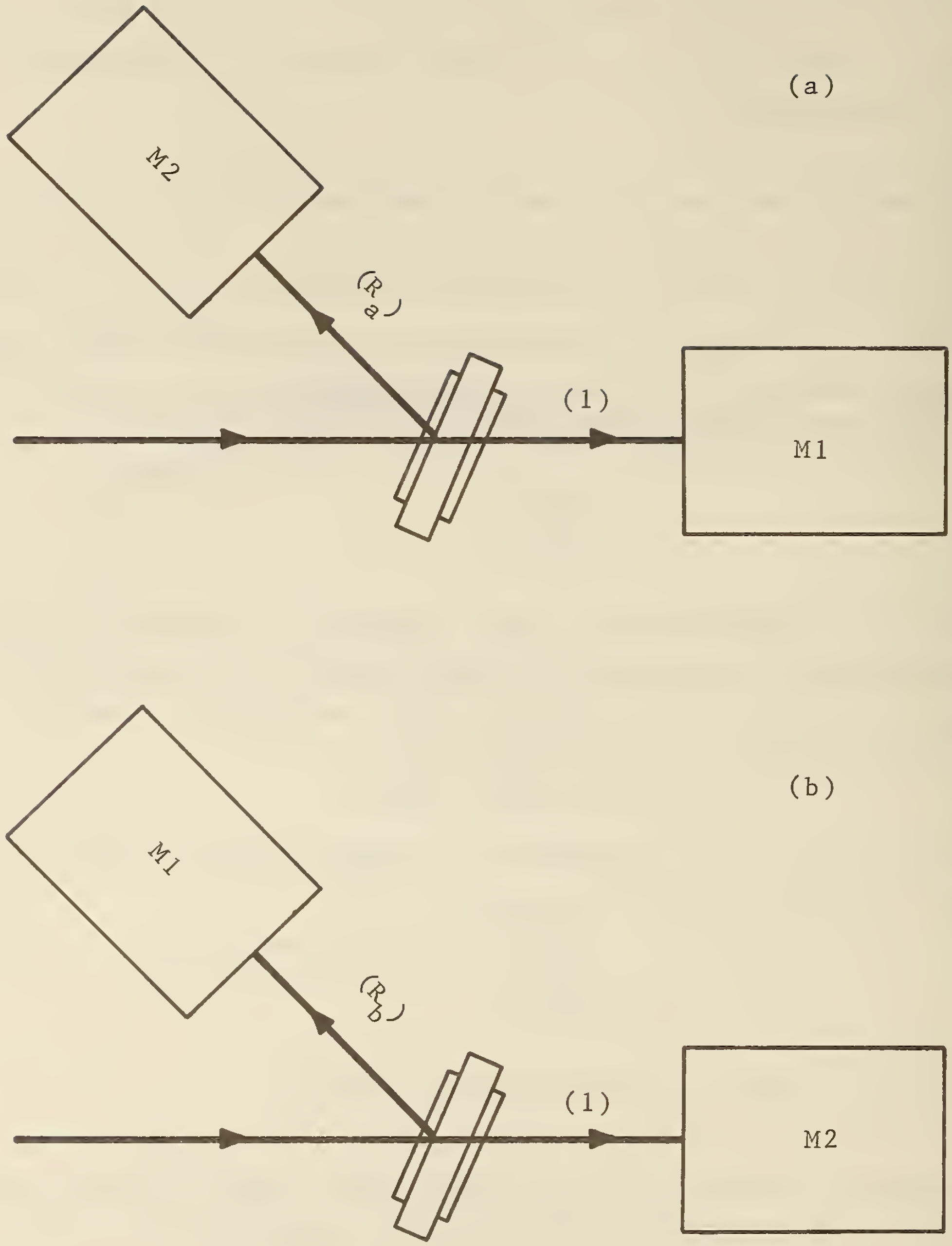


Figure 13. Calibration of beam splitter by an interchange method.

where r_a and r_b are the ratios of the (uncalibrated) meter readings before and after the meters are interchanged, and where R is the actual value of the splitter ratio.

Thus, we can measure R without knowing the calibration coefficient of either meter. The value of this technique is to reduce experimental error greatly by eliminating the calibration errors in the two meters; all that is needed is the knowledge that the meters are linear.

We calibrated the beam splitter by measuring M_1 and M_2 and calculating r_a for each of 10 shots. We interchanged the meters and calculated r_b in the same manner. We calculated the arithmetic means of the sets of r_a and r_b and calculated a best estimate of R from the geometric mean of the two calculated arithmetic means, as suggested by eq (10).

Table 3. Calibration of beam splitter.

	Splitter Ratio r (Raw Data)	Number of Samples	Sample Standard Deviation s	SLE
Figure 7a	1.398	10	0.008	0.4%
Figure 7b	1.001	10	0.008	0.5
Geometric Mean	1.183			0.5

Continuous-Laser Calibration. As an independent verification of the calibration, we also calibrated the power meters with the 1-watt, continuous laser. The experimental arrangement is shown in figure 14. The beam was focused onto a mechanical chopper and modulated at a frequency of approximately 1 kHz before being allowed to fall on the diffuser. The output of the detector was measured by using a lock-in amplifier and a digital voltmeter.

We calibrated the lock-in amplifier by replacing the power meter with a 1-kHz square-wave generator that had the same 50% duty cycle as the mechanically chopped laser beam. We measured the output of the generator by

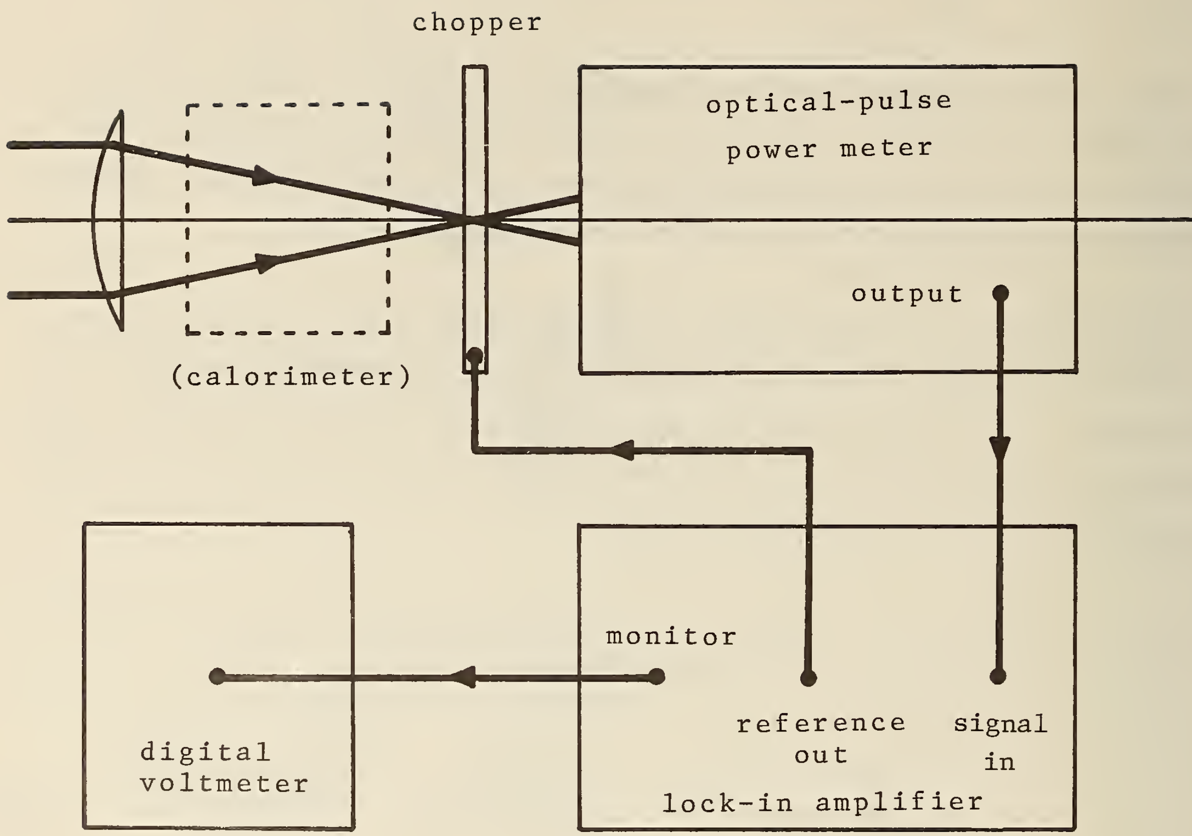


Figure 14. Calibration of the optical-pulse power meter with the continuous YAG laser and lock-in amplifier techniques.

reducing its frequency to less than 1 Hz and using a digital voltmeter. (Monitoring the output of the generator on an oscilloscope showed no detectable change in voltage with frequency.) We further used the generator to check the input impedance of the lock-in amplifier at 100 Hz by placing a precision resistance box in series with the amplifier input and adjusting the resistance until the output of the amplifier was reduced precisely in half. At this low frequency, inductive effects in the resistance box are negligible, so we conclude that the input impedance of the amplifier is equal to the resistance of the series resistance box. The value we measured was almost precisely that claimed by the manufacturer.

We measured the power emitted by the laser with a calorimeter that had also been calibrated against the C-series calorimeter. Because the laser was relatively stable, we merely replaced the pulse-power meter with the calorimeter; we could have achieved greater precision with the beam splitter technique of the previous section.

Finally, we calculated the responsivity of the power meter from the relation that

$$R = \frac{\text{[DVM reading} \times \text{calibration factor of lock-in amplifier] (volt)}}{\text{power meter output (watt)} \times \text{input impedance of amplifier (ohm)}} \tag{11}$$

where the units of R are again ampere/watt.

The results of this measurement are shown in table 4. In all cases, tables 2 and 4 agree to about 10% or better.

At other wavelengths, the meters must be recalibrated, in part because the responsivity of a given diode will not be known accurately enough from a generic curve.

5. Analysis of Errors

In this section, we estimate the precision of the two measurements and express the results as a limit of error. We take a comparatively conservative approach and treat errors that arise independently of each other as systematic errors. For example, if there were an actual error of 1% owing to random error in the original calibration of the C-series calorimeter, the error, which cannot be computed nor corrected, would appear as a systematic error when the calorimeter is used as a standard. There is no reason to believe that errors that arise from other sources will wholly or partly cancel the calibration error; that is, errors are likely to be correlated. Therefore, we shall treat each error in turn as a systematic error and add errors algebraically (rather than add the square root of the sum of the squares, as is done with uncorrelated errors such as those that involve sequential measurements of the same kind).

Statistical Limit of Error. For the pulsed-laser calibration, we computed the standard deviation s of the sample, where

$$s^2 = \frac{\sum \text{(deviations from mean)}^2}{n-1} . \tag{13}$$

Both s and the number n of measurements are shown in table 2. We estimate the statistical limit of error SLE (or confidence interval) by using Student's t function,

$$\text{SLE} = \frac{t\ s}{\sqrt{n}} . \tag{14}$$

We use the values of t appropriate to a 95% confidence level and n-1 degrees of freedom. Thus, excluding for the moment other error sources, there is about one chance in twenty that the mean value of the responsivity is in error by more than the SLE [10].

Beam-Splitter Ratio. According to eq (9), the beam-splitter ratio is equal to $(r_a r_b)^{1/2}$. If the SLE's of r_a and r_b are Δ_a and Δ_b, then we may write that

$$R \pm \Delta R = [(r_a \pm \Delta_a)(r_b \pm \Delta_b)]^{1/2}, \tag{15}$$

from which we conclude that ΔR (the SLE of R) is about

$$\Delta R = \frac{1}{2} (\Delta_a + \Delta_b). \tag{16}$$

Using the data presented in table 3, we conclude that the total SLE of the beam-splitter ratio is about 0.5%.

Systematic Errors Resulting from Finite Impulse Response. If the impulse response of the detector is not a delta function, then the electrical pulse that is recorded will be slightly longer than the incident optical pulse. In addition, the peak voltage will be slightly lower than the value expected for the ideal case. This results in a systematic error whose importance depends on the relative durations of the impulse response and the laser pulse. If necessary, the error can be corrected by accurately modeling the laser and the detector either digitally or analytically. In our system, as we shall show, the effect is small and need not be corrected.

To assess the effect of the finite impulse width, we model the system in the following way. We approximate the impulse response of the power meter with a Gaussian function,

$$h(t) = (1/\tau) \text{ Gaus } (t/\tau), \tag{17}$$

where

$$\text{Gaus } (t) = \exp(-\pi t^2). \tag{18}$$

The duration 2τ of the impulse response is about 1.3 ns (measured between the times when the photocurrent is 1/e times the maximum). The factor of $1/\tau$ in eq (17) is included to normalize the impulse response to unit area.

The detected laser pulse is not symmetrical. Its duration is approximately 32 ns (again measured between 1/e points), which is over one order of magnitude greater than the impulse width. We therefore assume that the actual laser pulse closely resembles the detected pulse.

Table 4. Meter responsivity, continuous-laser calibration.

		Responsivity $\mathcal{R}$	Total Limit of Error (TLE)
NBS 1	U	2.561×10^{-10} A/W	8%
	L	2.344	8%
NWK 1	U	2.623	8%
	L	2.273	8%
NWK 4	U	2.010	8%
	L	2.242	8%
Mean		2.342	--

Change of Wavelength. We calibrated the power meters using Nd:YAG lasers, whose wavelength is nominally 1.064 μm. Because the responsivity of the photodiodes is a strong function of wavelength, the calibration is accurate at that wavelength only.

To assess the effect of a wavelength change, we examined the manufacturer's curve of responsivity as a function of wavelength. In the region around 1.06 μm, we find that $\mathcal{R}$ varies approximately as $\exp(-0.0035\ \lambda)$ for λ in μm. Thus, if we change λ by a small amount $\Delta\lambda$, then the fractional change $\Delta\mathcal{R}/\mathcal{R}$ in $\mathcal{R}$ is given by the expression

$$\Delta\mathcal{R}/\mathcal{R} = -\ 0.0035\ \lambda. \qquad (12)$$

The wavelength of a typical glass laser may be 1.060 μm, or about 4 nm less than that of the YAG laser. This change of wavelength would result, according to eq (12), in a systematic error of about -1.4%; in principle, the systematic error may be corrected. Nearly all neodymium lasers oscillate within 10 nm or so of 1.064 μm. Thus, the meters may be used with any neodymium laser with only a slight systematic error that must be corrected.

The detected pulse can be fairly closely approximated by the convolution (or sum) of two negative-exponential functions, but this form is not convenient for calculation. Instead, we approximate only the leading edge with a Gaussian function,

$$f(t) = \text{Gaus}\ (t/T), \tag{19}$$

where T is approximately 7 ns. Because we are right now interested only in the peak of the detected pulse, this approximation will be sufficient.

If we assume that the laser pulse is described (until the peak) by eq (19) and the impulse response of the detector by eq (17), then the detected pulse is described by the convolution f*h of h with f [11]. Applying the convolution theorem, we readily find that

$$f*h = [1 + (\tau/T)^2]^{-1/2}\ \text{Gaus}\ [t/(\tau^2 + T^2)^{1/2}]. \tag{20}$$

The maximum value of the convolution is equal to $[1 + (\tau/T)^2]^{-1/2}$, whereas the maximum value of f is 1. (The duration of the convolution, incidentally, is $(\tau^2 + T^2)^{1/2}$.) Therefore, the effect of the impulse width is to lower the peak of the detected pulse by

$$[1 + (\tau/T)^2]^{-1/2} \cong 1 - \frac{1}{2}\ (\tau/T)^2. \tag{21}$$

Using the values of τ and T stated above, we estimate the systematic error to be about -0.5%. Because it is so small, we shall make no attempt to correct for this effect, but merely include the systematic error in our error budget, adding the 0.5% without regard to its sign.

In addition to having a finite duration, the impulse response displays a "tail" at long times. (We used an impulse generator to verify that the tail results from the transient digitizer and is not an artifact introduced by the mode-locked laser.) The peak of the tail is about 7% of that of the impulse response itself, and the tail is displaced by about 2.7 ns from the main waveform. Such a sizeable tail could produce a significant error in the measurement of peak power, even though it might not influence the shape of the waveform significantly.

We model the tail by assuming that it is the result of a reflection; thus, we rewrite the impulse response h(t) as

$$h'(t) = h(t) + Bh(t-t_o), \tag{22}$$

where B is the relative height of the reflection and t_o is the time at which the reflection appears with respect to the main waveform.

If f(t) is the actual laser pulse, then the observed waveform g'(t) is described by

$$g'(t) = f(t)*h(t) + B\ f(t)*h(t-t_o), \tag{23}$$

or [11]

$$g'(t) = g(t) + Bg(t-t_o). \tag{24}$$

Therefore, if the peak of the main pulse occurs at t=0,

$$g'_{max} = g_{max} + Bg(-t_o), \tag{25}$$

where g_{max} is the quantity we seek. We use figure 6 to measure $g(-t_o)$; the presence of the tail results in a systematic error that requires a correction factor of about 0.94; this correction is included in the values in table 2, column 1.

The largest errors involved in calculating the correction factor are in the measurements of B and t_o. Assuming that we can measure B to 1 part in 20, we estimate an error of about 0.3% from this source. To calculate the error that arises from uncertainty in measuring t_o, we assume that we can measure accurately in figure 6 to about 0.5 mm. This results in an uncertainty in g_{max} of no more than 0.2 or 0.3%.

If the tail cannot be modeled accurately as a reflection, then the uncertainty is somewhat greater than the half percent or so calculated above. Therefore, we conservatively add a full percent to the error budget enumerated in table 5a.

Other Calibration Errors. The systematic error of the calibration of the C-series calorimeter is currently about 1.4% (99% confidence level). The use of a secondary standard introduced an additional error of 0.2% in the case of the pulsed-laser measurements and 2% in the case of the continuous-laser measurements, where a different calorimeter was used. We estimate that the transient digitizer introduces an error of 1.5%. (See table 5 for a compilation of measurement errors.)

We therefore conclude that the total limit of error (TLE) of the pulsed measurement is about equal to the SLE plus 5.1%. The values of the TLE are shown in table 2.

Table 5a. Errors of calibation by pulsed laser.

Beam Splitter Calibration	±0.5%
C-series Calorimeter	±1.4
Secondary Energy Standard	±0.2
Impulse Width	-0.5
Impulse "Tail"	±1
Nonlinearity of Digitizer	±1.5
SUBTOTAL	±5.1%
PLUS:	
SLE of Individual Measurements	as in table 2

Table 5b. Errors of calibration by continuous laser.

Calibration and Linearity of Lock-in Amplifier	±1 %
C-series Calorimeter	±1.4
Secondary Power Standard	±2
Laser Stability	±2
Speckle	±2
TOTAL	±8 %

In addition to the 3.4% overall calibration error of the continuous-laser calorimeter, the lock-in amplifier introduces error into the measurement. According to the manufacturer, the lock-in amplifier is linear to about 0.2% of full scale; in our case, this translates to about 1% measurement error. This source of error could have been reduced somewhat by calibrating the lock-in with a voltage source that was close to the voltage that arose as a result of the photocurrent. In addition, the input-calibration voltage was known to a few tenths of a percent.

The laser itself was stable to 1 or 2%. Because we used a substitution technique, rather than a beam splitter, we introduced a source of error that we may conservatively estimate at no more than 2%. We could, of course, have used a calibrated beam splitter and largely eliminated this source of error by taking simultaneous measurements with the power meter and the calorimeter. Last, we take speckle and diffuser-nonuniformity errors to be 2% or less for the several-cm spot that fell on the diffuser.

The total limit of error of the continuous measurement is the sum of the errors just described, or about 8%, as indicated in table 4. (In any future calibrations, it will be reduced by 2 to 4% by using the beam splitter technique and the more precise calorimeter, and by calibrating the lock-in amplifier at very nearly the voltage that results from the photocurrent.)

6. Conclusions

We have calibrated the power meters using both pulsed- and continuous-laser techniques; in our opinion, both methods are important, in part because they serve as a check on one another.

A calibration made with a pulsed laser must be examined carefully to ensure that there is no systematic error resulting from the impulse response of the power meter. Therefore, it is necessary to measure the impulse response of the meter. In addition, a pulsed laser might exhibit a long afterglow that would be difficult to detect but could result in sizeable calibration error. We have eliminated this possibility by calibrating the meters with a well characterized, continuous laser in addition to the pulsed laser.

The continuous-laser measurement can probably be made to have a smaller limit of error, but it is made at a much lower power level than the level of pulsed-laser measurements. Therefore, if the photodiodes are not shown to be linear over a large enough range (say, by removing them from the meters and using the continuous laser), the calibration could be in error. Pulsed-laser calibrations made at nearly the energies at which the meters are to be used will suffer least from the effects of nonlinearity but may suffer from after-glow or other problems.

Thus, we may be confident of a calibration of a pulsed-laser power meter provided that we (1) know the impulse response and either (2) calibrate the meter with continuous-laser techniques and provide some independent verification of linearity over many decades or (3) calibrate with a pulsed laser and provide verification that the electrical pulse is neither distorted by the impulse width of the meter nor has an afterglow or other features that might cause significant calibration error. We have chosen options (1) and (3); that is, to perform the calibration at both high- and low-power levels and to use the two calibrations as independent verifications of one another. If the two calibrations had shown systematic error larger than the estimated TLE, it would have been necessary to check the photodiodes for nonlinearity. Nevertheless, option (1) would still be necessary because option (2) alone does not fulfill the need to deal with the impulse-response problem.

Because of the number of corrections that have to be made, a pulsed-laser calibration is extremely difficult and requires a very well characterized system. Thus, some readers may wish to place slightly more confidence in the continuous-laser calibrations, which differ, on average, by 5 or 6 percent from the pulsed-laser calibrations.

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We describe calibrating several optical-pulse power meters to an accuracy of about 8% or better. The meters are designed for Q-switched neodymium lasers with peak powers in excess of a few megawatts and pulses longer than five or ten nanoseconds. Combined with a fast oscilloscope or a transient digitizer, the meters display the time-domain waveform of the laser emission and thereby allow determination of parameters such as transition duration (risetime, falltime), duration and peak power. We discuss calibrating the meters by both pulsed and cw methods, and show why each method is useful as a check on the other. We treat in some detail the effect of speckle on the use of diffusers as attenuators in power meters such as ours.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Attenuators; calibration; laser; neodymium laser; peak power; power meter; pulsed laser; Q-switched; risetime; speckle; waveform.

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