

Improvement of measurement uncertainties in laser power detector calibration by convolving with the detector's impulse response function

Tao Xu,^{1,2,*} Jing Yu,¹ Erjun Zang,^{1,2} and Haiyong Gan¹

¹Optical Division, National Institute of Metrology, Bei san huan dong lu 18, Beijing, 10013, China

²Department of Precision Instruments and Mechanology, Tsinghua University, Beijing, 10084, China
[*xutao@nim.ac.cn](mailto:xutao@nim.ac.cn)

Abstract: For the calibration of thermal type laser power detectors with slow response time, instability of the input laser significantly contributes to the measurement repeatability. A convolution method is adopted to reduce the impact of source instability. The equivalent incident power is calculated by convolving the real-time power input and the detector impulse-response function (IRF). The value is applied in place of the traditional input power value for the calibration. The IRF is measured using the (1-70) W laser power primary standard at National Institute of Metrology of China. The measurement repeatability of the transfer detector's responsivity is improved from 1.1% using the traditional method to 0.19% using this method. The systematic errors, primarily due to source drift are also reduced. The proposed method can be applied in the calibration of general thermal type laser power detectors.

©2012 Optical Society of America

OCIS codes: (120.5630) Radiometry; (120.4800) Optical standards and testing; (140.3295) Laser beam characterization; (120.3940) Metrology; (040.0040) Detectors.

References and links

1. X. Li, T. R. Scott, C. L. Cromer, D. Keenan, F. Brandt, and K. Moestl, "Power measurement standards for high-power lasers: comparison between the NIST and the PTB," *Metrologia* **37**(5), 445–447 (2000).
2. P. B. Lukins, "New facility for measurement of laser power and calibration of laser power meters," in *Proceedings of the Sixth Bienni Conference of Metrology Society of Australia*, Australian National University, Canberra, October 19–21, 177–180 (2005).
3. V. S. Ivanov, A. F. Kotyuk, A. A. Liberman, S. A. Moskalyuk, and M. V. Ulanovskii, "The state primary standard for the unit of mean laser power," *Meas. Tech.* **50**(7), 695–699 (2007).
4. M. Endo and T. Inoue, "A double calorimeter for 10-W level laser power measurements," in *Proceedings of IEEE Conference on Instrumentation and Measurement* (IEEE, 2005), 688–691.
5. N. Miron and D. G. Sporea, "High accuracy laser power measurement In IR and visible region," *Proc. SPIE* **2321**, 175–178 (1994).
6. S. Kück, F. Brandt, and M. Taddeo, "Gold-coated copper cone detector as a new standard detector for F₂ laser radiation at 157 nm," *Appl. Opt.* **44**(12), 2258–2265 (2005).
7. D. J. Livigni, C. L. Cromer, T. R. Scott, B. C. Johnson, and Z. M. Zhang, "Thermal characterization of a cryogenic radiometer and comparison with a laser calorimeter," *Metrologia* **35**(6), 819–827 (1998).
8. X. Li, T. Scott, S. Yang, C. Cromer, and M. Dowell, "Nonlinearity measurements of high-power laser detectors at NIST," *J. Res. Natl. Inst. Stand. Technol.* **109**(4), 429–434 (2004).
9. S. Kueck, K. Liegmann, K. Moestl, F. Brandt, and J. Metzendorf, "Laser radiometry for UV lasers at 193 nm," *Proc. SPIE* **4932**, 645–655 (2003).
10. J. L. Zheng, Q. H. Ying, and W. L. Yang, *Signal and System* (High Education Press, 2000).

1. Introduction

Laser power metrology systems have been established in many countries for maintaining a nationally accepter standard [1–5]. Most laser power primary standards currently use thermal detectors (radiometers or calorimeters) with an electrical calibration unit [6, 7]. The link is established between the laser power and the electric power through heat. However, the thermal detectors generally have slow response time due to the large absorber heat capacity. The calibration work is mainly focused on the measurement of electrical calibration

responsivity and the laser monitor ratio (during calibration between two laser power meters), for value traceability and value transfer, respectively [8]. Typically, long observation times (usually 10 times of the time constant) after the input incidence is needed to achieve the final state. Then the output will be divided by the simultaneous input electric power or the laser monitor reading. However, there is a problem in this process as the output may not be simply decided by the simultaneous input. The current value wouldn't introduce big errors if the input power is stable enough. However, under a variety of circumstances the laser or the DC power supply may not be stable enough so that efforts need to be devoted for improved uncertainties.

To reduce the impact of unstable input we studied the (1-70) W laser power primary standard at National Institute of Metrology of China (NIM). The detector's IRF (Impulse Response Function) was obtained using fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT) methods. IRFs obtained under different excitation signals were compared. The IRF was applied in electric and laser calibration data processing to enhance measurement repeatability by convolving electric power or laser monitor reading with the detector's IRF. Measurement results by both the convolution method and the traditional method were contrasted.

2. Theory

In the process of laser power detectors' calibration the traditional method for responsivity calculation can be expressed as follows [9],

$$S = \frac{v(t_1)}{p(t_1)}, \quad (1)$$

where, S is the detector's responsivity, $p(t)$ the laser or electric power input signal, $v(t)$ the detector's output signal and t_1 the observation time.

According to the signal and system theory [10], laser power detector can be considered as a dynamic linear time-invariant system. The time domain relationship between the input and the output follows

$$v(t) = \int_0^t h(\tau)p(t-\tau)d\tau, \quad (2)$$

where, $h(t)$ is the detector's IRF which reflects the time domain response properties, and the symbol '*' represents the convolution operation. It can be seen from Eq. (2) that the detector response is not only determined by the transient input.

If the $h(t)$ is known, the equivalent power, $p_{equi}(t)$, which relates to $v(t)$ in practice, can be obtained by convolving $p(t)$ and the normalized $h(t)$, as

$$p_{equi}(t) = \int_0^t \frac{h(\tau)}{\int_0^{t_0} h(t')dt'} p(t-\tau)d\tau, \quad (3)$$

The detector responsivity is then

$$S = \frac{v(t)}{p_{equi}(t)}, \quad (4)$$

which may be employed to eliminate the impact of the unstable input by replacing $p(t)$ with $p_{equi}(t)$.

The time-frequency domain transformation method can be used to calculate $h(t)$. According to the properties of the Fourier transformation (FT), the relationship among frequency-domain functions in Eq. (2) can be expressed as

$$H(f) = \frac{V(f)}{P(f)}, \quad (5)$$

where, f is the frequency variable, $H(f)$ the detector's system transfer function, $V(f)$ and $P(f)$ are the FT of $v(t)$ and $p(t)$ obtained in measurements, respectively. $h(t)$ is obtained from $H(f)$ using IFT through,

$$h(t) = \int [H(f) \cdot \exp(i2\pi ft)] df. \quad (6)$$

The functions adopted in the analysis above are continuous functions though in practice measurements in discrete domain are often encountered. More details can be referred to signal and system theory for the specific transformation method [10].

3. Test device

The detector studied for IRF is the primary standard at NIM for (1-70) W laser power with an electrical calibration unit. It has a cavity absorptive structure to achieve flat spectral response and its time constant is about 85 second. An electrical calibration setup (Fig. 1) is used for the IRF and the responsivity measurements. A direct current (DC) power supply is employed to provide electric power for the detector's electrical calibration unit. A dual-cycle time relay controls circuit to realize automatic measurements. Two voltmeters and a standard resistance are applied for the loading voltage and current measurements. A third voltmeter is used to measure the detector output signal. The data on all voltmeters are recorded and exported for further processing.

The IRF was applied to the laser power detector responsivity measurements in the 532nm laser calibration system. A beam splitter with a 3 degree angle between two surfaces is used to split the laser beam. The transmitted beam enters into the standard detector or the calibrated detector. One of the reflected beams enters into the monitor detector which employs an integrating sphere system with much faster response comparing with the primary standard. A high power mechanical chopper with 3 laser transmittance (3.3%, 10% and 33%) is used for laser attenuation.

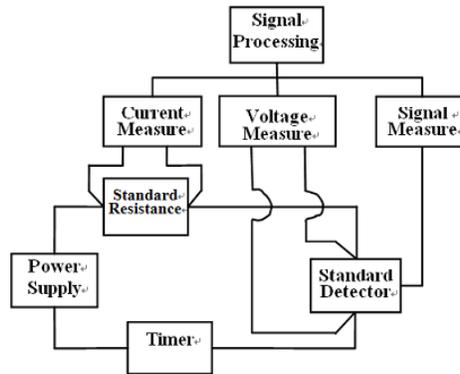


Fig. 1. Electrical calibration device for responsivity measurements.

4. Impulse Response Function (IRF) measurements

To apply the previously proposed convolution method in data processing, the detector's IRF is obtained first according to Eqs. (3) and (4). The IRF can be calculated by applying inverse fast Fourier transform (IFFT) to $H(f)$ (see Eq. (6)). For obtaining $H(f)$ through Eq. (5), a rectangle pulse, $p(t)$ shown in Fig. 2(a), was adopted as the incentive input. Note that the frequency width of $p(t)$ should be greater than that of $v(t)$. Considering the detector time constant ~85 seconds, $p(t)$ were tested at 10 and 15 second, respectively.

The sampling interval of $p(t)$ and $v(t)$, Δt , determines the maximum frequency of $P(f)$ and $V(f)$. In our system Δt was 0.1 second corresponding to 5Hz. This is much wider than the detector's bandwidth. The sampling length of $v(t)$ is 1000 second corresponding to 0.001Hz frequency interval of $P(f)$ and $V(f)$. By zero-padding $p(t)$ is set to the same length.

After measurements using the device shown in Fig. 1, two discrete functions, $p(n\Delta t)$ and $v(n\Delta t)$, are achieved. By applying the FFT to $p(n\Delta t)$ and $v(n\Delta t)$, the frequency domain functions, $P(n\Delta f)$ and $V(n\Delta f)$ (Fig. 2(a) and Fig. 2(b)), are calculated, and then the $H(n\Delta f)$ can be computed using Eq. (5).

Curves of measuring process both in time and frequency domain are shown in Fig. 2. It shows that zero values in $P(f)$ lead to the singular points in $H(f)$. To avoid affecting the IRF calculation, these values should be removed and replaced by linear interpolation before IFFT is done.

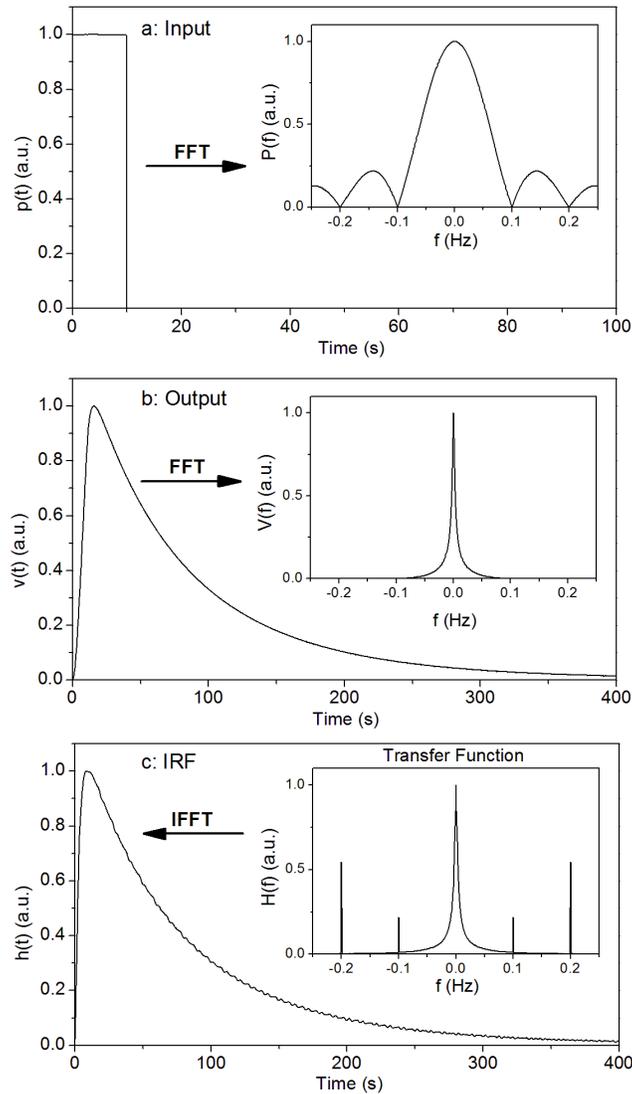


Fig. 2. The process of IRF measuring, (a) input signal and its FFT, (b) output signal and its FFT, (c) IRF and transfer function

For noise reduction, high frequency components of $H(f)$ are cut off at 0.2 Hz, 0.3 Hz and 0.4 Hz separately. By applying IFFT to the corrected $H(f)$, different IRFs are shown in Fig. 3. It shows that the curves are in good agreement because the high frequency components have small energy. However, removing the high frequency components results in an impractical shift at zero. The reserved frequency components of $H(f)$ are proposed to be 30 times wider than the detector's intrinsic bandwidth (0.012Hz in our system).

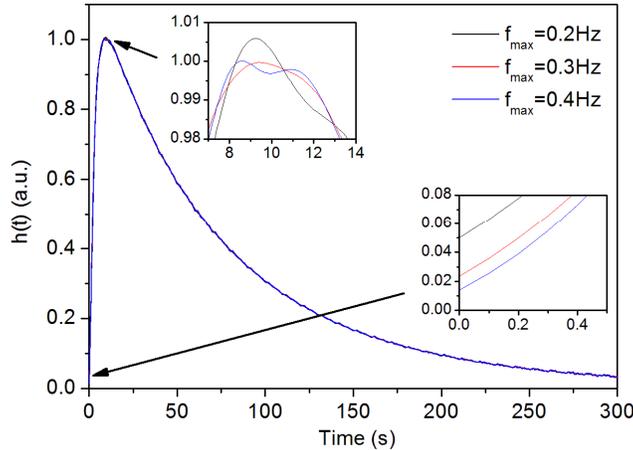


Fig. 3. IRF results calculated from different $H(f)$'s with high frequency components cut off to 0.2Hz, 0.3Hz and 0.4Hz.

The $h(t)$ is measured with both 10 seconds and 15 seconds width excitation signals separately, and their curves are in good consistency. In practical measurements, short pulse input means wider frequency band, and long pulse bring higher signal to noise ratio. The pulse width should be adjusted according to the actual situation.

5. IRF application

To test the effect of the convolution method, electrical calibration is done using the device shown in Fig. 1. Both the traditional method expressed in Eq. (1) and the convolution method showed in Eq. (4) are adopted independently for the responsivity measurement. The relative standard deviation of the responsivity calculated by convolution method is 0.017% which is 50% better than that (0.039%) by the traditional method.

The convolution method also is then applied to the transfer detector's responsivity measurements. The responsivity is calibrated by the primary standard with the 532nm laser calibration system. The laser output has a poor stability of 1.5% within 10 minutes. Both convolution and traditional methods are used in the standard's monitor ratio calculation. The measurement repeatability (shown in Fig. 4) is 1.1% with the traditional method and 0.19% with the convolution method, respectively. The requirements to the laser source stability have been lowered with the proposed method.

The convolution method can also reduce systematic errors. In addition to random fluctuations, the source may have drift characteristics. The power drift will inevitably lead to systematic error by the traditional method, while, it can be reduced with the convolution method. Figure 5 shows the trends of voltage, current, power and resistance versus time during electric calibration on our newly developed UVD10-1W laser power standard for excimer lasers. It can be seen that there is a positive power drift caused by voltage change. According to Eq. (1) the responsivity computed with the traditional method will be smaller than the actual situation. Combining 14 measurements the average responsivity by the traditional method is 0.06% smaller than that by the convolution method. The error (with traditional method) is led by the power drift. Furthermore, the repeatability is improved to 0.025% from 0.038%.

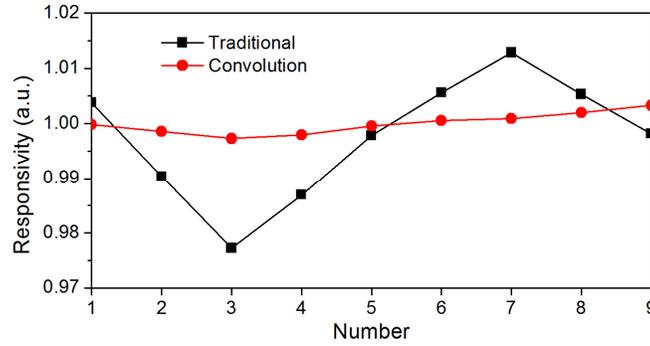


Fig. 4. Calibration data by both the traditional method and the convolution method under 532nm laser condition.

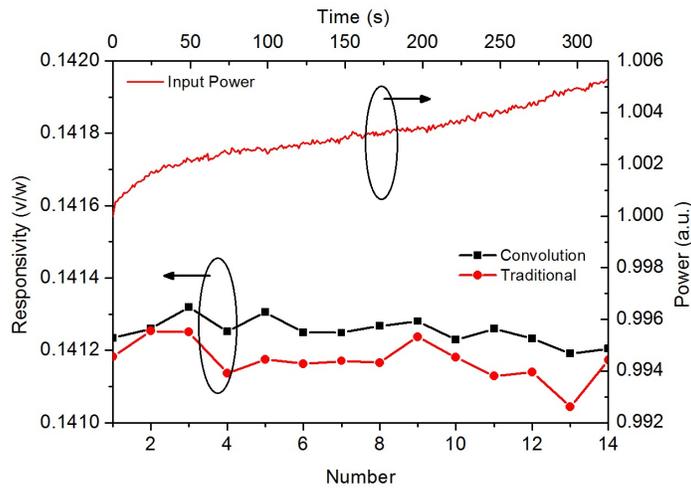


Fig. 5. Results comparison with different algorithms when source power exhibits drift

6. Conclusion

A convolution method based on the signal and system theory is adopted to reduce the impact of source instability. The IRF is measured using the (1-70) W laser power primary standard at NIM. The measurement repeatability of the transfer detectors responsivity is improved from 1.1% using the traditional method to 0.19% with the convolution method. The systematic errors dominated by source drift are also reduced. The proposed method can be applied in the calibration of general thermal type laser power detectors including cryogenic radiometers.