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A System for Measuring Energy and Peak Power of Low-Level 1.064 μm Laser Pulses

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A System for Measuring Energy and Peak Power of Low-Level 1.064 μm Laser Pulses

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For the first time, transfer standards have been developed for measuring 1.064 μm laser pulses of duration about 10-100 ns, peak irradiance of about 10^{-8}-10^{-4} W/cm^2, and fluences of about 10^{-16}-10^{-11} J/cm^2. These energy and power measurement devices use PIN and APD silicon detectors, respectively, and can be used as stable transfer standards with total uncertainties (random errors computed at the 95 percent confidence level) of 10 to 15 percent. The system for calibrating these transfer standards is also described and consists of a cw Nd:YAG laser beam acousto-optically modulated to provide low-level laser pulses of known peak power and energy. A detailed evaluation of systematic and random errors is also shown.

Key words: APD transfer standards; beamsplitter attenuator; impulse response measurements; low-level laser measurements; modulated cw measurement system; 1.064 μm laser pulse measurements; PIN transfer standards; pulse energy; pulse peak power.

1. Introduction

Various applications, including low-level guidance receivers and range finders, have developed a need for measuring the energy and peak power of low-level 1.064 μm laser pulses. Since such systems are engineered for specific bandwidths, e.g., 10-50 MHz, and since the nominal pulse durations of the lasers are typically 10-30 ns, the peak power of interest is usually the peak of the convolution of the laser pulses with the system impulse response. Also, energy in the tail of the laser pulse (at times longer than the response time of the system) is not usually "seen" by the system.

A system was developed for delivering 1.064 μm laser pulses of known energy and peak power. For the first time, transfer devices with PIN and avalanche silicon photodiode (APD) detectors were developed for measuring low-level energy and power, respectively, of laser pulses. We show in section 1 that if the transfer device is linear and time invariant then

$$\int_0^\infty V(t)\,dt = kE,$$

where V(t) is the response of the device from the laser pulse P(t), k is the calibration constant in V•s/J or V/W, and E is the energy in the laser pulse. From this relation, and since we also show the transfer devices to be linear and time invariant, we could use only one "fast" transfer device for either measurement (with a means for integrating the signal to get the pulse energy). We chose, however, to use separate units since the PIN detectors are not typically fast enough for the measurement of peak power and the APD detectors are more difficult to use and do not exhibit some of the better features of the PIN, e.g., large area, low bias, moderate insensitivity to bias voltage, uniformity of responsivity over the area of the detector, and demonstrated stability with time.

Section 1 reviews the theoretical basis for the measurements discussed in this technical note. There it is shown that the calibration constant is an invariant quantity provided that the instrument

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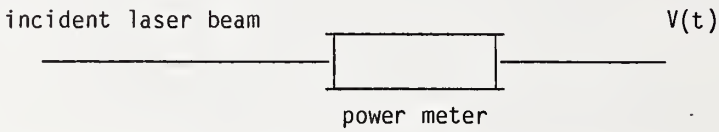
is linear and time invariant over its range of use. Section 2 describes the NBS measurement system for generating pulses of known power and energy (relative to national standards) and describes various tests accomplished to demonstrate the linearity and time invariance of the transfer detector. Sections 3 and 4 describe the transfer standards developed and present data on their construction and use. Section 4 also discusses calibration measurements and their uncertainty.

1.1 The Measurement Problem

Laser power/energy meters consist of devices which give some measurable response, V(t) usually electrical, as a result of absorbing some portion of the incident laser beam.



If the device is linear and time invariant, i.e., gives sinusoidal response for sinusoidal input, then one always has the convolution relationship

$$V(t) = k' \int_{-\infty}^{\infty} G'(t-t')\ P(t')dt', \tag{1}$$

where G'(t-t') is the unnormalized Greens function (impulse response of the system.)

By linear we mean that $V_1(t) + V_2(t)$ is the response of the system to $P_1(t) + P_2(t)$ if $V_1(t)$ and $V_2(t)$ are the responses of the system to $P_1(t)$ and $P_2(t)$, respectively. Time invariance implies the response to P(t-T) is V(t-T) for all T and P(t).

We have assumed in equation (1) that any background reading on the power meter has already been substracted, i.e.,

$$V(t) = V'(t) - C, \tag{2}$$

where

$$V'(t) = k' \int_{-\infty}^{\infty} G'(t-t')\ P(t')\ dt' + C \tag{3}$$

and C is the reading on the power meter before the laser power is incident on the meter (perhaps due to either electronic offset or background radiation).

The properties of linearity and time invariance are very important. Time invariance essentially means that the characterization and response of the power meter is stable with time. Linearity is often difficult to achieve and an instrument must be checked over all the ranges of power, power density, and pulse shapes for which its use is intended. As we shall see, linearity is so important that one should seriously question using a non-linear device as a laboratory standard.[1]

Referring to eq (1) and assuming linearity and time invariance, one can rewrite the convolution theorem in terms of the Fourier transform,

[1]Some devices, e.g., some electrically calibrated pyroelectric detectors are non-linear in the mechanism for achieving their final reading but linear in terms of the final results. The caution does not apply in this case provided one uses only the final results.

$$\tilde{V}(\omega) = k' \, \tilde{G}'(\omega) \, \tilde{P}(\omega), \tag{4}$$

where ~ denotes the Fourier transform defined as

$$\tilde{V}(\omega) = \int_{-\infty}^{\infty} V(t) \, e^{-i\omega t} \, dt, \tag{5}$$

$$V(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{V}(\omega) \, e^{i\omega t} \, d\omega. \tag{6}$$

Now, since $\tilde{V}(\omega)$ is valid for all ω, it holds in particular for ω=0, so we can write

$$\tilde{V}(0) = k' \, \tilde{G}'(0) \, \tilde{P}(0). \tag{7}$$

But since

$$\tilde{V}(0) = \int_{0}^{\infty} V(t) \, dt, \tag{8}$$

$$\tilde{G}'(0) = \int_{0}^{\infty} G'(t) \, dt, \tag{9}$$

and

$$\tilde{P}(0) = \int_{0}^{\infty} P(t) \, dt = E \qquad \text{(the energy)} \tag{10}$$

we obtain the important result

$$k' = \frac{\int_0^\infty V(t) \, dt}{E \int_0^\infty G'(t) \, dt}. \tag{11}$$

Further defining

$$k = k' \int_{0}^{\infty} G'(t) \, dt, \tag{12}$$

we have

$$k = \frac{\int_0^\infty V(t) \, dt}{E}, \tag{13}$$

where k is called the calibration constant and has units of V•s/J or equivalently V/W. It is important to note that k is an invariant and does not depend on the form of P(t) and that a power/energy meter will have the same calibration constant whether used in the energy or power mode. However, we stress again, this result is true <u>only if</u> the power meter is linear and time invariant.

1.1.1 The Case of Use with CW Laser

An important use of laser power meters is for the measurement of CW laser power. Or if a power meter is well characterized, and its calibration constant is known, it is often used with a CW laser to calibrate other power meters. This is often accomplished by capturing the nominally steady CW laser beam with the well-characterized power meter and observing the output reading until a steady state reading is observed. The cw power of the laser is then calculated. The laser of now known power is then captured by the meter to be calibrated and observed until its output reading achieves steady state. The calibration constant can then be determined by dividing the steady state value of the output reading by the known cw power. These steps are usually repeated a number of times so that statistical methods may be applied. Alternatively, a beamsplitter technique may be used.

The authors have observed that some confusion often exists in the relationship of the calibration constant of a power meter as determined by the above process for CW lasers and one obtained using pulse lasers. We will now use the previous theory to demonstrate the calibration constant is the same provided only that the power meter is linear and time invariant. We do this by expressing the Green's function as an over complete set of exponential and harmonic eigenfunctions and explicitly performing the convolution in eq (1). We will then be able to show the calibration constant obtained is identical to that of eq (13).

Suppose a laser beam of CW power, P_o, is incident upon a power meter at time t=0 and continues to irradiate the power meter until it is shut off at time T. We also assume that the time T is long compared to the longest time constant of the device (say at least 10 times the longest time constant). Equation (1) is valid and we have

$$V(t) = k \int_0^\infty G(t-t') \, P(t')dt', \tag{14}$$

where

$$P(t) = 0 \qquad t < 0, \quad t > T \tag{15}$$

$$P(t) = P_o \qquad 0 \leq t \leq T \tag{16}$$

and we have used the "normalized" Green's function G(t-t') defined as

$$G\,(t-t') = \frac{G'(t-t')}{\int_0^\infty G(t)\,dt}. \tag{17}$$

Since we are considering linear time-invariant systems, and since the eigenfunctions of such systems are exponential, we can write

$$G\,(t) = \sum_{n=1}^{\infty} A_n e^{-\alpha_n t}, \tag{18}$$

where we assume the A_n are chosen to normalize G(t) in accordance with eq (17). If ringing is present, which will not be the case for thermal systems, then we assume for conceptual clarity that this ringing is represented by letting some of the α_n be complex pairs, i.e.,

$$\alpha_n = \alpha_n^R + i\,\alpha_n^I, \tag{19}$$

$$\alpha_n' = \alpha_n^R - i\,\alpha_n^I$$

where the R and I superscripts denote the real and imaginary parts, respectively.

For the system we are considering, $\alpha_n^I > 0$ implies $\alpha_n^R > 0$ and implies that any ringing is damped. If $\alpha_n^I > 0$, we also have

$$A_n = A_n^R + i\,A_n^I \tag{20}$$

and

$$A_n' = A_n^R - i\,A_n^I \tag{21}$$

which follow from the fact that exponentials (real or complex) form a linearly independent set of eigenfunctions and the constraint that G(t) is real means $A_n e^{-\alpha_n t} + A_n' e^{-\alpha_n' t}$ must also be real. By referring to eq (18) and using the properties of the convolution, we can write

$$V(t) = k\,P_o \int_o^t \sum_{n=1}^{\infty} A_n e^{-\alpha_n t'}\,dt' \qquad t < T_c \tag{22}$$

$$V(t) = k\,P_o \qquad T_c < t < T \tag{23}$$

$$V(t) = kP_o - kP_o \int_o^{t-T} \sum_{n=1}^{\infty} A_n\, e^{-\alpha_n t'}\,dt' \qquad t > T \tag{24}$$

where T_c is the time equal to at least seven divided by the smallest α_n^R for which $|A_n|>0$, i.e., the power meter has reached its steady state value to within 0.1 percent.

By integrating eqs (22), (23), and (24) explicitly and using eq (17) we get,

$$V(t) = k\,P_o \sum_{n=1}^{\infty} \frac{A_n}{\alpha_n}\,(1-e^{-\alpha_n t}) \qquad t < T_c \tag{25}$$

$$V(t) = kP_o \qquad T_c < t < T \tag{26}$$

$$V(t) = kP_o \sum_{n=1}^{\infty} \frac{A_n}{\alpha_n}\, e^{\alpha_n T}\, e^{-\alpha_n t} \qquad t > T. \tag{27}$$

Equations (25), (26), and (27) show the response of the meter to a CW laser signal, and with reference to eq (26) we see that if we know P_o, the CW power, then by measuring V(t) we determine k, or if we know k, then we can specify P_o. Moreover, we note that this is the same k in eq (13). We could therefore also integrate V(t) and divide this by the energy, P_oT, to determine k. This follows directly from eq (14) or by direct integration of eqs (25), (26), and (27), remembering that we have defined T_c such that we can set

$$kP_o \int_{T_c}^{\infty} G(t)\, dt = 0 \tag{28}$$

with negligible error.

1.1.2 Impulse Response

For many applications of measurement, e.g., energy, pulse energy and CW power, one does not need to known the Greens function or impulse response. Knowledge of linearity and time invariance establishes its unique existence. Its approximate duration is all that really matters for the formulations previously shown. However, if one is interested in measuring pulse shape or peak power of laser pulses then some knowledge of the impulse response is required. This is typically measured by putting a laser pulse, P(t), incident on the detector and measuring the output V(t) where the duration of P(t) is much shorter than V(t) (approximately 10 times). If the impulse response of the detector system is very short compared to the pulses to be measured, then the incident pulse for determining the impulse response need only be short relative to the pulses to be measured.

During an actual measurement of a pulse the measurement result is given by equation (14).

$$V(t) = k \int_{0}^{\infty} G(t-t')\, P(t')\, dt' \tag{14}$$

We are, in effect, saying that if the duration of G(t) is short compared to P(t) then

$$P(t) = \frac{1}{k} V(t). \tag{29}$$

If, however, G(t) is comparable to P(t) in pulse duration then the precise shape of P(t) can only be realized if G(t) is known and one performs a deconvolution process. This is a complex process because of system noise and is not considered in this Technical Note. However, if one is only interested in peak power, which is often the case for laser measurements, and if G(t) is known, then correction factors can be provided to predict $P(t)_{max}$ from the measured V(t). This also requires some a priori knowledge of the "shape" of P(t). However, since many lasers are designed for Gaussian pulses, one can assume a Gaussian shape and then determine potential errors for deviation from a Gaussian shape. A specific example of this is shown in section 4.

2. NBS Measuring Systems Generating Known Pulses

The NBS measuring system generates low-level beams of known peak power and energy for calibrations. Peak power or energy in any one of several beams is determined from the known splitting ratios of a precision beamsplitter, model 1 (BA-1) [1,2,3], and transfer standard measurements of a higher-level beam. Calibrations of detector systems using cw, modulated cw, and Q-switched laser beams showed linear dependence upon power independent of pulse duration.

The beamsplitter attenuator BA-1 is a quartz beamsplitter that can attenuate a laser beam by about 59 dB (depending on the beam used). The principle of operation is shown in figure 1. The uncertainties associated with this attenuator are shown in table 1 and are carefully documented [3]. The attenuations are determined by Fresnel's equations and have been experimentally verified for this device.

The BA-1 attenuator is "supersmooth" quartz, wedged at about 2° with the incoming laser beam oriented at -8.71°. Emerging beams are thus approximately equal angles apart. For each reflection the incident beam is attenuated by a factor of about 30 (14.7 dB). Attenuation ratios used, dependent upon the angle and polarization of the incoming beam striking BA-1, are given in table 1. The various emerging beams are identified by the order number which represents the number of reflections the incident beam has undergone in the beamsplitter. Beams (m=+1) and (m=-1) are associated with one reflection. The plus and minus signs are arbitrarily assigned to the reflections off the back and front of the beamsplitter, respectively. Compared to its transmitted beam, (m=0), the BA-1 device produces beams (m=-1), (m=+1), (m=2), (m=3) and (m=4) with attenuation about 28, 30, $9 \cdot 10^2$, $26 \cdot 10^3$, and $8 \cdot 10^5$, respectively.

Two systems for generating low-level pulses were built and are demonstrated in figures 2 and 3. The modulated cw system in figure 2 uses a cw Nd:YAG laser of variable power. The acousto-optic modulator can produce a cw beam or approximately square pulses of variable pulse duration to a minimum of about 100 ns or 200 ns (depending on pulse shape needs) and to a maximum repetition rate of several megahertz. Peak power or pulse energy in any one of the beams is determined by the known BA-1 beamsplitter ratio and transfer standard measurements of a higher level beam. The transfer standard has been previously calibrated against the C- and the Q-series calorimetric measurement systems [4]. Since the transfer standard reads energy, it will respond to any energy between pulses. If the interval between pulses is very long compared to the pulse duration (as is the case of Q-switched Nd:YAG lasers with pulses of about 10-30 ns duration operating at typical repetition frequencies of about 1 to 30 pulses/s), then very low power levels may produce significant quantities of energy relative to the energy in the main part of the pulse. However, the methods commonly used to measure the energy in a pulse (oscilloscope or transient digitizer) may exclude energy between pulses whereas the transfer standard includes it. The modulated cw system has the following advantages over the Q-switched system: (1) negligible energy lies between pulses regardless of the pulse repetition rate, and (2) the peak power of pulses may be determined from cw power. On the other hand, this system is useful only if the response of the detector system is linearly dependent upon power and independent of pulse duration. A very low-level cw output (~1 percent) leaking through the modulator can be subtracted from transfer standard measurements so that even well-separated pulses can be measured.

A low-level Q-switched system (see fig. 3) was built in order to compare the calibration of devices at 200 and 10-30 ns pulse durations. The system was similar to the modulated cw system except the pulses were generated by a Q-switched Nd:YAG laser and were repetitive only to about 20 Hz. Moreover, since the pulses were typically 30 ns duration and since flash lamps of the laser remained lighted for a few milliseconds, we checked for relatively significant quantities of energy between pulses which may have had power levels below the threshold of the measurement instrumentation of the diode systems. However, the tests revealed insignificant energy between pulses.[2]

In all of the PIN and APD silicon photodiode systems studied, calibrations were linearly dependent upon power and independent of pulse duration within the experimental uncertainty. Therefore, we prefer the modulated cw system since it is much simpler to use.

In the modulated cw system, a 1.064 μm cw beam was reduced to less than 0.7 mm diameter in the acousto-optic modulator. A pulse generator, feeding the modulator power supply, controlled the pulse

[2]With a pockel-cell voltage of the Q-switch removed, the operating laser emitted only very faint 1.064 μm radiation in the area of the main beam. An infrared viewer with a 1.064 μm filter in front of it was used to observe the radiation. Based on these observations, the authors felt that the energy from radiation between pulses was insignificant. Later transfer standards measured negligible energy.

duration and pulse rate of the first diffracted beam leaving the modulator and subsequently entering the beamsplitter attenuator BA-1. A dc-voltage feeding the modulator generated a cw first diffracted beam. The laser, the modulator, and a coated-glass beam attenuator controlled the power and energy into BA-1. A shutter between the modulator and BA-1 timed the input to the transfer standard and systems for calibrations. A lens following the modulator determined the size of the beams. It was about 3 mm diameter at 1 m from BA-1. With a transfer standard in the (m=0) beam and previously calibrated against the NBS reference standards, peak power or the average energy of pulses is determined in the beams of BA-1. For peak power measurements, a function generator alternated the modulator between pulsed and cw power for 10 s each over a 100 s period.

The calibrations of the detector systems were time invariant for the periods of observation which ranged from months to about two years. Pulses used for APD calibrations were about 200 ns and for PIN calibrations were about 100 to 200 ns.

3. NBS Systems Measuring Peak Power And Energy of Low-Level Pulses

These systems can measure 1.064 µm laser pulses that are about 10-100 ns duration, 10^{-8}-10^{-4} W/cm^2 peak power density and 10^{-16}-10^{-11} J/cm^2. The systems are vulnerable to laser beam damage somewhat above these limits. To prevent system damage, input beams may be attenuated and premeasured as described later. The systems are portable and include optical components, avalanche (APD) and PIN silicon photodiodes, electronic instruments, and identifiable cables.

Each APD and PIN transfer standard is in a 7.6 cm wide x 10.2 cm high x 12.7 cm long box attached to a platform. An entrance for the laser beam is on one of the short sides. To measure the peak power and energy simultaneously, an APD and a PIN system, a large collector, a beamsplitter, and optics lie together inside a 29 cm wide, 21 cm high, and 71 cm long box. Each of the latter boxes is identified by the letter P and a digit.

Every diode system is also identified by three letters (APD or PIN referring to avalanche or PIN silicon photodiode, refectively) and two digits separated by a dash. The first digit, 4 or 5, also identifies the system as a PIN or an APD diode, respectively. The second digit identifies the individual instrument. The instrumentation of the APD, the PIN, and P systems is shown in figures 4 through 9.

3.1 APD Systems for Measuring Pulse Peak Power

The APD systems can measure 1.064 µm laser pulses of about 10 to 100 ns duration, 10^{-7} to 10^{-4} W/cm^2 and 11 to 15 percent uncertainty at the 95 percent confidence interval. A 50 Ω, 350 to 500 MHz bandwidth oscilloscope is used for readout. To avoid damage, output pulses should not exceed about 1 V height. The APD detectors can be used with smaller diameter apertures. Calibrations should be divided by the area in the calibration table and multiplied by the new area of the aperture in front of the detector.

See figures 4 and 7. The APD feeds a transimpedance preamplifier (or an amplifier on the same chip), a second wideband amplifier for the lowest levels, and a oscilloscope using 50 Ω input. Accessory equipment includes a negative high-voltage bias supply; a +12 or +15 V amplifier and temperature controller supply for about a 35°C environment of the APD and its amplifier; and a temperature (ma) meter shared with the PIN system for checking the temperature control system. A voltmeter with about 0.01 percent accuracy is needed to read bias voltages. In front of the APD are a lens and a diffuser. They collect and distribute the beam on the 0.07 cm^2 area of the diode. An aperture before the lens determines the area of the beam that APD 5-1, APD 5-3, and APD 5-5 receive. Threaded parts (sleeve, mirror and iris) and covers are provided for alignment or protection. These are removed during measurements.

3.2 PIN Systems for Measuring Pulse Energy

The PIN systems can measure 1.064 μm laser pulses of about 10 to 100 ns duration, 10^{-14} to 10^{-11} J/cm^2 and 6 to 13 percent uncertainty at the 95 percent confidence interval. A megohm, 200 MHz bandwidth oscilloscope and in some systems a pulse height analyzer in parallel with the oscilloscope are used for readouts. To avoid damage of the PIN systems, pulses shaped by charge and linear amplifiers should not exceed 8 to 10 V height. The PIN transfer standards can be used with smaller diameter apertures. Calibrations should be multiplied by the area in the calibration table and divided by the new area of the aperture in front of the detector.

See figures 5 and 6. The one cm^2 PIN diode feeds a charge amplifier, a linear amplifier using bipolar output, an oscilloscope using megohm input and sometimes a pulse height analyzer (PHA). Because the input impedance of the PHA is 600 Ω, the oscilloscope may not be used by itself if it was calibrated in parallel with the PHA without changing the calibration of the system. Finding the signal is easier with the oscilloscope than with the PHA. Accessory equipment include a -180 V bias supply, a + 15 V temperature controller supply for about a 35°C environment of the PIN diode, a temperature (ma) meter for checking the temperature control system, and a pulser for checking the linear amplifier and PHA response if desired. A voltmeter with about 0.1 percent accuracy is needed to read the -180 V bias. The PIN has a permanent, approximately 1 cm^2 aperture in front of it. Threaded parts (sleeves, mirror and iris) and covers are provided for alignment or diode protection. These are removed during measurements.

3.3 APD and PIN System Combined for Measuring Peak Power and Energy of Pulses

An APD and a PIN system combined in a portable box with a large collector, a beamsplitter, and optics can measure 1.064 μm laser pulses of about 10 to 100 ns duration and 10^{-8} to 10^{-6} W/cm^2 and 10^{-16} to 10^{-13} J/cm^2 at about 15 to 19 percent and 6 to 14 percent uncertainty, respectively, at the 95 percent confidence interval. A 50 Ω, 350 to 500 MHz bandwidth and a megohm, 200 MHz bandwidth oscilloscope are used for readouts of the APD and PIN systems, respectively. The PIN system also has a pulse height analyzer readout in parallel with the oscilloscope readout. To avoid damage, APD and PIN system output pulses should not exceed about 0.1 V and 8 to 10 V, respectively. The APD and PIN detectors can be used with smaller diameter apertures. Calibrations should be corrected for the new areas as described in sections 3.1 and 3.2 above.

See figures 4 through 9. In the Pinocchio 1 (P1) and 3 (P3) systems, a beam from several millimeters to 7 1/2 to 10 cm diameter feeds both the APD and the PIN diodes. The beam passes through a fixed aperture, a planoconvex collecting lens with antireflection coatings, and a large beam splitter before entering the PIN diode. The (m=-1) beam reflecting from the front surface of the beam splitter passes through a field lens with antireflection coatings, a collecting lens, and a diffuser before entering the APD. A relatively long tube or nose holds the field lens in front of the APD; hence, the name Pinocchio is given. The fixed aperture referred to above may be replaced with other ones provided the calibrations are corrected for aperture (beam) area. The variable aperture before the fixed one may also be used to control the beam area. This variable aperture and a smaller one before the beam splitter are used for alignment purposes. Targets provided are placed in front of the variable apertures, which are closed during alignment. Diodes and optical components are precisely prealigned and, therefore, never moved.

3.4 Alignment of Systems

To align systems like APD 5-1, APD 5-3, APD 5-5, PIN 4-1, PIN 4-3, and PIN 4-4, (1) the diode is oriented for maximum output or (2) the diode is oriented with mirror attached so that the beam almost reflects back on itself. If the laser has a small beam, it is centered in the iris attached to the mirror. Method (2) was used to calibrate these systems.

To align a system like P1 or P3, the diode entrances are covered with the mirrors or covers provided and alignment targets are inserted in front of the variable apertures (in closed position) before the collecting lens and the beamsplitter. The screw handles of the targets are oriented vertically above the target centers. An incorrect alignment can occur if a target falls between the variable aperture and its frame. A small beam is centered in both targets using their holes and rings. An exact alignment of the beam through both targets is necessary to align the diodes properly.

P1 - PIN 4-5 or P3 - PIN 4-2' with an iris in front of it can also be aligned by tuning for a maximum output with targets removed and variable apertures open. But P1 - APD 5-2 or P3 - APD 5-4 must be aligned as described in the above paragraph.

3.5 Instrumentation

Cables are connected to components as shown in figures 4 and 5. An improper connection can damage or destroy a diode or amplifier. Equipment is run about 1 h before applying biasing voltages to diodes and making measurements. Voltmeters of at least 0.1 percent accuracy are used to measure bias voltages. Bias power supplies are tested at the exact bias voltages before applying them to the diodes. Bias voltage is gradually increased from zero to the exact voltage. Never is it exceeded. At the end of measurements, the bias voltage is gradually decreased to zero. When the exact bias voltage is reached, disconnecting a noisy voltmeter may reduce measurement noise.

Oscilloscope scales are selected so that the center four vertical divisions are used as much as possible. Measurements are maintained within the calibrated regions of the oscilloscope, the wideband amplifier, the linear amplifier and the PHA. Outputs should never exceed those given in the calibration tables of the systems.

3.6 Checking Beam Levels Before Calibrated Measurements

Damage to the APD and the PIN silicon photodiodes and associated amplifiers can occur if the limits given in the table are exceeded. Care must be exercised to stay within these limits, especially in those systems with a large collector.

By attaching the signal output of a PIN system without a collector directly to an oscilloscope 50 Ω input, pulses to about 10^{-1} W/cm^2 (1 or 2 V readout) may be used without damaging the system to adjust the laser level.

The PIN 4-1, PIN 4-3, or PIN 4-4 system is attached directly to the oscilloscope 50 Ω input. It is aligned in the beam and the peak voltage is read. If the output is too low, the wideband amplifier (the modified HP 461A or the HP 462A) may be attached between the PIN and the oscilloscope. The peak power (P) of pulses in W/cm^2 is about

$$P \doteq \frac{V}{20\ \mathrm{V/W/cm^2}}, \quad \text{without 461A or 462A},$$

$$P \doteq \frac{V}{200\ \mathrm{V/W/cm^2}}, \quad \text{with 461A or 462A on 20 dB},$$

and

$$P \doteq \frac{V}{2{,}000\ V/W/cm^2},\ \text{with 461A or 462A on 40 dB},$$

where V in the numerator equals the peak voltage reading of the oscilloscope.

The approximate energy density per pulse (J/cm^2) is $E \doteq P\,\Delta t$, where Δt is the pulse duration.

If the laser output is within the ranges given in the tables for the PIN and the APD systems, then one can begin calibrated measurements.

4. Calibrated Measurements and Their Uncertainty

For calibrated measurements of the APD and PIN systems, the procedures discussed below are followed using the calibration tables and figures. The center four divisions of the oscilloscope scales are used as much as possible. Traces are read to one-quarter division of the scale. Measurements are maintained within the calibrated regions of the instruments. Calibration tables and figures are arranged in numerical order of the identification of the detectors. Instrumentation, calibration, error, range, aperture, and field of view information appear in the calibration tables. APD correction factors for peak voltage and for observed pulse duration appear in the figures 10 through 21.

Pulse height and duration corrections are made for changes of the pulses in going through the APD system. Unity height Gaussian or skewed Gaussian input pulses are convoluted with the unity area impulse response of the system to generate observed output pulses. Skewed Gaussian input pulses had a Gaussian right side with a full width half maximum 10 percent longer than a Gaussian left side. Corrections are calculated to determine the height and duration of the input pulses from the observed output pulses. They are essentially the same for Gaussian and skewed Gaussian input pulses, and are dependent upon the bandwidth of the system.

The systems were calibrated at several angles relative to the incoming beam in four cardinal directions. From these data, we determined the field of view of the calibrations or the correction factor of the calibrations corresponding to the beam divergence.

Modulation system pulses (a) observed by the APD silicon photodiode system and (b) converted by the PIN silicon photodiode system are shown in figure 22. The PHA normally shows a Gaussian distribution of PIN system pulses, the peak of which is used to determine average pulse energy.

Except for the APD 5-5 system which has the APD and preamplifier on a chip, input pulses of about 10 to 30 ns fed into the APD systems tend to ring strongly and overshoot from the inpulse response of the systems. See figure 23 for the typical impulse responses. Consequently, correction factors for the peak voltage versus the observed pulse duration from about 10 to 30 ns are less than one to compensate for pulse overshoot.

Since APD calibrations depend upon the equivalence of the peak power of pulses and cw power, we determined the error for the inequivalence of pulsed and cw power from the variation of the pulse height as pulses were stretched from 200 ns to 600 ns. As a second check we measured the calibration using (a) pulse energy and area and (b) cw power and pulse height.[3] Calibrations (a) and (b) agreed to about one percent.

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[3]Error budgets were also similar.

4.1 APD Measurement Procedures

Observe the peak voltage and pulse duration (FWHM). Traces are read to one-quarter division of the scale. Determine the corrected peak voltage and the actual pulse duration by multiplying the observed values by the correction factors in figures 10 through 19. Select the calibration from tables 2 through 6. Multiply it by the correction factor for the beam divergence when it appears in the table. Divide the corrected peak voltage by the calibration to get the power density (W/cm^2) corresponding to the actual pulse duration.

4.2 PIN Measurement Procedures

Observe the peak PHA reading and/or the positive peak voltage reading of the oscilloscope. Multiply each value by the calibration in tables 7 through 13 to compute the energy density (J/cm^2).

4.3 Assessment of Error

Error budgets for the modulated cw system and for the APD and PIN systems are given in the tables 14-24 at the 95 percent confidence level. They include uncertainties from the transfer standards, the beamsplitter, and measurement and readout instruments. Error budgets and calibrations apply to measurements from ~10 to ~100 ns pulse duration.

The measured sweep accuracy of the oscilloscopes used were within 3 percent over the center 4 to 8 divisions from 5 ns/division to 0.2 μs/division, the region used.

Figures 20 and 21, showing the correction factors for peak voltage and observed pulse duration, compare Gaussian and skewed-Gaussian pulse data[4] for APD 5-3 (with separate preamplifier) and for APD 5-5 (with APD and preamplifier on a single chip) systems. The correction factors are essentially unaffected whether the Gaussian data is skewed or not. Although there is a little difference for type APD 5-3 systems, it is within the error of the oscilloscope sweep.

The authors thank J. J. Skudler for designing and fabricating equipment; Dr. R. J. Phelan for suggesting and pursuing the use of the pulse height analyzer; Drs. G. W. Day, B. L. Danielson, D. L. Franzen, E. G. Johnson, R. J. Phelan, and M. Young, and Messrs. W. E. Case and P. A. Simpson for giving technical assistance; and M. P. Cawley, H. H. Garing, and M. W. Paris of the Instrument Shops Division for making system parts.

They also thank the Department of Defense, Calibration Coordination Group; the Aerospace Guidance and Metrology Center, Newark Air Force Station; and the Metrology Engineering Center, United States Navy for funding this work.

5. References

[1] Beers, Y. The theory of the optical wedge beam splitter. NBS Monograph 146 (1974).

[2] Danielson, B. L.; Beers, Y. Laser attenuators for the production of low power beams in the visible and 1.06 μm regions. NBS Tech. Note 677 (1976).

[3] Danielson, B. L. Measurement procedures for the optical beam splitter attenuation device BA-1. NBSIR 77-858 (1977).

[4] Franzen, D. L.; Schmidt, L. B. Absolute reference calorimeter for measuring high power laser pulses. Appl. Optics 15:3115; 1976 December.

[4]The skewed pulses had a Gaussian right side with a FWHM 10 percent longer than a Gaussian left side.

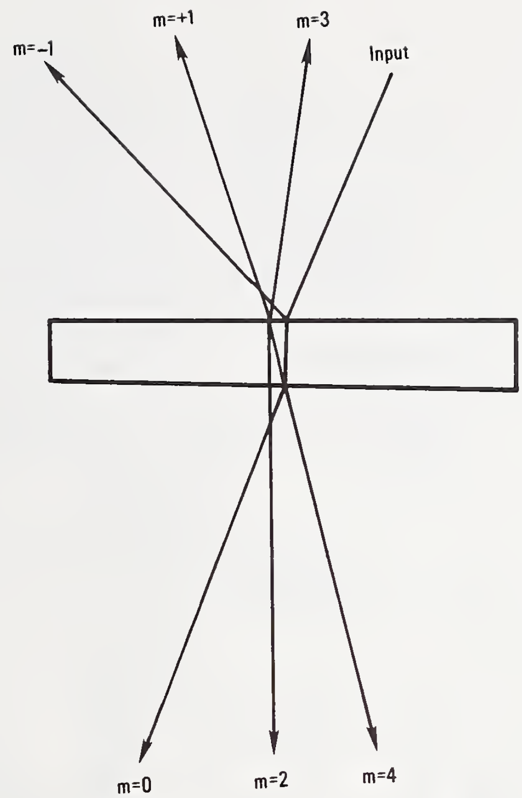


Figure 1. Path of a laser beam in the BA-1 wedged beamsplitter (for clarity, angles are not to scale).

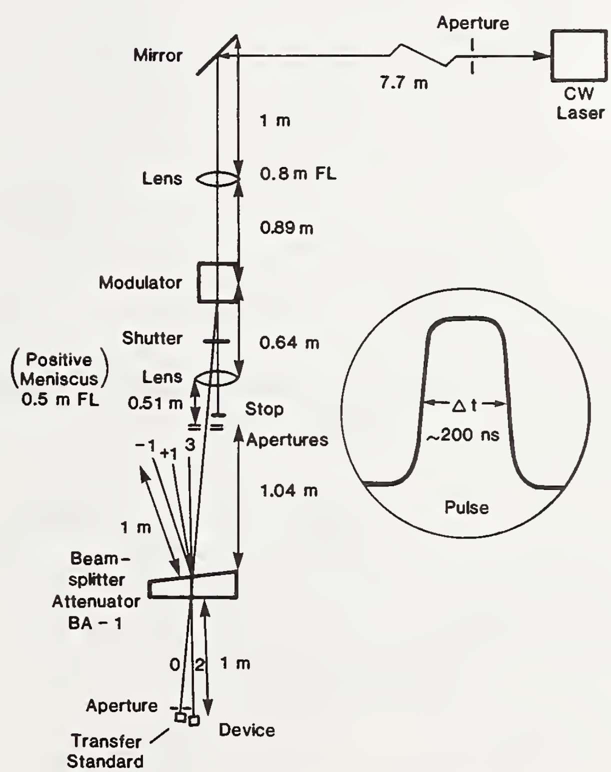


Figure 2. Low-level modulated cw measurement system.

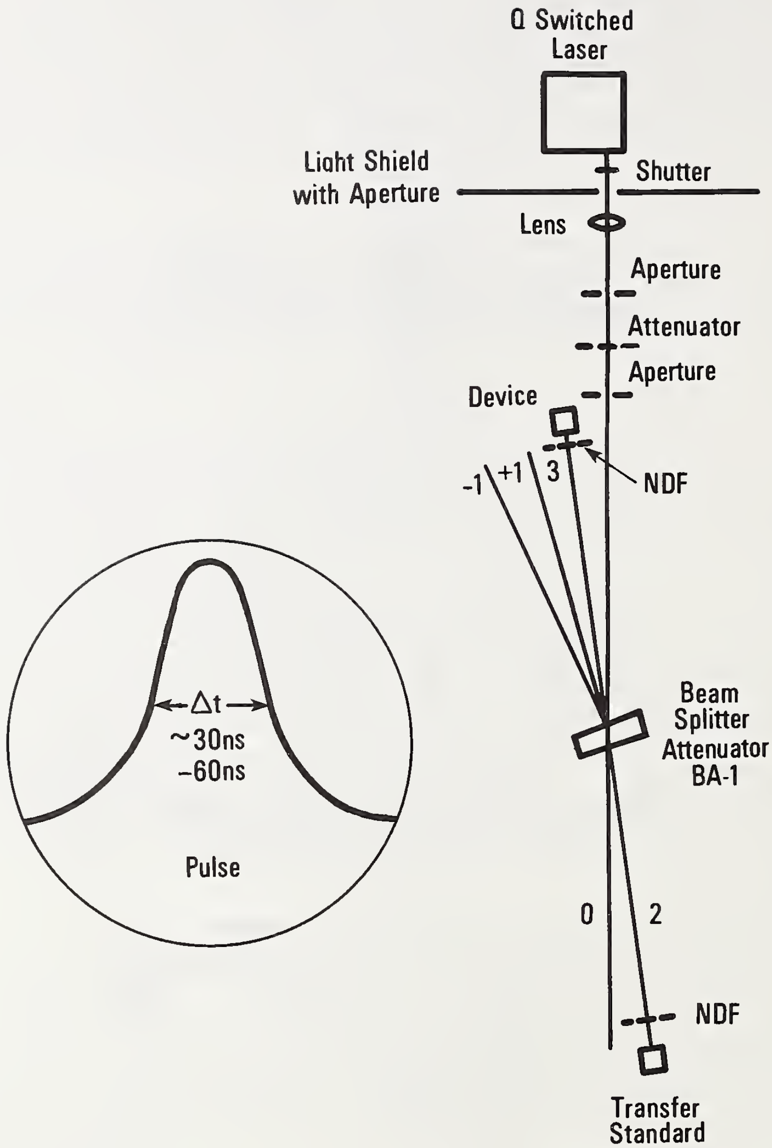


Figure 3. Low-level Q-switched measurement system.

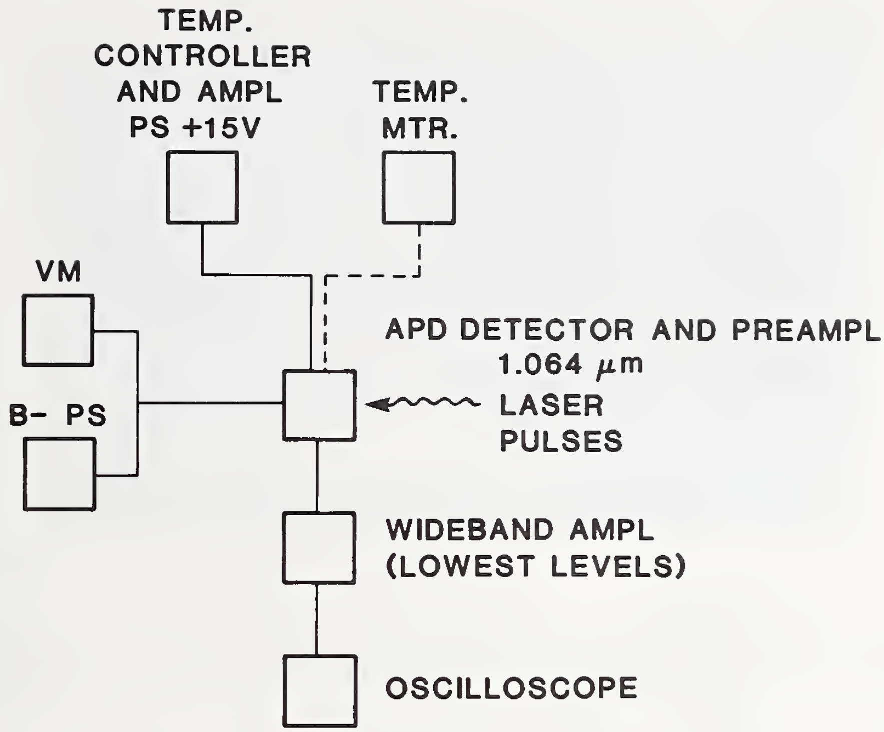


Figure 4. APD system. (P1 and P3 include both PIN and APD systems.)

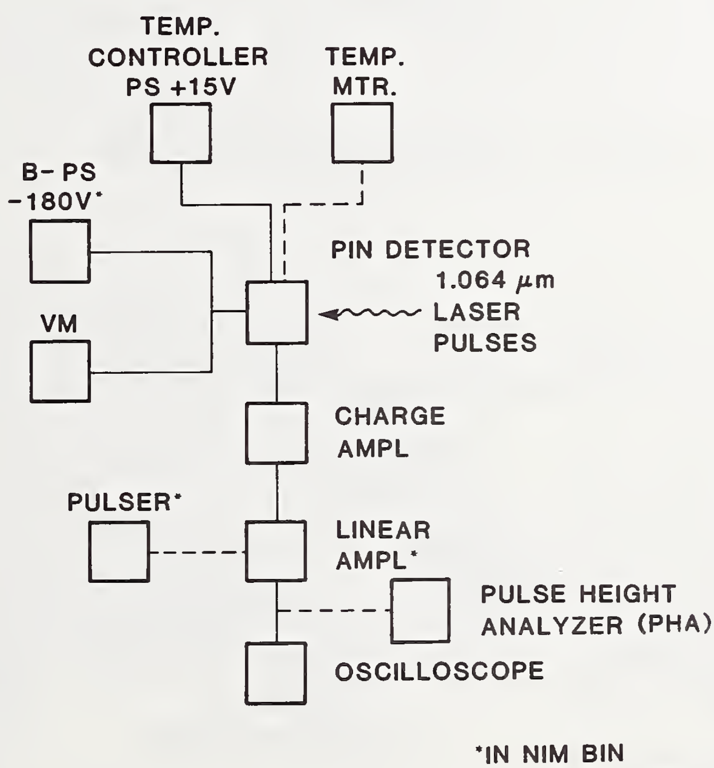


Figure 5. PIN system. (P1 and P3 include both PIN and APD systems.)

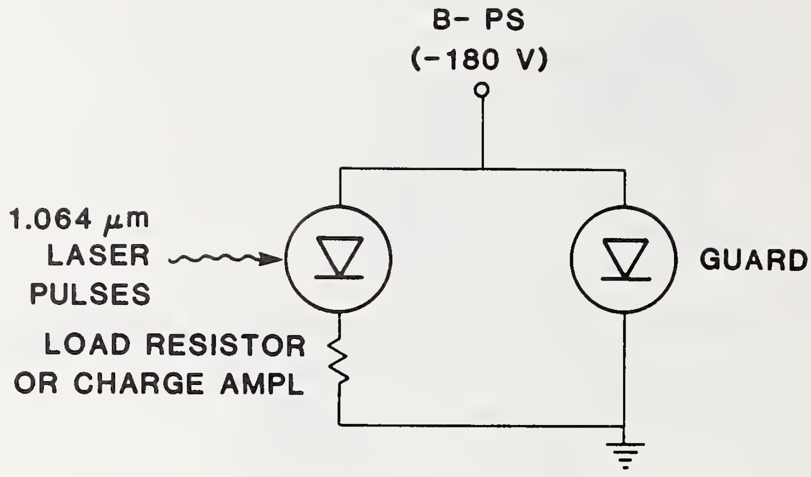


Figure 6. PIN circuit.

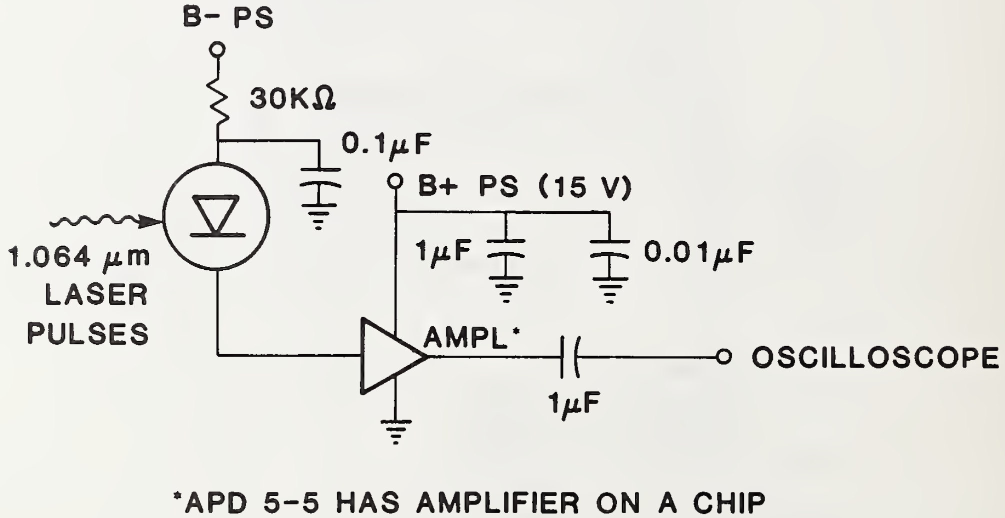


Figure 7. APD Circuit.

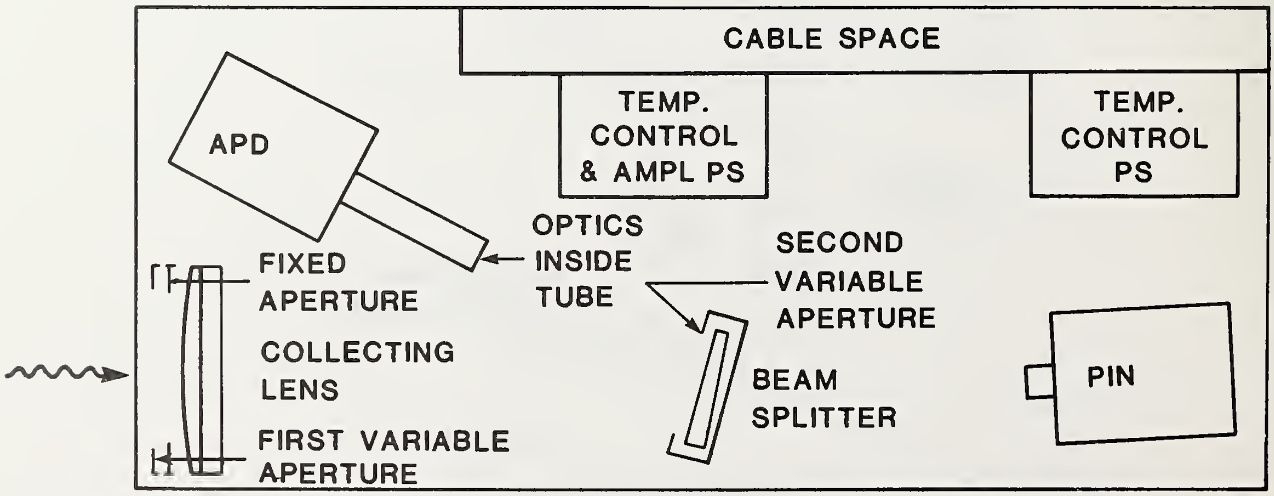


Figure 8. Top view of P1 or P3 system.

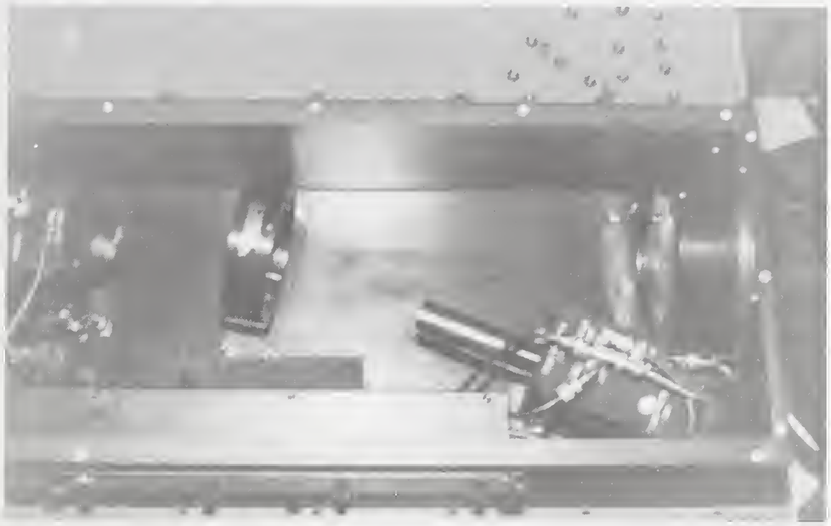


Figure 9. APD and PIN system combined for measuring peak power and energy of pulses. Left to right in the box are the PIN transfer standard, the beamsplitter, the APD transfer standard, and the collector.

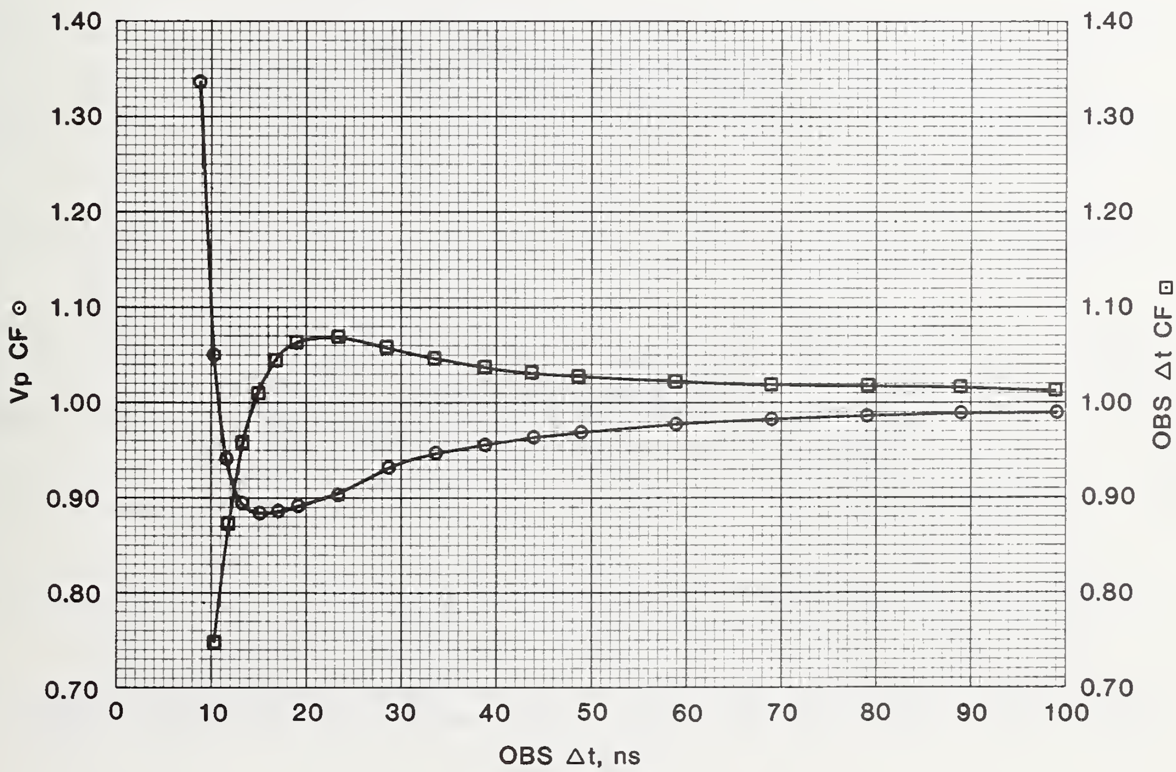


Figure 10. APD 5-1 correction factors (without HP amplifier) for peak voltage (V_p CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt).

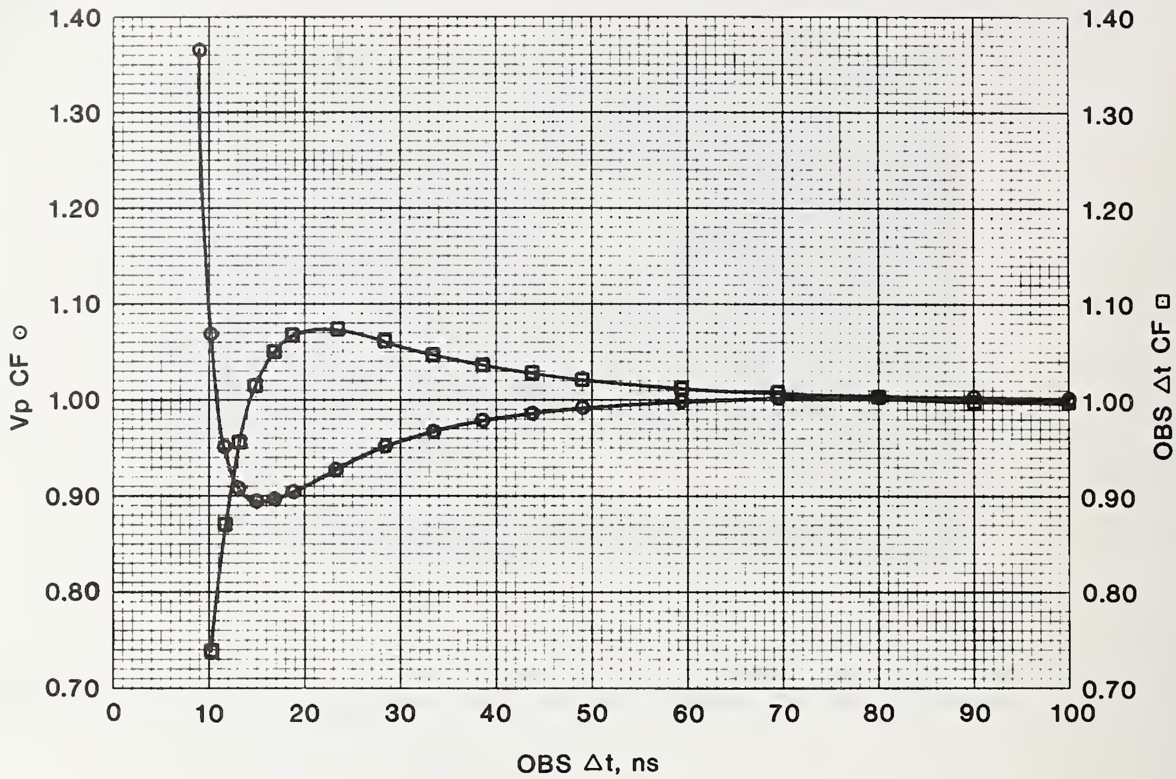


Figure 11. APD 5-1 correction factors (with HP 462A amplifier 20 dB and 40 dB) for voltage (V_p CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt).

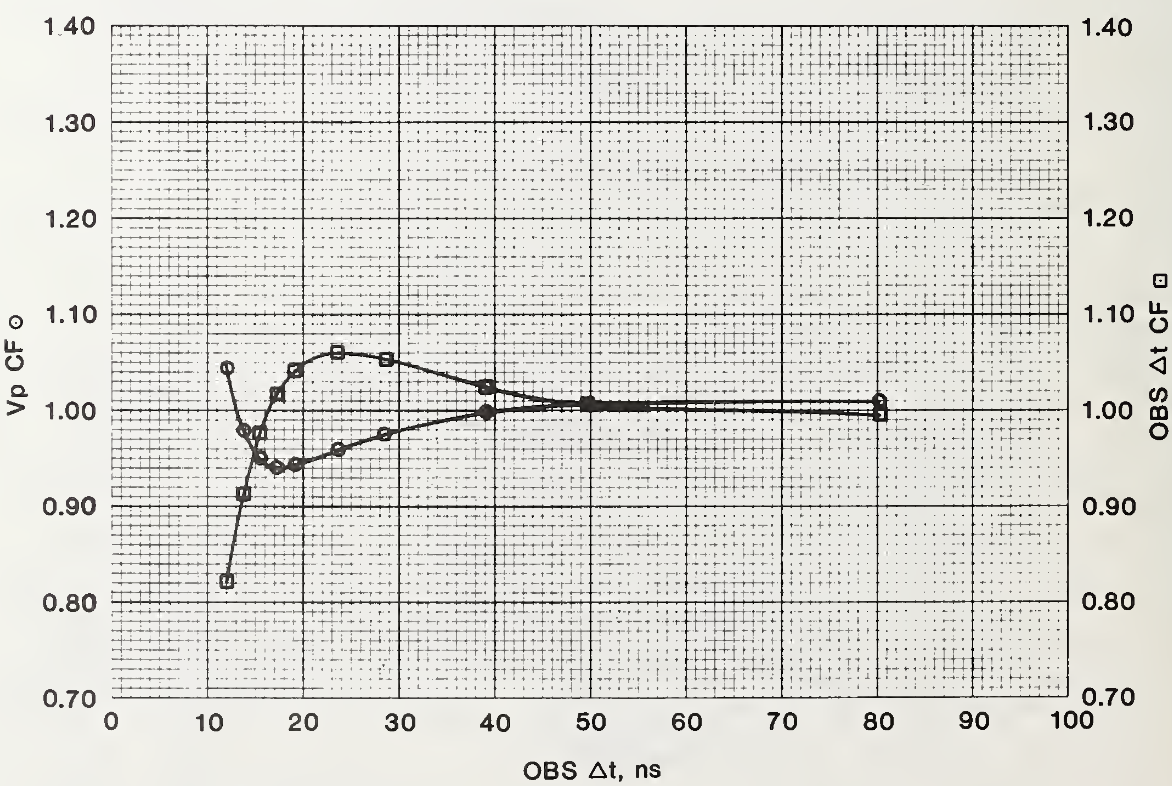


Figure 12. APD 5-2 correction factors (without HP amplifier) for peak voltage (V_p CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt).

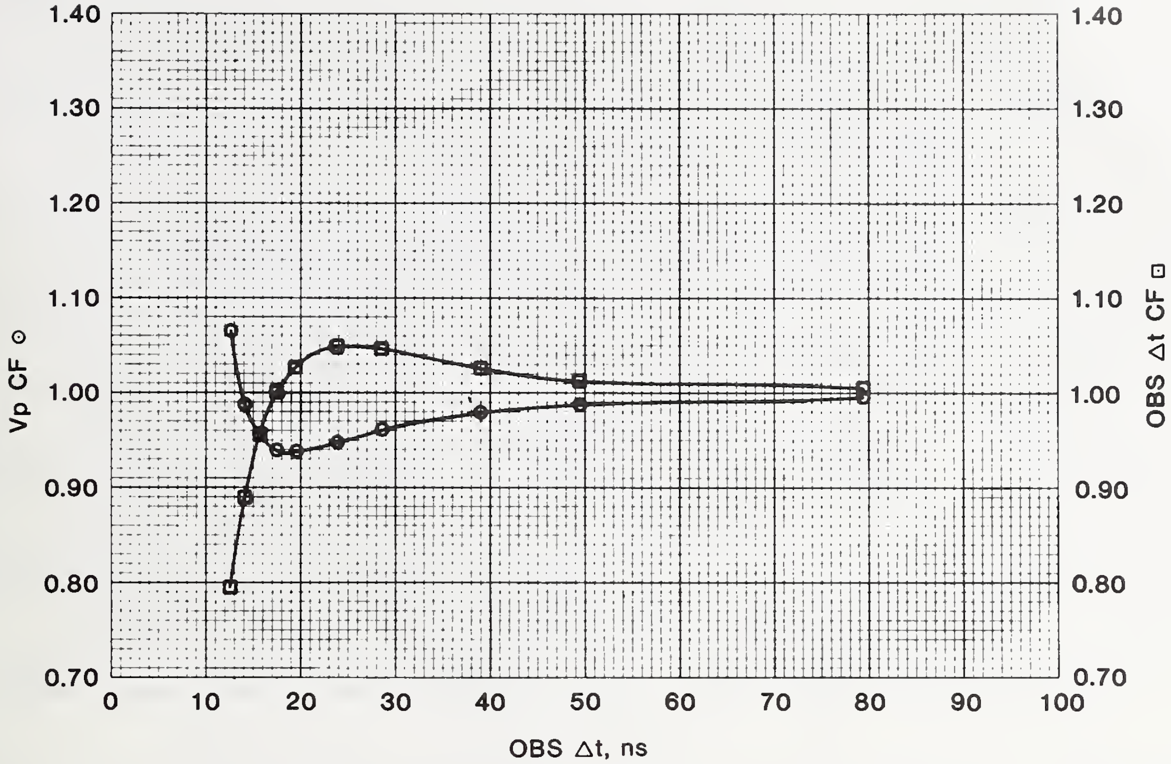


Figure 13. APD 5-2 correction factors (with HP 461A amplifier 20 dB and 40 dB) for peak voltage (V_p CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt).

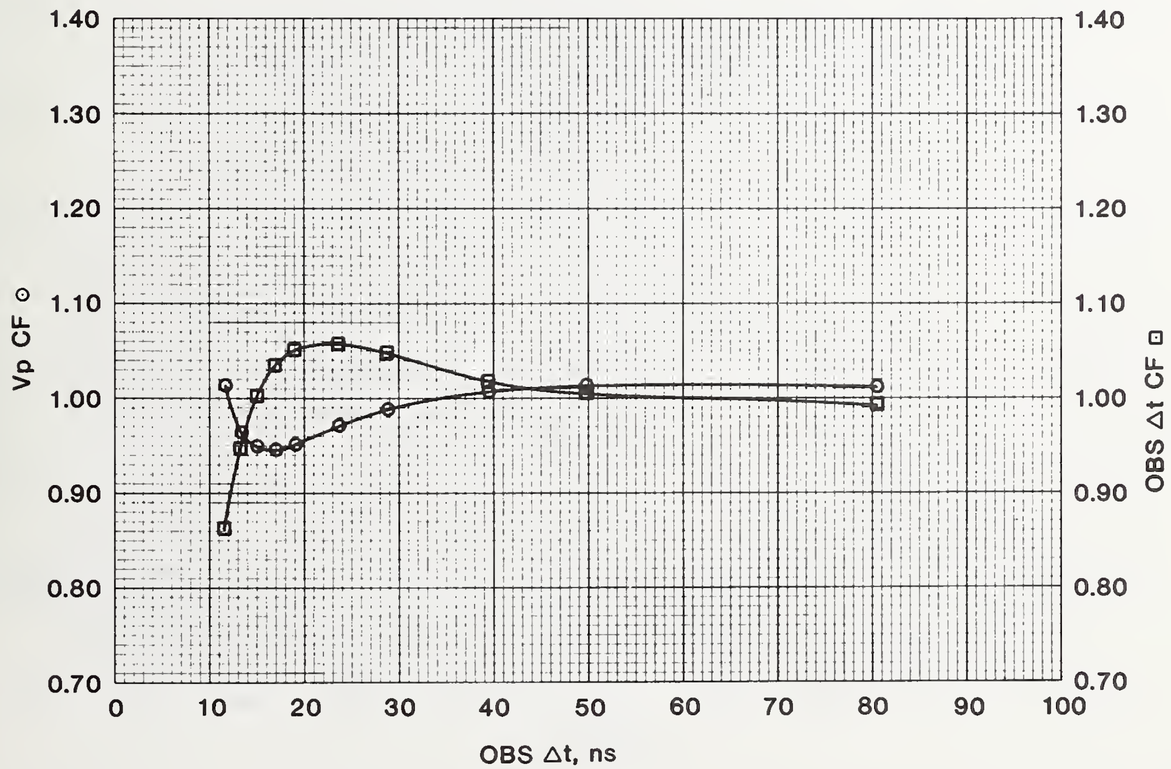


Figure 14. APD 5-3 correction factors (without HP amplifier) for peak voltage (V_p CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt).

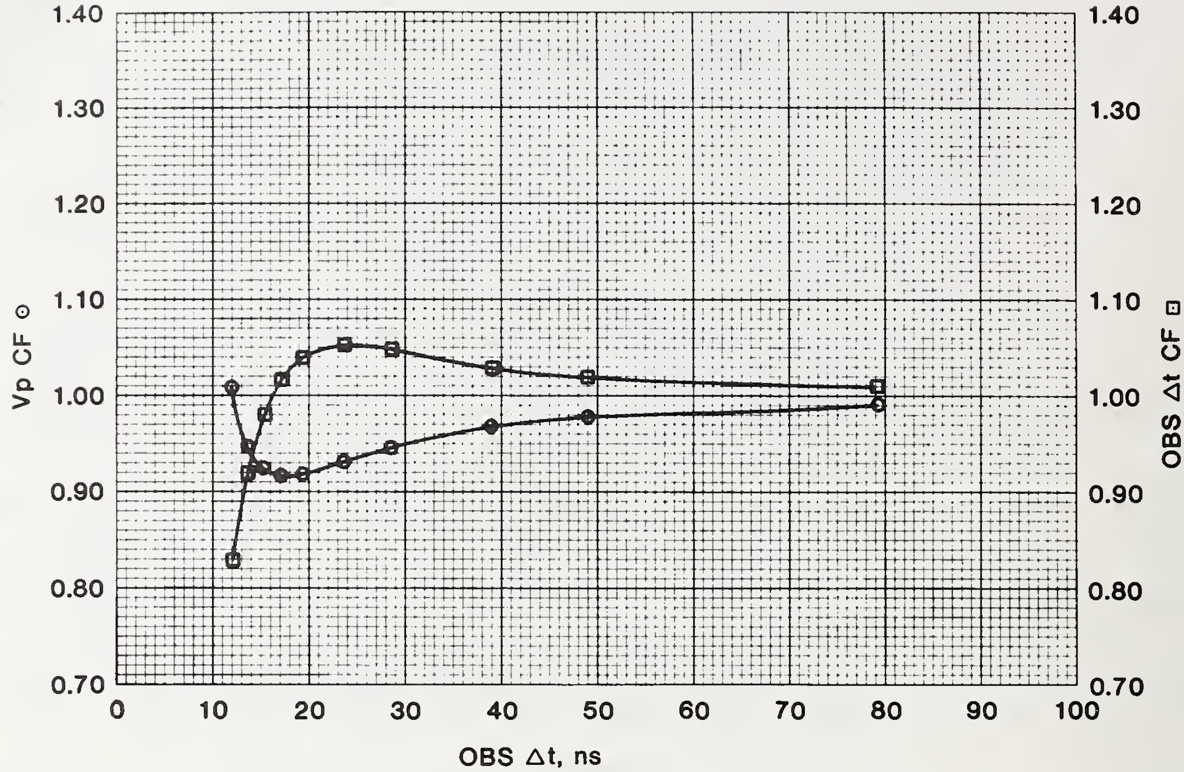


Figure 15. APD 5-3 correction factors (with HP 461A amplifier 20 dB and 40 dB) for peak voltage (V_p CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt).

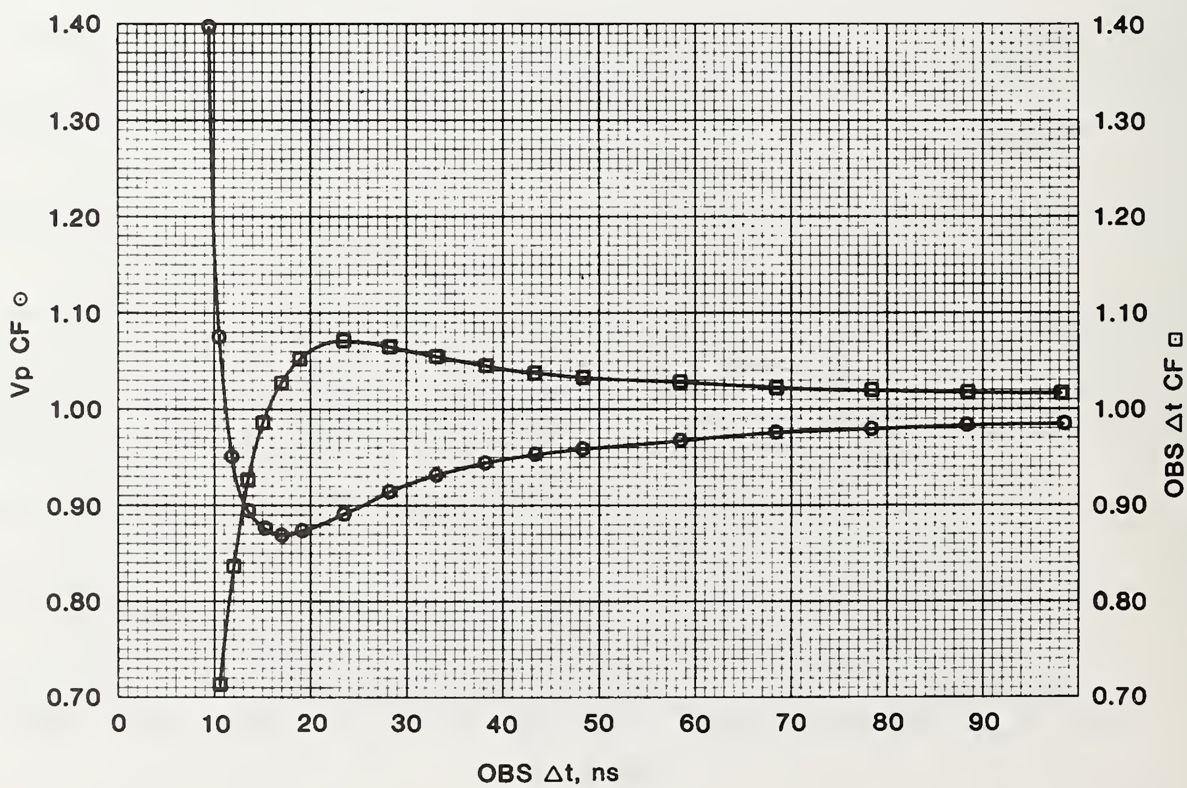


Figure 16. APD 5-4 correction factors (without HP amplifier) for peak voltage (V_p CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt).

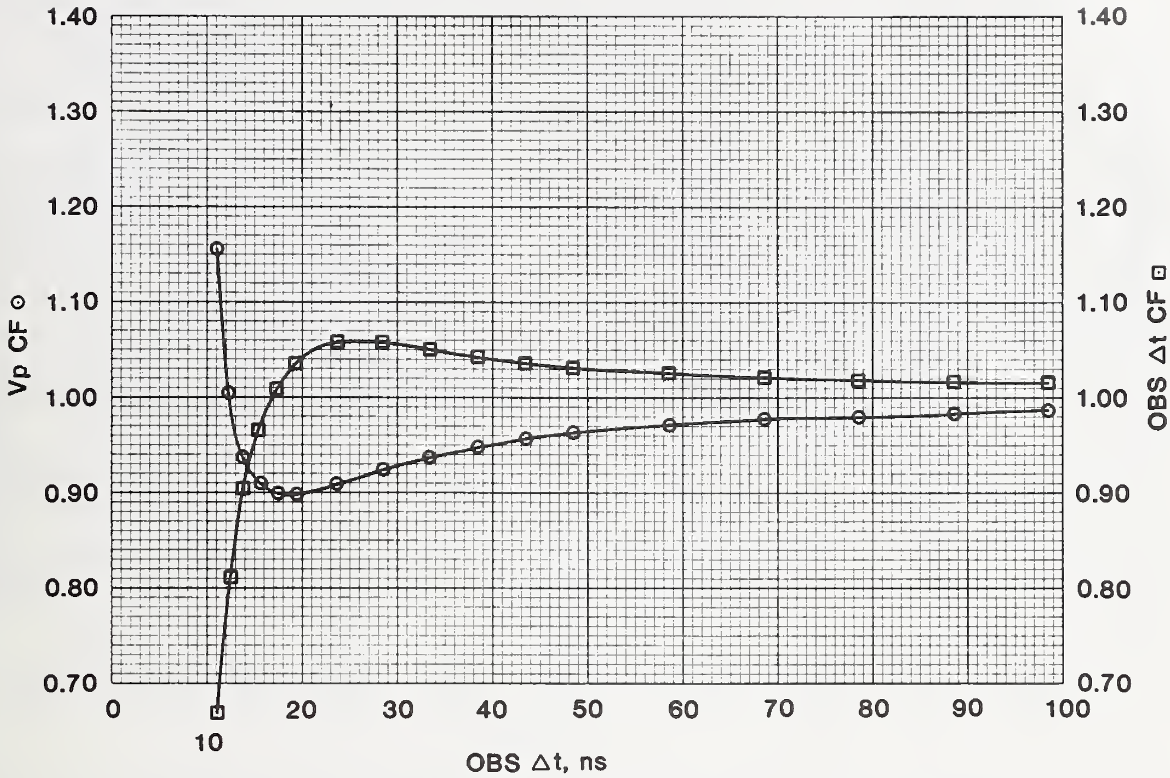


Figure 17. APD 5-4 correction factors (with HP 461A amplifier 20 dB and 40 dB) for peak voltage (V_p CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt).

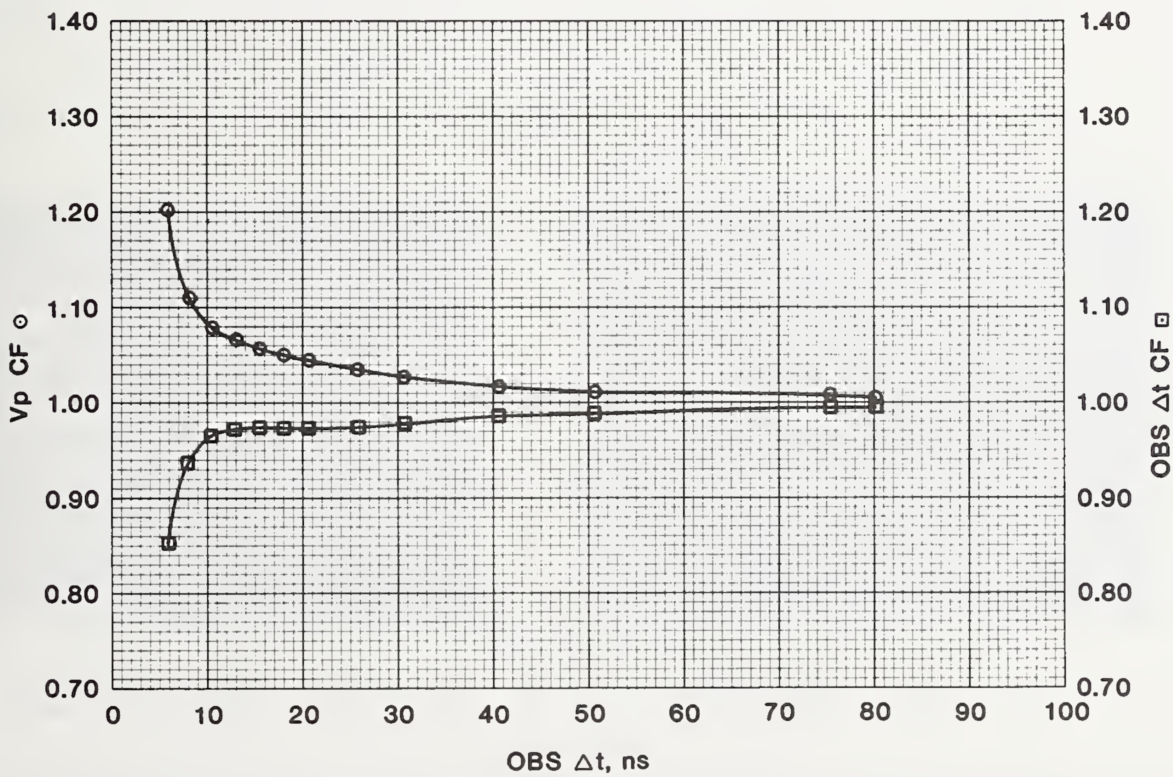


Figure 18. APD 5-5 correction factors (without HP amplifier) for peak voltage (V_p CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt).

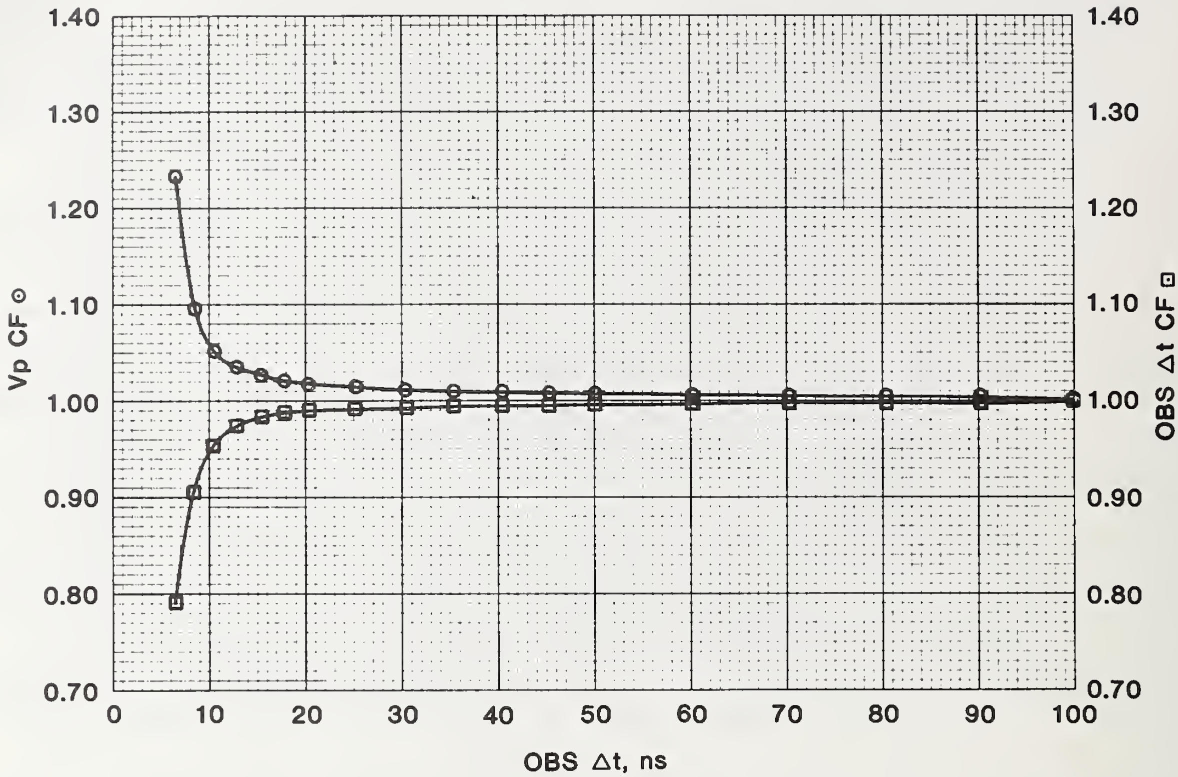


Figure 19. APD 5-5 correction factors (with HP 462A amplifier 20 dB and 40 dB) for peak voltage (V_p CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt).

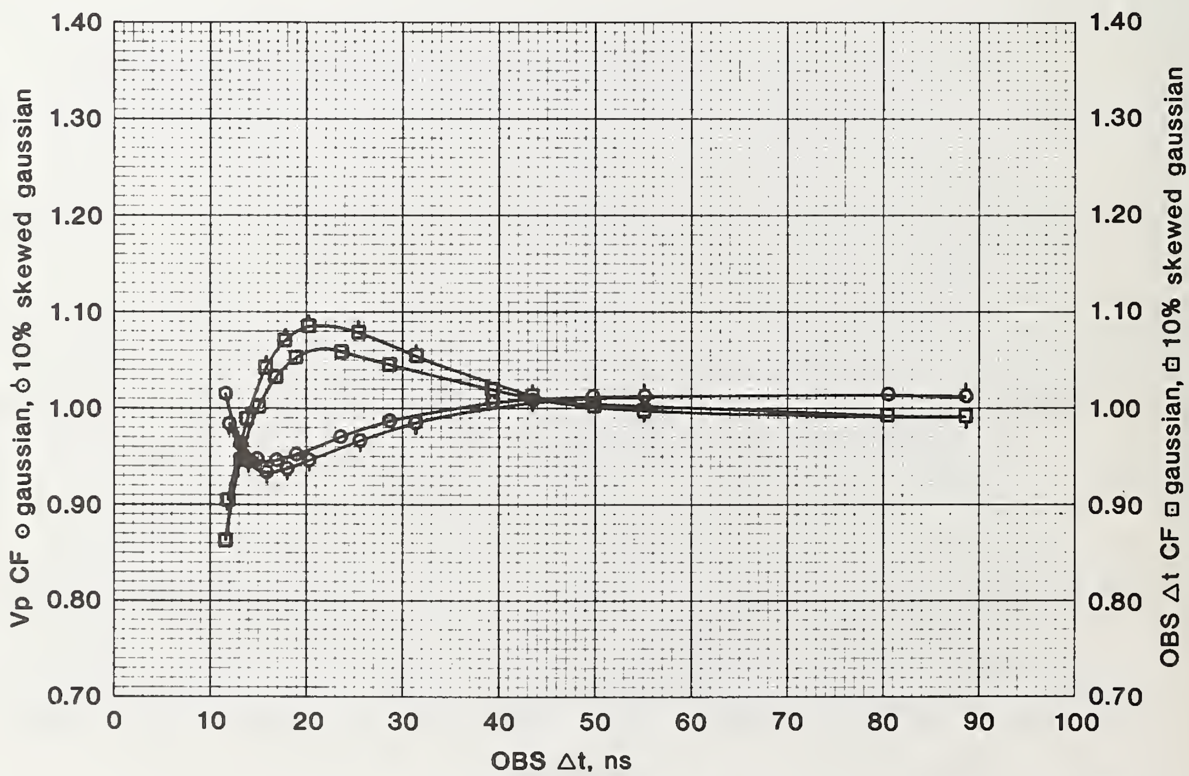


Figure 20. APD 5-3 correction factors (without HP amplifier) for peak voltage (V_p CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt) for a Gaussian and a 10 percent skewed Gaussian input. (The skewed pulses had a Gaussian right side with a FWHM 10 percent longer than a Gaussian left side.)

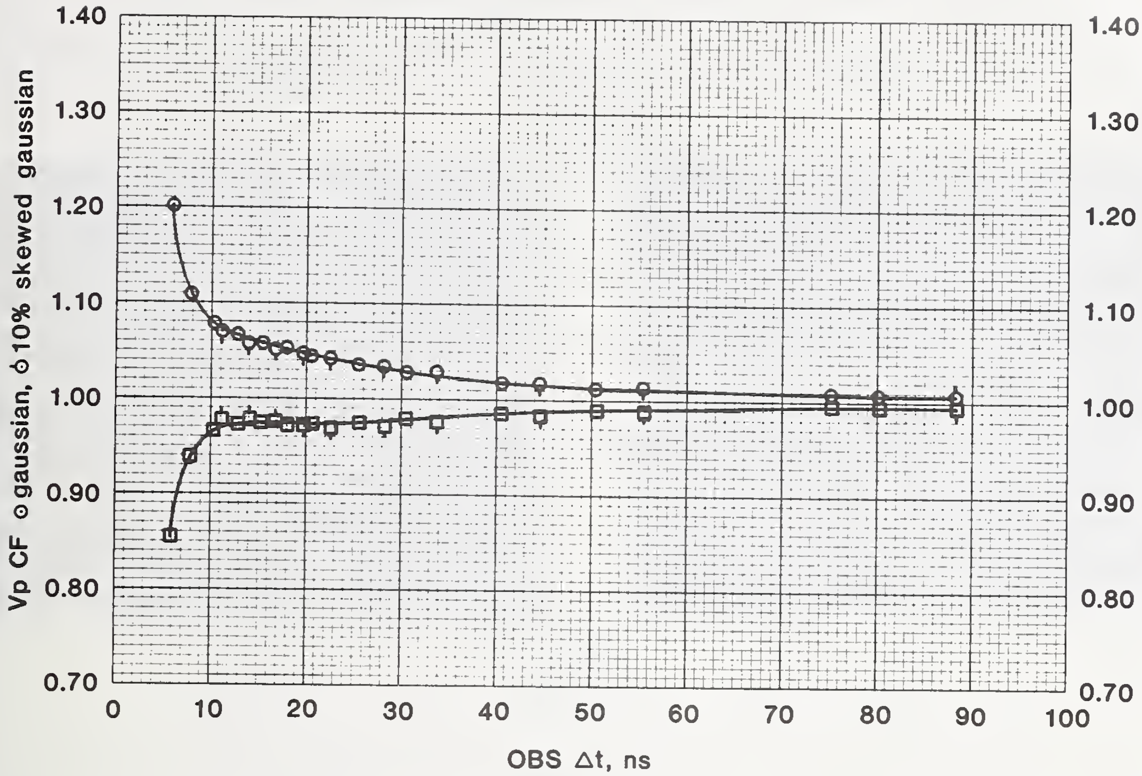
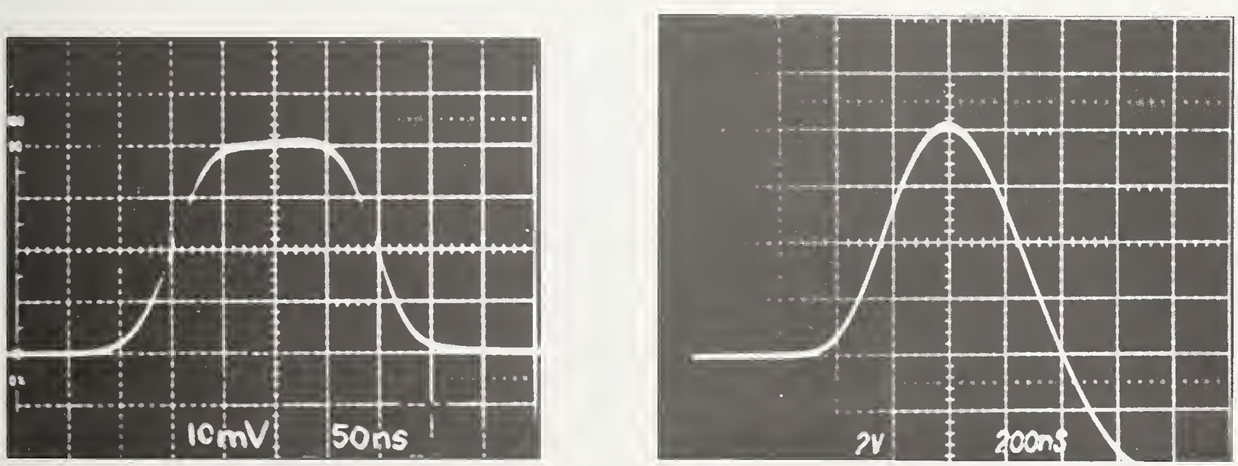
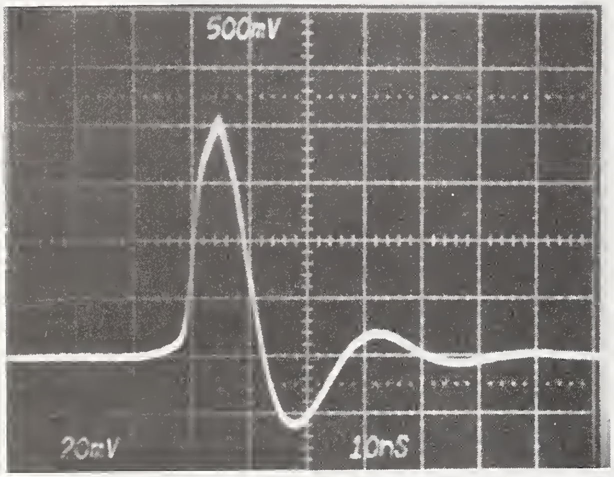


Figure 21. APD 5-5 correction factors (without HP amplifier) for peak voltage (V_p CF) and for observed pulse duration (OBS Δt CF) versus the observed pulse duration (OBS Δt) for a Gaussian and a 10 percent skewed Gaussian input. (The skewed pulses had a Gaussian right side with a FWHM 10 percent longer than a Gaussian left side.)

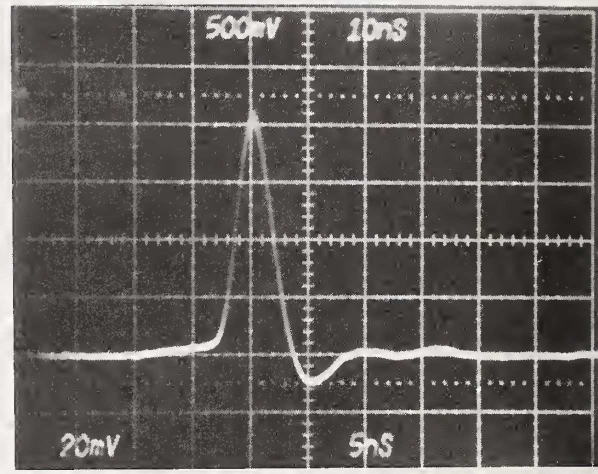


(a) (b)

Figure 22. Modulation system pulses (a) observed by the APD silicon photodiode system (peak power proportional to pulse peak) and (b) converted by the PIN silicon photodiode system (pulse energy proportional to positive pulse peak).



(a)



(b)

Figure 23. Typical impulse response for APD 5-1, 5-2, 5-3, and 5-4 systems (a) and for APD 5-5 (b) with a 300 ps impulse at 0.9 μm from a LED.

Table 1. Beamsplitter attenuator BA-1 attenuation ratios at 1.064 μm*

Beam ratio relative to (m=o) beam	Unknown polarization †	Total max. estimated uncertainty %	Horizontal polarization ‡	Total max. estimated uncertainty %
(m=0)/(m=-1)	$2.772 \cdot 10$	3.5	$2.868 \cdot 10$	0.11
(m=0)/(m=≠1)	$2.968 \cdot 10$	1.5	$3.012 \cdot 10$	0.04
(m=0)/(m=2)	$8.811 \cdot 10^2$	1.9	$8.975 \cdot 10^2$	0.08
(m=0)/(m=3)	$2.617 \cdot 10^4$	2.5	$2.664 \cdot 10^4$	0.69

*Incoming laser beam angle is -8.71°.

†Applies to low-level modulated cw measurement system described in the text.

‡Applies to low-level Q-switched measurement system described in the text.

Table 2. APD 5-1 system calibration*

	Calibration V·cm²/W *	Estimated error at 95% Ci (%)	Power range μW/cm² *	Readout range V
(1)†	$9.7 \cdot 10^3$	12.1	2.0 -156	0.019-1.52
(2)†	$8.7 \cdot 10^4$	14.6	0.92- 5.1	0.082-0.43
(3)†	$8.7 \cdot 10^5$	14.6	0.23- 0.48	0.20 -0.41

* Aperture area 0.947 cm². Field of view at least 25 mr.

†TX 7904 oscilloscope, 7A24 50 Ω plug-in
(1) plus polarity
(2) invert polarity, HP 462A amplifier 20 dB
(3) invert polarity, HP 462A amplifier 40 dB.

Table 3. P1 - APD 5-2 system calibration*

	Calibration V·cm²/W * ‡	Estimated error at 95% Ci (%)	Power range nW/cm² *	Readout range V
(1)†	$4.7 \cdot 10^4$	15.4	530-1730	0.024-0.082
(2)†	$4.3 \cdot 10^5$	18.9	51-930	0.022-0.40
(3)†	$4.1 \cdot 10^6$	18.9	18-111	0.08 -0.45

* Aperture area 45.62 cm², diameter 7.62 cm.

‡ Beam divergence / Correction factor

Beam divergence	Correction factor
≤ 3 mr	1.00
7 mr	0.98
8 mr	0.96

† TX 485 oscilloscope:
(1) CH 1, 50 Ω
(2) CH 2, 50 Ω, invert polarity, modified HP 461A amplifier 20 dB
(3) CH 2, 50 Ω, invert polarity, modified HP 461A amplifier 40 dB

Table 4. APD 5-3 system calibration*

	Calibration $V \cdot cm^2/W$ *	Estimated error at 95% Ci (%)	Power range $\mu W/cm^2$ *	Readout range V
(1)†	$6.4 \cdot 10^3$	10.9	3.1-120	0.02-0.8
(2)†	$5.7 \cdot 10^4$	14.2	0.67-7.1	0.04-0.4
(3)†	$5.5 \cdot 10^5$	14.2	0.15-0.74	0.08-0.4

* Aperture area 0.950 cm^2.

† TX 485 oscilloscope and TX 7904 oscilloscope:
(1) CH 1, 50 Ω (TX 485); CH 2, 7A24 50 Ω plug-in (TX 7904)
(2) invert polarity, modified HP 461A amplifier 20 dB
(3) invert polarity, modified HP 461A amplifier 40 dB

Table 5. P3 - APD 5-4 system calibration*

	Calibration $V \cdot cm^2/W$ * ‡	Estimated error at 95% Ci (%)	Power range nW/cm^2 *	Readout range V
(1) †	$2.77 \cdot 10^4$	15.5	720-2900	0.020-0.081
(2) †	$2.53 \cdot 10^5$	18.0	155-1540	0.040-0.40
(3) †	$2.42 \cdot 10^6$	18.0	40-160	0.10 -0.40

* Aperture area 45.63 cm^2, diameter 7.62 cm.

‡

Beam divergence	Correction factor
≤ 4 mr	1.00
8 mr	0.94
9 mr	0.90
10 mr	0.84

† TX 7904 oscilloscope, 7A24 50 Ω plug-in

(1) plus polarity

(2) invert polarity, modified HP 461 amplifier 20 dB

(3) invert polarity, modified HP 461 amplifier 40 dB

Table 6. APD 5-5 system calibration*

	Calibration $V \cdot cm^2/W$ *	Estimated error at 95% Ci (%)	Power range $\mu W/cm^2$ *	Readout range V
(1) †	$5.5 \cdot 10^3$	11.6	3.7 -37	0.02-0.2
(2) †	$5.0 \cdot 10^4$	14.1	0.74-8.2	0.04-0.4
(3) †	$5.0 \cdot 10^5$	14.1	0.16-0.99	0.08-0.5

* Aperture area 0.947 cm^2. Field of view at least 15 mr.
Aligned with beam reflected on itself. If aligned by adjusting detector for maximum output, multiply calibration by 1.063 and add 0.9 percent estimated error.

† TX 7904 oscilloscope: CH 2 7A24 50 Ω plug-in:
(1) Plus polarity
(2) invert polarity, HP 462A amplifier 20 dB
(3) invert polarity, HP 462A amplifier 40 dB

Table 7. PIN 4-1 system calibration*

Linear amplifier TC 222† coarse gain	fine gain	Calibration $J/V\ cm^2$ * ‡	Estimated error at 95% Ci (%)	Energy range fJ/cm^2 *	Readout range V ‡
5	0.500	$1.07 \cdot 10^{-12}$	8.5	220-8900	0.20-8.3
10	1.000	$2.71 \cdot 10^{-13}$	8.9	210-1700	0.75-6.2
50	1.000	$5.29 \cdot 10^{-14}$	12.2	35-430	0.67-8.1
100	1.000	$2.71 \cdot 10^{-14}$	12.5	12-220	0.44-8.3

* Aperture area 0.819 cm^2.

† BLR: ASYM. 1, RATE OUT
OUTPUT: Bipolar positive peak
INSIDE: Tc 2 μs, x 0.2, delay out (set at NBS)
MAKE NO OTHER ADJUSTMENTS.

‡TX 7904 oscilloscope, CH2, 7A26 1 MΩ plug-in, sweep 0.2 μs.

Table 8. P3 - PIN 4-2' system calibration* (aperture diameter 7.62 cm)

Linear amplifier TC 222** coarse gain	fine gain	Calibration J/PHA rdg·cm² * †	Estimated error at 95% Ci (%)	Calibration J/V cm² * ‡	Estimated error at 95% Ci (%)	Energy range fJ/cm² *	Readout range PHA †	Readout range (V) ‡
5	0.500	$2.12 \cdot 10^{-16}$	9.4	$2.61 \cdot 10^{-14}$	9.4	26 -193	117-911	0.9-7.5
10	1.000	$4.51 \cdot 10^{-17}$	9.4	$5.57 \cdot 10^{-15}$	9.4	5.5-41	123-903	1.0-7.3
50	1.000	$8.8 \cdot 10^{-18}$	13.0	$1.09 \cdot 10^{-15}$	13.0	1.0-8.2	114-924	0.9-7.5
100	1.000	$4.56 \cdot 10^{-18}$	13.0	$5.60 \cdot 10^{-16}$	13.0	0.57-4.2	126-927	1.0-7.5
200	1.000	$2.29 \cdot 10^{-18}$	13.0	$2.84 \cdot 10^{-16}$	13.5	0.23-2.2	97-936	0.8-7.6

* Aperture area 45.63 cm², diameter 7.62 cm. Field of view at least 18 mr.

**BLR: ASYM. 1, RATE OUT
OUTPUT: Bipolar positive peak
INSIDE: TC 2 μs, x 0.2, delay out
MAKE NO OTHER ADJUSTMENTS

† PHA: DO NOT CHANGE THE ZERO CONTROL. MODE PHA. HORIZONTAL FULL. PRESET CURSOR. CONVERSION GAIN 1024. OFFSET 0. TIME BASE FULL CLOCKWISE. PEN POSITION. ADD POSITION.

‡ TX 7904 oscilloscope, 7A26 1 MΩ plug-in, sweep 0.2 μs, parallel with PHA

Table 9. P3 - PIN 4-2' system calibration* (aperture diameter 10.16 cm)

Linear amplifier TC 222** coarse gain	fine gain	Calibration J/PHA rdg·cm² * †	Estimated error at 95% Ci (%)	Calibration J/V cm² * ‡	Estimated error at 95% Ci (%)	Energy range fJ/cm² *	Readout range PHA †	Readout range (V) ‡
5	0.500	$1.19 \cdot 10^{-16}$	9.4	$1.47 \cdot 10^{-14}$	9.4	14 -109	117-911	0.9-7.5
10	1.000	$2.54 \cdot 10^{-17}$	9.4	$3.13 \cdot 10^{-15}$	9.4	3.1-23	123-903	1.0-7.3
50	1.000	$4.97 \cdot 10^{-18}$	13.0	$6.14 \cdot 10^{-16}$	13.0	0.57-4.6	114-924	0.9-7.5
100	1.000	$2.56 \cdot 10^{-18}$	13.0	$3.15 \cdot 10^{-16}$	13.0	0.32-2.3	126-927	1.0-7.5
200	1.000	$1.29 \cdot 10^{-18}$	13.0	$1.60 \cdot 10^{-16}$	13.5	0.13-1.2	97-936	0.8-7.6

* Aperture area 81.11 cm², diameter 10.16 cm. Field of view at least 18 mr.

**BLR: ASYM. 1, RATE OUT
OUTPUT: Bipolar positive peak
INSIDE: TC 2 μs, x 0.2, delay out
MAKE NO OTHER ADJUSTMENTS

† PHA: DO NOT CHANGE THE ZERO CONTROL. MODE PHA. HORIZONTAL FULL. PRESET CURSOR. CONVERSION GAIN 1024. OFFSET 0. TIME BASE FULL CLOCKWISE. PEN POSITION. ADD POSITION.

‡ TX 7904 oscilloscope, 7A26 1 MΩ plug-in, sweep 0.2 μs, parallel with PHA

Table 10. PIN 4-3 system calibration*

Linear amplifier TC 222† coarse gain	fine gain	Calibration J/V cm² * ‡	Estimated error at 95% Ci (%)	Energy range fJ/cm² *	Readout range V ‡
5	0.500	$9.4 \cdot 10^{-13}$	8.6	18-9200	0.02-9.7
10	1.000	$2.34 \cdot 10^{-13}$	8.6	160-940	0.69-4.0
50	1.000	$4.68 \cdot 10^{-14}$	12.1	34-220	0.76-4.9
100	1.000	$2.35 \cdot 10^{-14}$	12.3	10-180	0.44-7.7

* Aperture area 1.00 cm².

† BLR: ASYM. 1, RATE OUT
OUTPUT: Bipolar positive peak
INSIDE: Tc 2 μs, x 0.2, delay out (set at NBS)
MAKE NO OTHER ADJUSTMENTS.

‡TX 7904 oscilloscope, CH1, 7A12 1 MΩ plug-in, sweep 0.2 μs.

Table 11. PIN 4-4 System calibration*

Linear amplifier TC 222** coarse gain	fine gain	Calibration J/PHA rdg·cm² * †	Estimated error at 95% Ci (%)	Calibration J/V cm² * ††	Estimated error at 95% Ci (%)	Energy range fJ/cm² *	Readout range PHA †	Readout range (V) ††
5	0.500	$7.6 \cdot 10^{-15}$‡	6.0	$9.5 \cdot 10^{-13}$	8.8	720-7300	90-950	0.8-7.8
10	1.000	$1.91 \cdot 10^{-15}$‡	6.0	$2.38 \cdot 10^{-13}$	8.8	240-1100	130-570	1.0-4.7
50	1.000	$3.8 \cdot 10^{-16}$‡	6.0	$4.7 \cdot 10^{-14}$	8.8	120-370	300-980	2.5-8.1
100	1.000	$1.95 \cdot 10^{-16}$	9.3	$2.38 \cdot 10^{-14}$	12.3	10-180	70-920	0.5-7.6
200	1.000	$9.8 \cdot 10^{-17}$	9.3	$1.20 \cdot 10^{-14}$	12.3	10-80	110-840	0.9-6.9

* Aperture area 0.984 cm².

**BLR: ASYM. 1, RATE OUT
OUTPUT: Bipolar positive peak
INSIDE: TC 2 μs, x 0.2, delay out
MAKE NO OTHER ADJUSTMENTS

† PHA: DO NOT CHANGE THE ZERO CONTROL. MODE PHA. HORIZONTAL FULL. PRESET CURSOR. CONVERSION GAIN 1024, EXCEPT WHEN PHA RDG ≤ 100 CONVERSION GAIN 2048. OFFSET 0. TIME BASE FULL CLOCKWISE. PEN POSITION. ADD POSITION.

††TX 485 oscilloscope: CH 1, 1 MΩ, sweep 0.2 μs, parallel with PHA.

‡ At ≤ 10^4 pps.

Table 12. P1 - PIN 4-5 system calibration* (aperture diameter 7.62 cm)

Linear amplifier TC 222** coarse gain	fine gain	Calibration J/PHA rdg·cm² * †	Estimated error at 95% Ci (%)	Calibration J/V cm² * ††	Estimated error at 95% Ci (%)	Energy range fJ/cm² *	Readout range PHA †	Readout range (V) ††
5	0.500	$2.02 \cdot 10^{-16}$‡	6.2	$2.50 \cdot 10^{-14}$	9.4	18 -190	90-960	0.7-7.9
10	1.000	$5.1 \cdot 10^{-17}$‡	6.1	$6.4 \cdot 10^{-15}$	9.1	5.1-45	100-890	0.8-7.3
50	1.000	$1.01 \cdot 10^{-17}$‡	10.1	$1.24 \cdot 10^{-15}$	13.0	2.9-6.8	290-670	2.4-5.5
100	1.000	$5.2 \cdot 10^{-18}$	9.7	$6.4 \cdot 10^{-16}$	12.8	0.24-4.6	47-890	0.4-7.4
200	1.000	$2.62 \cdot 10^{-18}$	9.9	$3.18 \cdot 10^{-16}$	12.5	0.31-2.1	120-820	1.0-6.8

* Aperture area 45.62 cm², diameter 7.62 cm. Field of view at least 15 mr.

**BLR: ASYM. 1, RATE OUT
OUTPUT: Bipolar positive peak
INSIDE: TC 2 μs, x 0.2, delay out
MAKE NO OTHER ADJUSTMENTS

† PHA: DO NOT CHANGE THE ZERO CONTROL. MODE PHA. HORIZONTAL FULL. PRESET CURSOR. CONVERSION GAIN 1024, EXCEPT WHEN PHA RDG ≤ 100 CONVERSION GAIN 2048. OFFSET 0. TIME BASE FULL CLOCKWISE. PEN POSITION. ADD POSITION.

††TX 485 oscilloscope: CH 1, 1 MΩ, sweep 0.2 μs, parallel with PHA.

‡ At ≤ 10^4 pps.

Table 13. P1 - PIN 4-5 system calibration* (aperture diameter 10.16 cm)

Linear amplifier TC 222** coarse gain	fine gain	Calibration J/PHA rdg·cm² * †	Estimated error at 95% Ci (%)	Calibration J/V cm² * ††	Estimated error at 95% Ci (%)	Energy range fJ/cm² *	Readout range PHA †	Readout range (V) ††
5	0.500	$1.14 \cdot 10^{-16}$‡	6.2	$1.41 \cdot 10^{-14}$	9.4	10-110	90-960	0.7-7.9
10	1.000	$2.89 \cdot 10^{-17}$‡	6.1	$3.59 \cdot 10^{-15}$	9.1	3.0-26	100-890	0.8-7.3
50	1.000	$5.7 \cdot 10^{-18}$‡	10.1	$7.0 \cdot 10^{-16}$	13.0	1.7-3.8	290-670	2.4-5.5
100	1.000	$2.91 \cdot 10^{-18}$	9.7	$3.58 \cdot 10^{-16}$	12.8	0.12-2.6	47-890	0.4-7.4
200	1.000	$1.47 \cdot 10^{-18}$	9.9	$1.79 \cdot 10^{-16}$	12.5	0.12-1.2	120-820	1.0-6.8

* Aperture area 81.07 cm^2, diameter 10.16 cm. Field of view at least 15 mr.

**BLR: ASYM. 1, RATE OUT
OUTPUT: Bipolar positive peak
INSIDE: TC 2 μs, x 0.2, delay out
MAKE NO OTHER ADJUSTMENTS

† PHA: DO NOT CHANGE THE ZERO CONTROL. MODE PHA. HORIZONTAL FULL. PRESET CURSOR. CONVERSION GAIN 1024, EXCEPT WHEN PHA RDG ≤ 100 CONVERSION GAIN 2048. OFFSET 0. TIME BASE FULL CLOCKWISE. PEN POSITION. ADD POSITION.

††TX 485 oscilloscope: CH 1, 1 MΩ, sweep 0.2 μs, parallel with PHA.

‡ At ≤ 10^4 pps.

Table 14. Error budget of energy and peak power in the modulated cw 1.064 μm system

Source of error	Uncertainty %*
First order Redw 3 transfer standard	2.5
Second order PIN transfer standard	6.0 - 6.1
Beamsplitter attenuator (depends on beam used)	
(m=0)/(m=+1)	1.5
(m=0)/(m=2)	1.9
(m=0)/(m=3)	2.5
Oscilloscope readout	3.0
Equivalence of pulsed and cw power	2.5
Total error budget †	
Energy measurements	4.0 - 11.8
Peak power measurements	9.5 - 10.5

*At the 95 percent confidence interval.

†Depends upon beam and transfer standards used. Excludes precision and uniformity of device measurements. Also excludes any other equipment in the device system.

Table 15. Error budget PIN 4-1 system

Source of error		Uncertainty %*
Redw 3 transfer standard for linear amplifier gain 5, 0.500 and 10, 1.000		2.5
PIN 4-3 transfer standard for linear amplifier gain 50, 1.000 and 100, 1.000		6.0
Beamsplitter attenuator		2.5
Oscilloscope readout		3
Precision and uniformity for linear amplifier gain		
5, 0.500	0.5	
10, 1.000	0.9	
50, 1.000	0.7	
100, 1.000	1.0	
Total error budget for linear amplifier gain		
5, 0.500	8.5	
10, 1.000	8.9	
50, 1.000	12.2	
100, 1.000	12.9	

*At the 95 percent confidence interval.

Table 16. Error budget P3 - PIN 4-2' system

Source of error			Uncertainty %*
Redw 3 transfer standard for linear amplifier gain 5, 0.500 and 10, 1.000			2.5
PIN 4-3 transfer standard for linear amplifier gain 50, 1.000; 100, 1.000; and 200, 1.000			6.1
Beamsplitter attenuator			2.5
P3 beamsplitter			0.5
Oscilloscope readout			3.0
Precision, uniformity and divergence (≤18 mr)			
Linear amplifier gain	PHA readout (%)	Oscilloscope readout (%)	
5, 0.500	0.9	0.9	
10, 1.000	0.9	0.9	
50, 1.000	0.9	0.9	
100, 1.000	0.9	0.9	
200, 1.000	0.9	1.4	
Total error budget			
Linear amplifier gain	PHA readout (%)	Oscilloscope readout (%)	
5, 0.500	9.4	9.4	
10, 1.000	9.4	9.4	
50, 1.000	13.0	13.0	
100, 1.000	13.0	13.0	
200, 1.000	13.0	13.5	

*At the 95 percent confidence interval.

Table 17. Error budget PIN 4-3 system

Source of error	Uncertainty %*
Redw 3 transfer standard for linear amplifier gain 5, 0.500 and 10, 1.000	2.5
PIN 4-1 transfer standard for linear amplifier gain 50, 1.000 and 100, 1.000	6.0
Beamsplitter attenuator	2.5
Oscilloscope readout	3.0
Precision and uniformity for linear amplifier gain	
5, 0.500	0.6
10, 1.000	0.6
50, 1.000	0.6
100, 1.000	0.8
Total error budget for linear amplifier gain	
5, 0.500	8.6
10, 1.000	8.6
50, 1.000	12.1
100, 1.000	12.3

*At the 95 percent confidence interval.

Table 18. Error budget PIN 4-4 system

Source of error	Uncertainty %*
Redw 3 transfer standard for linear amplifier gain 5, 0.500; 10, 1.000; and 50, 1.000	2.5
PIN 4-3 transfer standard for linear amplifier gain 100, 1.000 and 200, 1.000	6.1
Beamsplitter attenuator	2.5
PHA rdg at pulse rate for linear gain 5, 0.500; 10, 1.000; and 50, 1.000	0.2
Oscilloscope readout	3.0
Precision and uniformity for all linear amplifier gain settings and both PHA and oscilloscope readouts	0.8
Total error budget for	

Linear amplifier gain	PHA readout (%)	Oscilloscope readout (%)
5, 0.500	6.0	8.8
10, 1.000	6.0	8.8
50, 1.000	6.0	8.8
100, 1.000	9.3	12.3
200, 1.000	9.3	12.3

*At the 95 percent confidence interval.

Table 19. Error budget P1 - PIN 4-5 system

Source of error	Uncertainty %*
Redw 3 transfer standard for linear amplifier gain 5, 0.500 and 10, 1.000	2.5
PIN 4-3 transfer standard for linear amplifier gain 50, 1.000; 100, 1.000; and 200, 1.000	6.1
Beamsplitter attenuator	2.5
P1 beamsplitter	0.5
PHA rdg at pulse rate for linear amplifier gain 5, 0.500 and 10, 1.000	0.2
Oscilloscope readout	3.0
Precision and uniformity for	

Linear amplifier gain	PHA readout (%)	Oscilloscope readout (%)
5, 0.500	0.5	0.7
10, 1.000	0.4	0.4
50, 1.000	1.0	0.9
100, 1.000	0.4	0.5
200, 1.000	0.8	0.4

Total error budget for

Linear amplifier gain	PHA readout (%)	Oscilloscope readout (%)
5, 0.500	6.2	9.2
10, 1.000	6.1	8.9
50, 1.000	10.1	13.0
100, 1.000	9.5	12.6
200, 1.000	9.9	12.5

*At the 95 percent confidence interval.

Table 20. Error budget APD 5-1 system

Source of error	Uncertainty %*
Redw 3 transfer standard	2.5
Beamsplitter attenuator	2.5
Equivalence of pulsed and cw power	2.5
Oscilloscope readout	3.0
Amplitude response of HP 462A amplifier	2.5
Precision and uniformity	
(1) Without HP 462A amplifier	0.9
(2) With HP 462A amplifier	
at 20 dB	0.9
at 40 dB	1.9
Total error budget	
(1) Without HP 462A amplifier	11.4
(2) With HP 462A amplifier	
at 20 dB	13.9
at 40 dB	14.9

*At the 95 percent confidence interval.

Table 21. Error budget P1 - APD 5-2 system

Source of error	Uncertainty %*
Redw 3 transfer standard	2.5
Beamsplitter attenuator	1.9
P1 beamsplitter	4.0
Equivalence of pulsed and cw power	2.5
Oscilloscope readout	3.0
Amplitude response of modified HP 461A amplifier	2.5
Precision and uniformity	
(1) Without modified HP 461A amplifier	1.5
(2) With modified HP 461A amplifier	2.5
Total error budget	
(1) Without modified HP 461A amplifier	15.4
(2) With modified HP 461A amplifier	18.9

*At the 95 percent confidence interval.

Table 22. Error budget APD 5-3 system

Source of error	Uncertainty %*
Redw 3 transfer standard	2.5
Beamsplitter attenuator	
(1) Without modified HP 461A amplifier	1.9
(2) With modified HP 461A amplifier	2.5
Equivalence of pulsed and cw power	2.5
Oscilloscope readout	3.0
Amplitude response of modified HP 461A amplifier	2.5
Precision and uniformity	
(1) Without modified HP 461A amplifier	1.0
(2) With modified HP 461A amplifier	1.2
Total error budget	
(1) Without modified HP 461A amplifier	10.9
(2) With modified HP 461A amplifier	14.2

*At the 95 percent confidence interval.

Table 23. Error budget P3 - APD 5-4 system

Source of error	Uncertainty %*
Redw 3 transfer standard	2.5
Beamsplitter attenuator	1.9
P3 beamsplitter	4.0
Equivalence of pulsed and cw power	2.5
Oscilloscope readout	3.0
Amplitude response of modified HP 461A amplifier	2.5
Precision and uniformity	1.6
Total error budget	
(1) Without modified HP 461A amplifier	15.5
(2) With modified HP 461A amplifier	18.0

*At the 95 percent confidence interval.

Table 24. Error budget APD 5-5 system

Source of error	Uncertainty %*
Redw 3 transfer standard	2.5
Beamsplitter attenuator	
(1) Without HP 462A amplifier	1.9
(2) With HP 462A amplifier	2.5
Equivalence of pulsed and cw power	2.5
Oscilloscope readout	3.0
Amplitude response of HP 462A amplifier	2.5
Precision and uniformity	1.6
Aligned for maximum output and using 1.063 correction factor	0.9
Total error budget	
(1) Without HP 462A amplifier	11.5
(2) With HP 462A amplifier	14.6

*At the 95 percent confidence interval.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

For the first time, transfer standards have been developed for measuring 1.064 µm laser pulses of duration about 10-100 ns, peak irradiance of about 10^{-8}-10^{-4} W/cm^2, and fluences of about 10^{-16}-10^{-11} J/cm^2. These energy and power measurement devices use PIN and APD silicon detectors, respectively, and can be used as stable transfer standards with total uncertainties (random errors computed at the 95 percent confidence level) of 10 to 15 percent. The system for calibrating these transfer standards is also described and consists of a cw Nd:YAG laser beam acousto-optically modulated to provide low-level laser pulses of known peak power and energy. A detailed evaluation of systematic and random errors is also shown.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

APD transfer standards; beamsplitter attenuator; impulse response measurements; low-level laser measurements; modulated cw measurement system; 1.064 µm laser pulse measurements; PIN transfer standards; pulse energy; pulse peak power.

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