Dual-wavelength transfer standard for laser peak-power measurement

Rodney Leonhardt
National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305

Daniel King
Naval Surface Warfare Center – Corona Division, 1999 4th Street, Norco, CA 92860

ABSTRACT

The National Institute of Standards and Technology (NIST) and the Naval Surface Warfare Center – Corona Division (NSWC) have jointly developed a dual-wavelength extended-sensitivity radiometer (D-ESR) that functions as a portable transfer standard for measuring laser pulses at wavelengths of 1.06 µm and 1.55 µm. The peak-power irradiance range is from 500 pW/cm² to 50 µW/cm² within the wavelength range of 1.54 µm to 1.58 µm. A similar peak-power range is covered at a wavelength of 1.06 µm. The measurement range is covered by using smaller apertures or a neutral-density filter to reach the highest peak powers. The D-ESR radiometer is based on an InGaAs avalanche photodiode (APD) detector that is integrated with a transimpedance preamplifier module. The light-capturing optical system has a maximum aperture of approximately 125 cm². The D-ESR is able to measure Gaussian pulse duration from 4 ns to 400 ns. The output is a negative-going pulse waveform that is measured with an oscilloscope. The total expanded uncertainty of a calibrated peak-power measurement with a D-ESR radiometer is approximately 9 % (k=2).

1. INTRODUCTION

Laser rangefinders for military systems have been moving from the established 1.06 µm wavelength to the more eye-safe 1.55 µm region. The 1.55 µm laser light does not come to a focus directly on the photoreceptors of the eye, so it takes much more energy before hazardous conditions are reached. However it is considered eye-safe at the energy levels and conditions at which the laser rangefinders are operated. This allows the same systems to be used for training exercises as well as field operations. This paper describes a radiometer designed to provide laser peak-power calibration traceability at these wavelengths.

1.1 Radiometer design

The design of a field-level transfer standard must balance the requirements for accuracy, size, sensitivity, measurement range, bandwidth, ease of use, and cost, and still be calibration-traceable to national standards. The detector itself must satisfy the competing demands for sensitivity, bandwidth, noise, and active area in order to meet the calibration requirements.

Research into the available commercial detectors revealed only a few that had the potential to be used in a portable radiometer. Detectors that are fast enough to give adequate temporal resolution are quite small in size (≤200 µm diameter) to reduce the capacitance low enough to allow a wide enough (>180 MHz) bandwidth. The small size then imposes more difficult conditions on the collection optics, which must focus the full aperture down to the detector active area. In order to meet these requirements an InGaAs APD (avalanche photodiode) integrated with a transimpedance amplifier module was selected as the only viable detector candidate.

1.2 APD detector module

The light sensor is a module containing the InGaAs APD and a transimpedance preamplifier to provide the current-to-voltage conversion (Figure 1). The preamplifier has a bandwidth of approximately 180 MHz, and produces a negative-going output. The detector active area has a diameter of 200 µm and is mounted in the same package with the preamp to minimize capacitance of the connection leads and maximize the signal bandwidth.

Publication of the National Institute of Standards and Technology, not subject to copyright.
2. D-ESR RADIOMETER ARCHITECTURE

2.1 Electronics

D-ESR Radiometer electronics consist of the detector preamp, x10 voltage signal amplifier, detector temperature controller, and the translation system controller (Figures 2, 3, 4).

Figure 1. InGaAs detector module.

Figure 2. D-ESR functional diagram.
2.2 Temperature control

APD detector sensitivity and the reverse bias voltage have some temperature dependence therefore stabilization is necessary for a calibrated instrument. We decided to heat the detector module above room temperature due to package geometry and the lack of a thermoelectric cooler option for this particular detector. Heating had worked well for a previous radiometer design using a silicon APD\(^1\).

Heating was implemented by mounting an electrical resistance heater in good thermal contact with the detector package. Thermistor sensors and control circuitry provide temperature stability to ±1 °C, at a set point near 30 °C. Unfortunately there was some loss of sensitivity and increased noise in the APD due to the higher operating temperature when compared to the properties of a cooled detector. Recently we found an APD of large area that can be mounted on a thermoelectric cooler for temperature control and we are evaluating the performance of this detector module.

2.3 Signal amplifier

A wideband amplifier with a voltage gain of 10 (or 20 dB) can be switched into the signal path to boost levels and increase the measurement range of the D-ESR radiometer. The amplifier bandwidth is dc to 500 MHz, with excellent gain flatness. The responsivity of the D-ESR is calibrated both with and without the amplifier in the signal path.

2.4 Translation system

Limitations of the optical system require that the APD detector be moved between the focal points for the two operational wavelength regions of the D-ESR. This is accomplished by an automated Z-axis translation system that simplifies the task for the user to select the operational wavelength region by pushing a button. A microprocessor controller moves the APD detector platform to the experimentally tested locations for optimal lens focus in the wavelength regions of 1.06 µm and 1.55 µm (Figures 3, 4).
2.5 Light Collection optics

The D-ESR radiometer has an input aperture of 12.6 cm diameter to meet the performance capability, which required a large optical gain. Collimated light is focused down to the active area of a 200 µm diameter detector by the radiometer optics.

The optical system (Figure 5) uses three dual-wavelength anti-reflection coated lenses to receive the collimated light. Two large plano-convex lenses are used to reduce the spherical aberrations as well as shorten the optical systems focal length by nearly one half. A custom manufactured plano-convex aspheric lens is mounted about 20 mm from the detector to provide the final correction to focus onto the 200 µm diameter active area.

The input aperture (~125 cm^2) can be fitted with smaller apertures that are provided to allow higher peak irradiances to be measured and still remain in the linear range of the electronics. Calibrated response with attenuation filters is provided for the 1.06 µm and 1.55 µm wavelength regions to reach the highest peak irradiance measurable by the D-ESR.

![Figure 5. Radiometer optical system.](image)

3. MEASUREMENT CAPABILITIES

The D-ESR radiometer (Figure 6) is capable of measuring from 50 nW to 250 µW absolute peak power in the wavelength range of 1.54 µm to 1.58 µm. The nominal peak-power irradiance range is from 500 pW/cm^2 to 50 µW/cm^2 in the same wavelength range.

The measurement range at a wavelength of 1.06 µm is 50 nW to 900 µW absolute peak power. The nominal peak-power irradiance range is from 500 pW/cm^2 to 180 µW/cm^2. The radiometer can measure even lower levels if an external trigger synchronized with the laser pulse is provided to the oscilloscope. This reduces false triggers when the signal is near the noise floor.
The maximum aperture for the D-ESR is 125 cm$^2$, with smaller apertures (typically 25 cm$^2$, 5 cm$^2$, 1 cm$^2$) provided to allow the radiometer to reach higher irradiance levels. A neutral-density filter with a 5 cm$^2$ aperture allows the highest range of irradiance to be measured.

**4. IMPULSE RESPONSE AND BANDWIDTH LIMITATIONS**

Bandwidth limitations of the APD detector/preamplifier provide challenges for measurement of laser pulses less than about 60 ns in duration. Pulse fidelity is very important as the radiometer is calibrated for peak-power response that is correlated to the measured peak voltage of the pulse waveform.

The APD detector/preamplifier combination has a bandwidth of approximately 180 MHz. This is insufficient bandwidth to replicate the typical laser pulse with the required accuracy. Distortion of the peak voltage and duration will occur when laser pulses with nanosecond features are measured.

Potential waveform distortions of the peak and duration of the pulse are accounted for by use of correction factors, which are obtained by the following method. First the impulse response of the APD module is measured with a 1 GHz oscilloscope and a 120 ps laser pulse. The Full-Duration Half-Maximum (FDHM) of the D-ESR impulse response is approximately 2.5 ns (Figure 7).

The correction factors were calculated by convolving the impulse response of the APD with Gaussian pulses of varying durations and comparing the result to the original unit-height pulse to determine how much the peak height and duration were changed by the radiometer. Results are presented in table form for the required measurement range of pulse durations.
A calibration report of the D-ESR radiometer includes correction factors to be used with pulse measurements from 4 ns to 25 ns in duration. These correction factors assume a temporal Gaussian shape to the laser pulse intensity, which has been typical for 1.06 µm laser rangefinders but cannot be assumed for 1.55 µm lasers. NIST research has shown that significant errors can occur if the pulse is not Gaussian shaped. Non-Gaussian shapes can also be corrected for but require specific knowledge of the duration and shape of the laser pulse.

The radiometer requires a fast oscilloscope to measure the peak negative-going voltage, which is correlated to watts or watts per square centimeter by using the calibration factors. Figures 8 and 9 are representative of the output signals from the prototype radiometer for a 90 ns flat-top laser pulse at 1.55 µm and a 20 ns Gaussian laser pulse at 1.06 µm.

Figure 7. Typical impulse response curve of D-ESR.

Figure 8. D-ESR with 90 ns flat-top pulse.

Figure 9. D-ESR with 20 ns Gaussian pulse.
5. CALIBRATION OF THE D-ESR RADIOMETER

The D-ESR radiometer is calibrated for peak-power responsivity (V/W) and bandwidth correction at wavelengths of 1.06 µm and 1.55 µm (Figure 10). The responsivity calibration of the D-ESR radiometer uses a technique similar to the comparison method for the APD-800 (which is performed at 1.06 µm)\textsuperscript{2,3}.

An electro-optic modulator generates equal levels of pulsed and CW power from a 1.55 µm laser beam. A characterized fused-silica beamsplitter divides the laser output into a high-power beam for the laboratory standard and a low-power beam for the radiometer. The laboratory standard measures the CW power, and the D-ESR radiometer measures the pulsed signal with an oscilloscope. A comparison of the measured power and pulsed voltage levels using the beamsplitter attenuation ratio provides a calibration factor in V/W.

Figure 10. Calibration system layout.

In order to accurately measure laser pulses with duration less than 60 ns, the limited electrical bandwidth of the D-ESR radiometer must be compensated for. The measured impulse response of the radiometer is convolved with unit height Gaussian pulses of 4 ns to 25 ns. This data were used to generate correction factors for the observed pulse duration and amplitude (Figure 11). The correction factors are to be used with the calibrated responsivity.
6. CALIBRATION UNCERTAINTY

The uncertainty estimates for the NIST laser peak-power measurements are expressed and combined by use of the following guidelines. To establish the uncertainty limits, the sources are separated into (1) Type A uncertainty components whose magnitudes are obtained statistically from a series of measurements, and (2) Type B uncertainty components whose magnitudes are determined by scientific judgment\(^4\).

All the Type B components are assumed to be independent and have rectangular or uniform distributions (that is, each has an equal probability of being within the region \(\pm \delta_i\) and zero probability of being outside that region). If the distribution is rectangular, then the standard deviation, \(\sigma_i\), for each Type B component is equal to \(\delta_i / 3^{1/2}\) and the total standard deviation is approximated by \((\sum \sigma_i^2)^{1/2}\), where the summation is performed over all Type B uncertainty components.

The Type A uncertainty components are assumed to be independent and normally distributed; consequently the standard deviation, \(S_r\), for each component is

\[
S_r = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N - 1}},
\]

where the \(x_i\) values represent the individual measurements and \(N\) is the number of \(x_i\) values used for a particular Type A component. The standard deviation of the mean is \(S_r / N^{1/2}\), and the total standard deviation of the mean is \([\sum (S_r^2 / N)]^{1/2}\), where the summation is carried out for all the Type A uncertainty components.

The expanded uncertainty is determined by combining the Type A and Type B uncertainty estimates in quadrature and multiplying this result by a coverage factor of two (\(k=2\)). The expanded uncertainty, \(U\), is then

\[
U = 2 \sqrt{\sum \sigma^2 + \sum \frac{S_r^2}{N}}.
\]
Typical measurement uncertainty components and values are listed in Table 1 and discussed in detail in Reference [3].

<table>
<thead>
<tr>
<th>Source</th>
<th>Type B</th>
<th>Type A</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low-level Measurement System</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lab Standard Cal (6725B)</td>
<td>0.23 %</td>
<td>0.33 %</td>
</tr>
<tr>
<td>Fused Silica Beamsplitter</td>
<td>1.73 %</td>
<td></td>
</tr>
<tr>
<td>Oscilloscope (digital)</td>
<td>1.21 %</td>
<td></td>
</tr>
<tr>
<td>Modulator Leakage Effect</td>
<td>0.58 %</td>
<td></td>
</tr>
<tr>
<td>Wavelength Uncertainty</td>
<td>0.58 %</td>
<td></td>
</tr>
<tr>
<td>CW/Pulse Inequivalence</td>
<td>1.44 %</td>
<td></td>
</tr>
<tr>
<td>Laser Stability</td>
<td>1.15 %</td>
<td></td>
</tr>
<tr>
<td><strong>Radiometer Assessment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Stability</td>
<td>0.58 %</td>
<td></td>
</tr>
<tr>
<td>Bandwidth Correction</td>
<td>1.15 %</td>
<td></td>
</tr>
<tr>
<td>Aperture Area</td>
<td>0.87 %</td>
<td></td>
</tr>
<tr>
<td>APD/Lens Nonuniformity</td>
<td>2.89 %</td>
<td></td>
</tr>
<tr>
<td>Impulse Response</td>
<td></td>
<td>1.00%</td>
</tr>
<tr>
<td>D-ESR Calibration</td>
<td></td>
<td>4.84%</td>
</tr>
</tbody>
</table>

Relative Expanded Uncertainty (k=2) 9.0 %

7. CONCLUSIONS

A pulsed-laser radiometer has been developed and calibrated to function as a transfer standard at the wavelength of 1.06 μm and in the region of 1.54 μm to 1.58 μm. The wavelength range is user-selected, but the movement of the detector itself is under automated control. The calibration uncertainty for the D-ESR is on the order of 8 % to 9 %. The impulse response of the D-ESR has been measured and is approximately 2.5 ns (FDHM). Correction factors for Gaussian-shaped laser pulses have been calculated over a range of 4 ns to 25 ns. Typical specifications for a D-ESR radiometer are shown in Table 2.

<table>
<thead>
<tr>
<th>Table 2. Typical D-ESR performance specifications.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance</td>
</tr>
<tr>
<td>Peak Power</td>
</tr>
<tr>
<td>Uncertainty (NIST calibration)</td>
</tr>
<tr>
<td>Pulse Width</td>
</tr>
<tr>
<td>Pulse Width Uncertainty</td>
</tr>
<tr>
<td>Wavelength</td>
</tr>
<tr>
<td>Field-Of-View</td>
</tr>
<tr>
<td>Alignment FOV</td>
</tr>
<tr>
<td>Temperature Range</td>
</tr>
<tr>
<td>Aperture sizes</td>
</tr>
<tr>
<td>Weight</td>
</tr>
</tbody>
</table>
7. REFERENCES


