Nonlinearity Measurement of UV Detectors using Light Emitting Diodes in an Integrating Sphere

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Abstract. We measured the nonlinearity of UV detectors using a linearity tester which consists of four UV light emitting diodes (LEDs) and an integrating sphere. The tester measures photocurrent ratios of a detector by flux addition for a range over 6 decades with high speed and accuracy. The nonlinearity of irradiance responsivity is determined from the measured of photocurrent ratios by interpolation. We observed a clear dependence of nonlinearity upon the size of detector aperture.

I. Introduction

In the ultraviolet (UV) radiometry, most detectors are calibrated for their spectral irradiance responsivity. Nonlinearity of a detector is the property that the responsivity does not remain constant when the signal is higher than a certain level. An established method to measure the nonlinearity of detectors is the flux addition method using lamps or lasers as light source, which requires no reference standard [1,2]. However, this method measures the nonlinearity of photocurrent ratios rather than that of detector responsivity. Another method for directly measuring the nonlinearity of responsivity is to use neutral filters with a laser [3], but this method requires a calibrated reference detector.

We present in this paper a new flux-addition type linearity tester, in which the detector under test is illuminated by LEDs inside an integrating sphere. The linearity tester using LEDs as light source is recently reported with its advantages of fast and accurate measurement in a wide range [4]. The additional use of integrating sphere eliminates the need of light shielding and flux alignment, resulting in the increased practicability and operator's safety especially in the UV radiometry. We used this linearity tester to measure the nonlinearity of a Si photodiode with different aperture sizes at a UV wavelength around 400 nm. We show how the nonlinearity of irradiance responsivity can be determined from the measured photocurrent ratios, and present also the measured effect of aperture size on the detector nonlinearity.

II. Experimental setup

Figure 1 shows schematically the experimental setup. LEDs are installed in pair on an integrating sphere and driven independently by two current sources (Keithley, Model 2400). For high irradiance level, more than one LED can be simultaneously driven by each current source, which we designate collectively as LED A or LED B. In the experiment, we used four UV LEDs (Opto Technology, Model OTLH-360-UV); two for LED A and two for LED B. Note that this scalability of irradiance level simply by changing the number of LEDs is one of the important practical advantages the LED-based linearity tester provide. The peak wavelength and the spectral bandwidth of the LEDs are measured to be 396 nm and 20 nm, respectively.

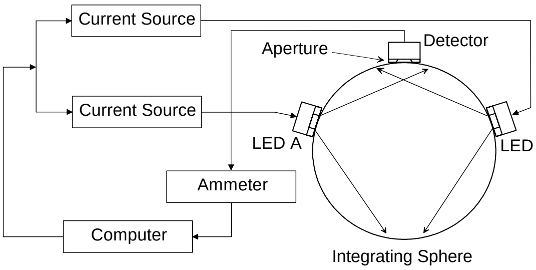

Figure 1. Schematic setup of the linearity tester using LEDs in an integrating sphere.

The integrating sphere is made of synthetic resin with a diameter of 40.0 cm, and its inside is uniformly coated with polytetrafluoro-ethylene (PTFE). Using two kinds of jig, PTFE powder is formed into the pentagonal and hexagonal shape plates, which build, similar to a football, a sphere surface with the outside diameter of 40.0 cm. The surfaces of jigs are roughened to an average roughness of (2.8 ± 0.015) μm for enhancing the diffuse reflection of the PTFE plate surface. The plates have a density of 1.2 g/cm^3 and a thickness of 1.2 cm, and are glued to the inside wall of the sphere with vacuum grease. Figure 2 shows the formed PTFE plates and the hemisphere coated with such PTFE plates.

(a) **(b)**

Figure 2. Photographs of the PTFE plates formed to a pentagonal and hexagonal shape (a) and the hemisphere coated with such PTFE plates (b).

The photodiode under test (UDT Sensors Inc., Model UV-100) is positioned on a hole at the top of the integrating sphere (see Fig. 1). In order to define the active area irradiated, an aperture of known diameter is placed in front of the detector. The photocurrent of the photodiode is measured with a calibrated ammeter (Keithley, Model 6485). All instruments are interfaced with a computer.

The procedure of nonlinearity measurement in detail is described in the reference [4]. We performed the measurement for different active aperture areas with a diameter of 11.28 mm (no aperture), 8 mm, 5 mm, and 2 mm. For the apertures with diameter not smaller than 5 mm, two LEDs, i.e. one for LED A and one for LED B, were sufficient for measuring the detector nonlinearity, where the injection current for each LED is varied from 0.1 mA to 300 mA. For the 2-mm diameter aperture, however, two additional LEDs were required, i.e. two for LED A and two for LED B, so that the injection current is varied up to

600 mA for each set. In both cases, the resulting photocurrent of the photodiode spanned from 10^{-10} A to 10^{-4} A over six decades. We repeated the measurement three times for each aperture size with different initial photocurrents of $1.0 \cdot 10^{-10}$ A, $3.0 \cdot 10^{-10}$ A, and $5.0 \cdot 10^{-10}$ A.

III. Results

Figure 3 shows the measured photocurrent ratios $(i_{A+B})/(i_A + i_B)$ for different aperture diameters as a function of the photocurrent level i_A. Here, i_A, i_B, and i_{A+B} are the photocurrent of the photodiode irradiated by LED A, LED B, and both of them, respectively. Each symbols show the measured values, while the lines are the numerically interpolated values. From the measured photocurrent ratios in Fig. 3, the nonlinearity of the detector responsivity is determined as described below.

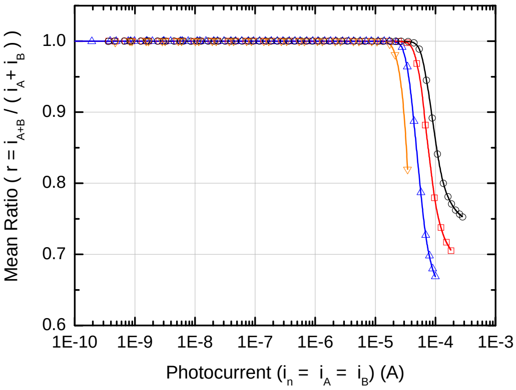

Figure 3. Plot of the measured photocurrent ratios $(i_{A+B})/(i_A + i_B)$ for different aperture diameters (○: no aperture, □: 8 mm, △: 5 mm, ▽: 2 mm) and the numerically interpolated values (lines) as a function of the single photocurrent level i_A.

According to the measurement procedure [4], the single photocurrents i_A and i_B are adjusted to be nearly the same and the combined photocurrent i_{A+B} is set as the single photocurrent level in the next step, so that the current ratio r_n in the n-th measurement step can be written as following:

$$r_n = \left.\frac{i_{A+B}}{(i_A + i_B)}\right|_n = \frac{i_{n+1}}{2 \times i_n} \quad for \ i_A = i_B = i_n \ and \ i_{n+1} = i_{A+B}. \tag{1}$$

As the initial value i_0, the lowest photocurrent can be chosen so that the repetition runs until the maximal injection currents for LEDs are achieved. Because the detector responsivity R_n in each step is defined as the ratio of the photocurrent i_n and the irradiance E_n, and the irradiance is doubled in each step, i.e. $E_{n+1} = 2E_n$, we can also write Eq. (1) as following:

$$r_n = \frac{R_{n+1} \cdot E_{n+1}}{2R_n \cdot E_n} = \frac{R_{n+1}}{R_n} \tag{2}$$

From Eq. (2), we can calculate the relative responsivity of the detector from the photocurrent ratios r_n as

$$R_n(i_n) = \ r_{n-1} \cdot r_{n-2} \cdots r_0 \cdot R_0(i_0) \ , \tag{3}$$

where R_0 is the constant relative responsivity in the linear range of low photocurrent. We repeat the calculation of the relative responsivity R_n according to Eq. (3) beginning with different initial values i_0, which are photocurrent values around $1.0 \cdot 10^{-8}$ A in Fig. 3, such as $1.0 \cdot 10^{-8}$ A, $3.0 \cdot 10^{-8}$ A, and $5.0 \cdot 10^{-8}$ A. In this range, the detector can be regarded as linear ($R = R_0$). Numerically interpolating the data sets of photocurrents and relative responsivities $(i_n, R_n(i_n))$, we obtain the relative responsivity as a function of photocurrent. Finally, we obtain the nonlinearity of the detector responsivity NL as a function of photocurrent i:

$$NL(i) = \frac{R(i)}{R_0} - 1. \tag{4}$$

Figure 4 shows the resulting nonlinearity of the irradiance responsivity for the photodiode with different aperture diameters. The result shows clearly that the photocurrent level at which the nonlinearity occurs decreases, as the aperture size decreases. The nonlinearity of the photodiode with the 2-mm diameter aperture become nonlinear to $NL = 1.0 \cdot 10^{-4}$ at a photocurrent of $3.0 \cdot 10^{-7}$ A, while the same nonlinearity occurred at $3.0 \cdot 10^{-5}$ A without aperture.

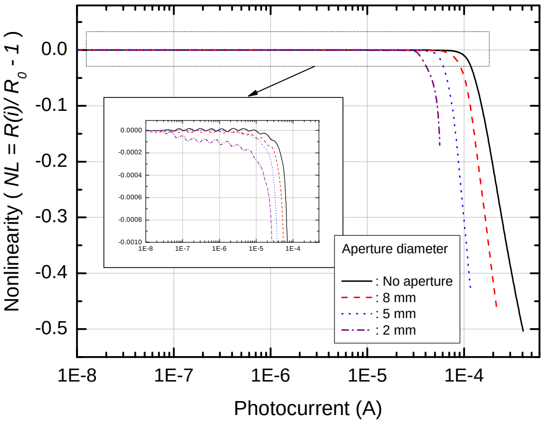

Figure 4. Nonlinearity of the irradiance responsivity for the photodiode with different aperture diameters, determined from the measured nonlinearity of the photocurrent ratios.

IV. Conclusion

We developed a linearity tester using LEDs in an PTFE coated integrating sphere. The use of integrating sphere enhanced the practicality and safety of the LED-based linearity tester in the UV radiometry. The feasibility of the tester is demonstrated by measuring the nonlinearity of a Si photodiode with different aperture sizes at a wavelength around 400 nm. We introduced a method to determine the nonlinearity of irradiance responsivity from the nonlinearity of photocurrent ratios measured by flux addition. With the presented methodology, we expect to be able to accurately calibrate a UV detector even in the nonlinear region for applications at high irradiance level.

References

[1] L. P. Boivin, Automated absolute and relative spectral linearity measurements on photovoltaic detectors, *Metrologia, 30*, 355-360, 1993.

[2] J. Fischer, L Fu, Photodiode nonlinearity measurement with an intensity stabilized laser as a radiation source, *Appl. Opt. 32*, 4187-4190, 1993.

[3] T. Kubarsepp, A. Haapalinna, P. Karha, E Ikkonen, Non-linearity measurements of silicon photodetectors, *Appl. Opt. 37*, 2716-2722, 1998.

[4] D. J. Shin, D. H. Lee, C. W. Park, S. N. Park, A novel linearity tester for optical detectors using high-brightness light emitting diodes, *Metrologia, 42*, 154-158, 2005.