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溯源至低温辐射计的硅陷阱探测器紫外波段绝对光谱响应度测量

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摘　要:介绍了溯源至低温辐射计的紫外绝对光谱响应度测量装置,对硅陷阱探测器在三个激光波长点进行了绝对光谱响应度校准实验.测量了硅陷阱探测器的空间均匀性和非线性系数,分析了影响测量准确度的各不确定度分量.实验表明:硅陷阱探测器在紫外波段 266、325、379 nm 三个激光波长点处的绝对光谱响应度测量扩展不确定度分别为 0.19%、0.14%、0.11%,可作为紫外波段光辐射功率基准保持和传递的标准探测器,用于提高紫外波段光谱辐射度的校准能力.

关键词:紫外波段;硅陷阱探测器;绝对响应度;低温辐射计;空间均匀性;非线性

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Ultraviolet Spectral Responsivity of Silicon Trap Detectors Traceable to a Cryogenic Radiometer

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Abstract: An experimental facility designed for the calibration of silicon trap detectors against a laser-based cryogenic radiometer at three laser wavelengths in the Ultraviolet (UV) region was described. The experimental results for the spatial nonuniformity and nonlinearity of the silicon trap detector were shown and discussed. The component uncertainties associated with the measurement of radiation power and spectral responsivity of silicon trap detectors were analyzed. As the secondary detector standards, the expanded uncertainty of the spectral responsivity at three UV laser lines 266, 325, 379 nm is 0.19%, 0.14%, 0.11%, respectivily. This can improve the calibration capability of UV band spectral radiance.

Key words: Ultraviolet; Silicon trap detector; Spectral responsivity; Cryogenic radiometer; Spatial nonuniformity; Nonlinearity

OCIS Codes: 120.3940; 120.5630; 040.6040; 040.7190; 350.4800

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0 Introduction

Radiometry in the Ultraviolet (UV) spectral region is a very important subject for several fields, such as optical technology, remote sensing, and atmospheric research[1]. In the visible and near-infrared spectral regions, the traceability chain for radiometry is mainly based on the silicon trap detectors, consisting three silicon photodiodes (reflectance type), calibrated against the cryogenic radiometer at some discrete wavelengths[2-3]. The spectral responsivity scale is then extended over the visible and near-infrared spectral region by a combination of measurements and a interpolation physical model[3-5]. In the visible wavelength range, this interpolation allows the estimation uncertainties down to 0.02%[6]. However, in the UV range, it is difficult to find a satisfactory physical model for the extrapolation of trap silicon detectors spectral responsivity. Consequently, improved calibrations have to use laser-based cryogenic radiometer at several UV laser lines combining a monochromator-based facility. For instance, the Physikalisch-Technische Bundesanstait (PTB, Germany) has achieved relative standard uncertainties of about 0.1% to 0.2% between 200 nm to 410 nm by utilizing the monochromatized radiation of an argon arc plasma, and comparison with their laser-based cryogenic radiometer at five laser lines in the UV indicated excellent agreement[7]. In many national metrology institutes, the typical relative standard uncertainty of the spectral responsivity of the Si-photodiode-based transfer detectors is between 0.1% to 1% in the wavelength range from 250 nm to 400 nm in the CCPR K2.c key comparison carried out by 14 participating national metrology institutes[8]. In our study, laser-based calibration in the UV is carried out at three wavelengths and their uncertainty budgets are presented for optical power and spectral responsivity measurements made on this calibration facility.

1 Description of the facility

Fig. 1 shows the schematic setup of the calibration facility. The primary standard for the optical power measurement is a mechanically cooled cryogenic radiometer, manufactured by the National Physical Laboratory (NPL) and Oxford Instruments Ltd, UK[9]. The cryogenic radiometer has a specified wavelength range from 0.2 μm to 50 μm. The copper cavity is placed in high vacuum and operated at 15 K. The cavity, geometrically designed to reduce the light losses, has an absorptance of 0.99997 at 632.8 nm measured by the manufacture. The change of the cavity absorptance is neglible with wavelength down to 200 nm[7]. In the spectral range between 488 nm and 1 064 nm, the spectral responsivity of silicon trap detectors is realized with uncertainty below 0.03% by calibrated against the cryogenic radiometer at a set of laser wavelengths in our previous study[10].

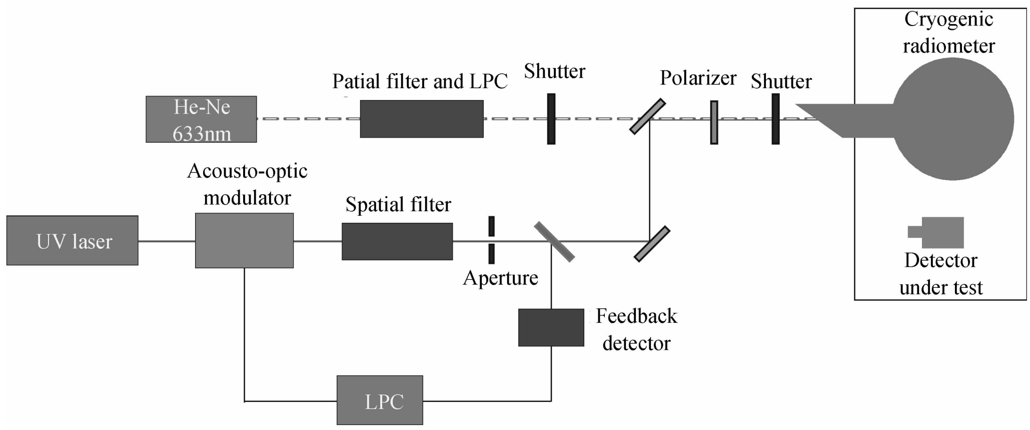

Fig. 1 The schematic setup of the calibration facility

The laser sources employed are three single frequency CW lasers at 266 nm, 325 nm and 379 nm. The calibrationradiation power is about 100 μW at three laser points, higher than monochromator-based radiation. Usually, the monochromator sources provide spectral radiation power less than 20 μW below 350 nm[7-8]. The laser beam passing through an acousto - optic modulator for stabilization , is spatially filtered, collimated to a beam diameter of about 3 mm ($1/e^2$) and then sampled by the beam splitter to a reference detector which provides feedback for the laser power controller (LPC). The beam is stable to better than ±0.05%, ±0.03%, ±0.015% typically, over a period of at least 35 mins at 266 nm, 325 nm, 379 nm, respectively(Fig. 2).

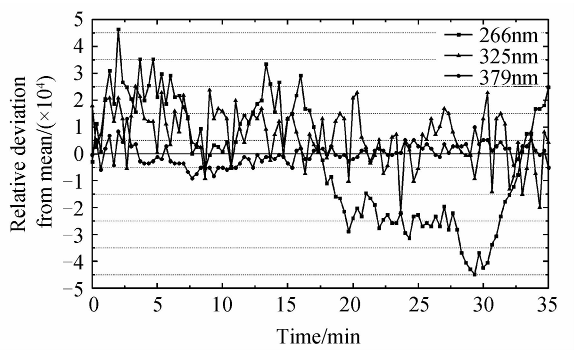

Fig. 2 Temporal profile of the intensity-stabilized UV laser output over a half-hour period

Comparison of the detectors against the cryogenic radiometer is carried out with the detectors in the same relative position with respect to the laser beam. Although, a quadrant photodiode assembly inside the cryogenic radiometer is used to measure the scattering light, but because the detectors are of different apertures, the same size diaphragm relative to the aperture size of the cryogenic radiometer is in front of the detectors in order to reduce the stray light correction. As the quadrant photodiodes are not sensitive in the UV spectral region, the visible He-Ne laser is used to align the UV laser beam into the cavity of the cryogenic radiometer to minimize the scattering light.

Accurate and quick Brewster window transmittance measurements are not easy to make and contribute significantly to the total uncertainty of the calibration. Conventionally, the window was moved in and moved away from the beam path, to allow measurement of the incident beam using a detector, and the transmittance was calculated as the ratio of these two measurements[11]. In our study, a three-limb vacuum tube was installed between the cavity and the window, seen in Fig. 3. On one side of the tube, a clip-type quick open blind plate was designed to measure the optical power behind the window with a photodiode. The photodiode moved to the front of the window and adjusted to allow for the displacement of the beam by a precision platform, measure the optical power again. The window transmittance was calculated as the ratio of these two measurements . In comparison with

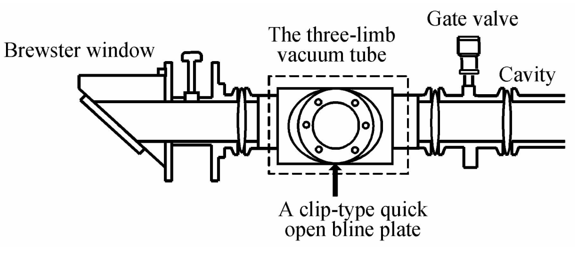

Fig. 3 Layout for measurement of transmittance of the Brewster window using a three-limb vacuum tube

conventional measurement method, we think this method is easier to operate without moving the window and also available in other spectral regions.

2 Characterization of silicon trap detectors

Silicon trap detectors as transfer detectors have been extensively described by other authors[12-13]. Inside the silicon trap detector, several photodiodes are arranged in such a way that the incoming beam undergoes several reflections before it leaves the detector. Almost all the light is absorbed during the process and the residual beam is either returned along the incident beam, in the so-called reflection trap.

In the UV spectral region, the stability of silicon photodiodes has been investigated[14]. Comparing all investigated silicon photodiodes, the S1337 and S5227 were the most stable ones in the wavelength range above 250 nm. Therefore, our transfer standard detectors are composed by three single-element photodiodes (Hamamatsu S1337-1010), disposed in a reflective-trap configuration. In this letter, the properties of the transfer standarddetectors, such as the spatial uniformity and non-linearity, have been investigated in the UV.

2.1 Spatial uniformity

Fig. 4 shows the result of the uniformity measurement of a silicon trap detector, one of the transfer standard detectors, using the cryogenic radiometer facility at 379 nm. The spot size, focused onto the detector surface, has a diameter of about 0.5 mm. The detector is scanned over a 12 mm× 12 mm area with a step width of 0.5 mm. For the summary of results given in Table 1, the uniformity of detector contributing to the total uncertainty of spectral responsivity is taken into account only within a circular area of 4 mm diameter in the center of the sensitive

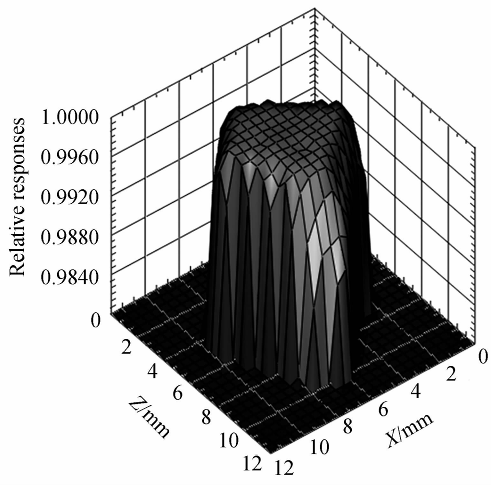

Fig. 4 Uniformity of responsivity of the silicon trap detector at 379 nm

Table 1 Spatial nonuniformity measured for the silicon trap detector

Diameter/mm	Nonuniformity/($\times10^{-4}$)
3	2.6±0.3
4	3.0±0.5
5	4.1±1.2

surface. The detector exhibits a good uniformity up to area with diameter of 4 mm. Further increasing the diameter up to 5 mm degrades continuously the uniformity.

2.2 Nonlinearity

The non-linearity of the detectors has been studied from microwatt power level to milliwatt power level over three orders of magnitude, in which the silicon trap detectors are calibrated. A similar technique, described in details in Ref. [15], is used to measure the non-linearity of the detectors. An intensity-stabilized laser beam is split into two beams. Blocking one or the other of the beams or superimposing them on the detector, the photocurrents, and are measured. The non-linearity is

$$NL=(i_{A+B}-i_A-i_B)/i_{A+B} \quad (1)$$

Fig. 5 shows nonlinearity versus photocurrent of the silicon trap detector at 379 nm. It turns out that the non-linearity of the silicon trap detector is within $\pm2\times10^{-4}$ from several microwatt power to hundreds of micro watts level, which cover the most of monochromator-based sources. The maximum optical power tested is 2 mW avoiding to damage the detector, and the NL rises to 3.6×10^{-4}, which may be caused due to the test optical power is close to the saturation level.

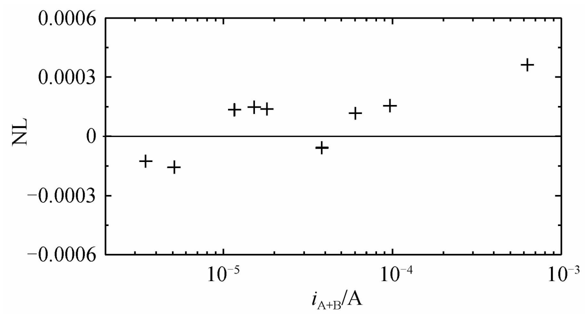

Fig. 5 Nonlinearity of silicon trap detector at 379 nm

3 Uncertainties of the spectral responsivity

The component uncertainties which contribute to the combined uncertainty associated with UV radiation power at three laser lines are shown in Table 2. This is dominated by the uncertainty component due to the measurement of the transmittance of the Brewster window and the measurement repeatability of radiation power. The window transmittance is measured at all wavelengths before and after a calibration. The relative uncertainty is 3×10^{-4} at 379 nm and rise up to 7×10^{-4} at 266 nm. This is mainly because the stability of laser beam and the silicon photodiode used to measure the transmittance is a little worse in the short wavelength UV.

Table 2 Uncertainty components associated with the measurement of the UV power (all values are percentages)

Source of uncertainty	266 nm	325 nm	379 nm
Type A			
	0.03	0.02	0.01
Type B			
Window transmittance	0.07	0.05	0.03
Cavity absorptance	0.001	0.001	0.001
Stray light	0.02	0.02	0.02
Electrical power measurement	0.001	0.001	0.001
Sensitivity of radiometer	0.0006	0.0006	0.0006
Changes in scat. & thermal rad.	0.0006	0.0006	0.0006
Combined standard uncertainty	0.079	0.058	0.038
Expanded uncertainty (k=2)	0.16	0.12	0.08

Table 3 lists the uncertainty associated with the measurements of spectral responsivity of silicon trap detector based on the cryogenic radiometer. In addition, the polarization dependence of the silicon trap detectors is not considered because the detector calibration is performed with a linear polarized beam. But the analysis of the polarization dependence of the trap detectors is important when using the detectors with light at other states of polarization, lamps as optical sources, for example. The reproducibility of angle of incidence has minimal impact on the responsivity with a strict angle control better than ±0.1°. Summarized, the expanded uncertainty ($k=2$) is 0.11% at 379 nm, rising to 0.19% at 266 nm.

Table 3 Uncertainty components associated with the measurement of spectral responsivity of silicon trap detector (all values are percentages)

Source of uncertainty	266 nm	325 nm	379 nm
Type A			
	0.03	0.03	0.02
Type B			
Optical power measurement	0.079	0.058	0.038
Detector and amplifier calibration	0.01	0.01	0.01
Non-uniformity of detector	0.03	0.02	0.02
Nonlinearity	0.02	0.02	0.02
Reproducibility of angle of incidence	0.005	0.005	0.005
Combined standard uncertainty	0.093	0.069	0.053
Expanded uncertainty (k=2)	0.19	0.14	0.11

4 Conclusion

A calibration set-up based on a cryogenic radiometer at three laser lines has been described for the measurements of spectral responsivity of silicon trap detectors in the UV spectral region. The spatial nonuniformity and nonlinearity of silicon trap detectors are investigated via experiments. The component uncertainties which contribute to the total uncertainty associated with the measurement of radiation power and spectral responsivity of silicon trap detectors are analyzed. The relative expanded uncertainty of the spectral responsivity of silicon trap detectors at laser lines is $U=10^{-3}$ ($k=2$) in the UV. The silicon trap detectors will be used as transfer detectors to calibrate working detectors in the UV spectral region.

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