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2012 Metrologia 49 S124
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A new method for spectral irradiance and radiance responsivity calibrations using kilohertz pulsed tunable optical parametric oscillators

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Received 18 October 2011, in final form 22 November 2011
Published 2 March 2012
Online at stacks.iop.org/Met/49/S124

Abstract
Continuous-wave (CW) tunable lasers have been used for detector calibrations, especially for spectral irradiance and radiance responsivity, for many years at the National Institute of Standards and Technology (NIST) and other national metrology institutes. These CW tunable lasers, however, are expensive and difficult to automate. To address these issues, we developed a new method for spectral irradiance and radiance responsivity calibrations using relatively low cost, fully automated kilohertz pulsed tunable optical parametric oscillators (OPOs). The new method is based on measurements of the total energy of a pulsed OPO train using two synchronized current integrators (also called charge amplifiers) to measure the total integrated electric charges from a test detector and a standard detector, respectively. The absolute expanded uncertainty of this method is estimated to be 0.05% (with a coverage factor of $k = 2$) for spectral irradiance responsivity calibrations, and the dominant uncertainty contribution is from the reference trap detector.

1. Introduction
To overcome the low radiant power of double monochromators, calibration set-ups using high-power continuous-wave (CW) tunable lasers with continuous coverage from the ultraviolet (UV) to near infrared (NIR) were developed at the National Institute of Standards and Technology (NIST) [1] and other national metrology institutes including the National Physical Laboratory (NPL) in the UK [2], the Helsinki University of Technology (HUT) in Finland [3] and the Physikalisch-Technische Bundesanstalt (PTB) in Germany [4]. CW tunable lasers are used for spectral irradiance and radiance responsivity calibrations in primary scale realizations and for many other applications such as characterization/calibration of high-accuracy remote-sensing instruments [1]. For added spectral coverage into the deep UV and infrared (IR) regions, picosecond (ps) mode-locked tunable pulsed lasers with 78 MHz to 100 MHz repetition rates (often called quasi-CW lasers) and ps optical parametric oscillators (OPOs) have also been used for detector calibrations with satisfactory results [5–7]. These ps or femtosecond (fs) systems can be stretched to duty cycles of the order of $10^{-3}$ without much difficulty. They can also be stabilized using a laser power controller so that detector calibration is performed under quasi-CW mode, similar to when a CW laser is used. Current CW, ps and fs systems, however, are expensive and difficult to automate.

Newly developed, commercially available OPO-based tunable systems with kilohertz (kHz) repetition rates and nanosecond (ns) pulse lengths are much more affordable than tunable CW lasers and are fully automated over a wide spectral range from approximately 200 nm to 2500 nm. At present, the duty cycle of a kHz OPO is limited to approximately $10^{-5}$ and is difficult to extend using fibre optics and/or integrating spheres. This small duty cycle causes problems when conventional measurement systems consisting of a detector, a trans-impedance amplifier and a digital multimeter are used. To avoid saturation at the peak OPO power, the ranges of the trans-impedance amplifier and the digital multimeter must be
set to several orders of magnitude higher than that for the corresponding averaged dc signal, which results in a large measurement uncertainty. A voltage integrator can be used to replace the multimeter to avoid peak saturation, in which case, measurement uncertainty is limited by the trans-impedance amplifier.

In this paper we describe a new method for spectral irradiance and radiance responsivity calibrations using a ns pulsed OPO with kHz repetition rates. The new method is based on the measurement of the total energy of a pulsed OPO train using two synchronized current integrators (also called charge amplifiers) to measure total electric charges (unit: coulomb, symbol: C) from the test detector and standard detector, respectively. The measurement method used to overcome OPO pulse-to-pulse fluctuations, detector saturation and overall calibration uncertainty are discussed below.

2. Principle of the new calibration method

A schematic diagram of the new method developed for calibrating a test detector for spectral irradiance responsivity is shown in Figure 1 as an example. The calibration system is composed of a 1 kHz pulsed OPO, a laser shutter and its controller, a 5 m multimode fibre optic, an ultrasound bath, a 50 mm integrating sphere, a test detector, a standard trap detector, a monitor detector, a single-channel electrometer and a multichannel electrometer. The laser shutter is used to control the length of the OPO pulse train. The OPO is coupled into the 50 mm integrating sphere through the multimode fibre optic to form a uniform irradiance source. The ultrasound water bath is used to remove speckle from the coherent OPO radiation on the detectors by routing the fibre through the water bath. The monitor detector is used to correct fluctuation of the pulsed OPO during the two measurements. The two electrometers are set to ‘Coulomb’ mode to measure the total electric charge from the test detector (or standard trap detector) and the monitor detector. The single-channel electrometer is used to measure the total charge of the monitor detector, and the multichannel electrometer is used to alternately measure the total charge of the test detector and the standard trap detector. In this way, systematic measurement error from the electrometer is cancelled.

![Schematic diagram of a kHz OPO-based calibration system.](image)

Figure 1. Schematic diagram of a kHz OPO-based calibration system.

Charge measurements between the test detector (or standard trap detector) and the monitor detector are synchronized. Figure 2 shows the time sequence for measurement of a pulsed OPO train. The interval between the measurement start time and the laser shutter opening and that from the laser shutter closing to the measurement end time should be as short as possible to minimize the dark charges (e.g. 1 s or less). However, the timing is not critical if dark-charge subtraction is applied or the measured dark charge is negligible.

A test detector calibration is performed using the substitution method. The test detector and the standard trap detector are aligned, in turn, to measure a pulsed OPO train over a period of time. The entire measurement sequence is controlled by a computer.

The spectral irradiance responsivity of the test detector, $R_{\text{test}}(\lambda)$, is given by

$$R_{\text{test}}(\lambda) = \frac{Q_{\text{test}}^o(\lambda) - Q_{\text{test}}^d(\lambda)}{Q_{\text{monitor}}^o(\lambda) - Q_{\text{monitor}}^d(\lambda)} \times R_{\text{standard}}(\lambda),$$

where $Q_{\text{test}}^o(\lambda)$ and $Q_{\text{test}}^d(\lambda)$ are the total charges of the test detector for OPO measurement and dark measurement, respectively; $Q_{\text{monitor}}^o(\lambda)$ and $Q_{\text{monitor}}^d(\lambda)$ are the total charges of the monitor detector for OPO measurement and dark measurement, respectively, when the test detector is used. Correspondingly, $Q_{\text{standard}}^o(\lambda)$ and $Q_{\text{standard}}^d(\lambda)$ are the total charges of the standard trap detector for OPO measurement and dark measurement, respectively; $Q_{\text{monitor}}^o(\lambda)$ and $Q_{\text{monitor}}^d(\lambda)$ are the total charges of the monitor detector for OPO measurement and dark measurement, respectively, when the standard trap detector is used; $R_{\text{standard}}(\lambda)$ is the spectral irradiance responsivity of the standard trap detector.

3. The kilohertz pulsed tunable OPO

The measured average OPO power, spectral width and pulse width of the 1 kHz tunable OPO used in this study are shown in figures 3, 4 and 5, respectively. This tunable OPO has
continuous coverage from 210 nm to 2400 nm with radiant power of the order of 100 mW in the visible range. The spectral widths of the OPO at wavelengths of 350 nm, 600 nm and 1100 nm are 0.08 nm, 0.14 nm and 0.48 nm, which correspond to wavenumbers of 6.4 cm$^{-1}$, 4 cm$^{-1}$ and 4 cm$^{-1}$, respectively. The finite spectral width is, in fact, very beneficial in reducing or even completely eliminating interference fringes formed on optical elements of detectors (e.g. windows) and instruments (e.g. filters). Interference fringes can result in large calibration errors if not properly mapped out. Figure 5 shows that the pulse width of the OPO, approximately 4 ns, does not change after going through the 5 m multimode fibre and is only slightly stretched—from 4 ns to 6 ns—after the 50 mm integrating sphere. Therefore, unlike ps or fs laser pulses, ns OPO pulses can be difficult to stretch.

4. The electrometer

Two electrometers are used to measure the total electric charge. The electrometers are set to Coulomb mode so that they act as current integrators to measure the total charge. A schematic diagram of a detector and an electrometer for measurement of the total charge is shown in figure 6. The total charge, $Q$, of a pulse train, $i(t)$, of photocurrent of a detector is obtained by

$$Q = \int_0^T i(t)\,dt = C \cdot V,$$

where $T$ is the length of a pulse train (unit: s), $C$ is the capacitance of the feedback capacitor of the operational amplifier and $V$ is the output voltage of the operational amplifier.

The two electrometers have measurement ranges from 2 nC to 2 µC. The bias current and burden voltage are low and are 3 fA and 20 µV, respectively. A plug-in 10-channel multiplexer is used for charge measurements for the test detector and the standard trap detector so that the meter-to-meter systematic error is eliminated in the calibration.

5. Measurement of detector non-linearity

Non-linear response of silicon photodiodes must be investigated when a pulsed laser or OPO is used as a calibration
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Figure 5. Pulse width of the OPO.

source, especially when the source is a kHz pulsed OPO with a duty cycle of approximately $10^{-5}$, which is three orders of magnitude smaller than that of a ps or fs pulsed laser after its pulse width is stretched. To investigate the extent of the non-linearity, a silicon photodiode (Hamamatsu Model S2281) was tested for non-linearity over three orders of magnitude using the 1 kHz OPO at a wavelength of 450 nm. The same measurement apparatus as shown in figure 1 was used. A silicon photodiode, identical to the test photodiode, was used as the reference detector for this test. A small diffuser was placed in front of the reference detector to reduce the light level so that the photocurrent is two orders of magnitude lower and, thus, its non-linearity is negligible compared with that of the test detector. Similar to the detector calibration, the charge measurement between the test detector and the reference detector is synchronized. Figure 7 shows the measured relative responsivity of the test detector over an averaged photocurrent range from $2 \times 10^{-9}$ A to $2 \times 10^{-6}$ A, which is obtained by normalizing the charge ratio of the test detector to the reference detector. The measurement result shows that the non-linearity threshold value of this particular test photodiode is approximately at an averaged photocurrent of $1 \times 10^{-6}$ A (corresponding to a peak photocurrent of $1 \times 10^{-1}$ A or 100 mA), which is 2 to 3 orders of magnitude lower than a typical non-linear threshold value for measurement of a dc light source. On the other hand, the peak threshold photocurrent is 2 to 3 orders of magnitude higher than a typical dc threshold value. Note the non-linearity threshold value depends not only on the detector, but also on the wavelength, repetition rate and duty cycle of the pulsed source. A more thorough investigation is planned for different detectors, pulsed lasers (or OPOs) and wavelengths.

6. Experimental results

A test silicon photodiode (Hamamatsu Model S2281) was calibrated against a standard trap detector for spectral irradiance responsivities using the apparatus shown in figure 1. The calibration system was first tested for measurement repeatability. Figures 8(a) and (b) show the measurement repeatability.
Figure 7. Test result of detector non-linearity.

Figure 8. Plots of measurement repeatability: (a) for the test detector and (b) for the standard trap detector.

Figure 9. Comparison of calibration results: (a) relative difference with charge amplifiers versus conventional trans-impedance amplifiers; (b) relative difference with the 1 kHz pulsed OPO using charge amplifiers versus CW lasers using trans-impedance amplifiers.

Repeatability

\[
\frac{Q^{\text{o,test}}(450) - Q^{\text{d,test}}(450)}{Q^{\text{o,monitor}}(450) - Q^{\text{d,monitor}}(450)}
\]

of the test detector and

\[
\frac{Q^{\text{o,standard}}(450) - Q^{\text{d,standard}}(450)}{Q^{\text{o,monitor}}(450) - Q^{\text{d,monitor}}(450)}
\]

of the standard trap detector for measurement of the 1 kHz pulsed OPO at a wavelength of 450 nm, which are the first and second terms of equation (1). The measurement repeatability is rather high and is of the order of 10 ppm in both cases. The integration time (pulse train length) for each measurement is approximately 1 s (≈1000 pulses).

The test detector was calibrated at several wavelengths for absolute spectral irradiance responsivity. In addition to the pulsed 1 kHz OPO, a CW argon-ion laser and four CW helium–neon lasers with laser line filters were used for this calibration to validate the new calibration method. The pulsed OPO was tuned to be at the same wavelengths as that of the CW lasers for this calibration.

The test detector was first calibrated using the 1 kHz pulsed OPO with the two electrometers with a charge amplifier for measurement of the total charge of the test detector and monitor detector at seven wavelengths of 458 nm, 488 nm, 514 nm, 543.5 nm, 594 nm, 612 nm and 632.8 nm. Then the 1 kHz pulsed OPO was replaced by the CW lasers for calibration at four wavelengths of 458 nm, 488 nm, 514 nm and 632.8 nm. Finally the two electrometers were replaced by two trans-impedance amplifiers for calibration of the test detector at all seven wavelengths of 458 nm, 488 nm, 514 nm, 543.5 nm, 594 nm, 612 nm and 632.8 nm under dc mode using the conventional trans-impedance amplifier scheme. The CW lasers were stabilized using a laser power controller for the calibration under dc mode.

The three different calibration methods were compared and the relative differences at the measured wavelengths are
shown in figures 9(a) and (b). The difference in calibration results using the two charge amplifiers in the electrometers and two trans-impedance amplifiers is shown in figure 9(a). The average difference is approximately 0.02%, an indication that charge amplifiers are equivalent to trans-impedance amplifiers for measurement of CW sources. Figure 9(b) shows the relative difference in responsivity obtained using the new calibration method (with the 1 kHz pulsed OPO and charge amplifiers) and using the conventional calibration method (with a CW laser and two trans-impedance amplifiers). The average difference is also 0.02%. The comparison results show that there was a systematic difference of 0.02% between the charge amplifier-based system and the trans-impedance amplifier-based system, most likely due to the accuracy of amplifier’s gain, and the change from the CW lasers to the pulsed tunable OPO did not make a meaningful difference in the calibration results. These measurements demonstrate the equivalence between the new kHz pulsed OPO-based method and the CW laser-based method.

7. Uncertainty

An example spectral irradiance responsivity uncertainty budget for calibration of a silicon photodiode against a standard silicon trap detector at a wavelength of 450 nm using a kHz pulsed OPO is shown in table 1. The absolute expanded uncertainty, with coverage factor of \( k = 2 \), is 0.05%; the dominant component is the irradiance responsivity uncertainty of the standard trap detector.

### Table 1. Uncertainty budget.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type A</th>
<th>Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference trap detector</td>
<td>0.020</td>
<td></td>
</tr>
<tr>
<td>OPO wavelength (0.02 nm)</td>
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<td></td>
</tr>
<tr>
<td>Sphere source irradiance non-uniformity</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Detector reference plane</td>
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<td></td>
</tr>
<tr>
<td>Detector non-linearity</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Transfer to test detector</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Electrometer (range to range gain error)</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>100 ( \times ) Combined uncertainty</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>100 ( \times ) Expanded uncertainty ( (k=2) )</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

8. Conclusions

A new method using compact, fully automated kHz pulsed OPOs has been developed for calibrating detectors for spectral irradiance and radiance responsivity. The new method was validated by comparing the calibration results obtained using a 1 kHz OPO (with a tunable range from 210 nm to 2400 nm) with those obtained using the CW laser-based conventional method. The agreement of the pulsed OPO-based method and CW laser-based method is 0.02%, which is much smaller than their respective calibration uncertainties. Therefore, these two methods are virtually equivalent. The kHz pulsed OPO has the advantage in reducing or eliminating interference fringes due to its finite spectral width, while the CW laser method has the advantage in 2 to 3 orders of magnitude higher non-linear threshold level. This new method can also be used in other applications such as measurement of optical properties of materials (e.g. spectral transmittance and reflectance). Automated pulsed OPO-based systems can be used to replace double monochromator-based systems, enabling spectral irradiance and radiance responsivity calibrations with significantly reduced uncertainties.

### References


