Absolute spectral response calibration of a photodetector using a spectrally flat detector and a self-calibrated silicon photodiode

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ABSTRACT. In this communication we describe the absolute spectral response calibration of a photodetector by a method which extends the spectral range of the silicon photodiode self-calibration technique. The self-calibration of a photodiode was performed at the 632.8 nm HeNe laser line and then used to calibrate the absolute response of a spectrally flat thermal detector (ECPR). The other characteristics of the thermal detector that are important to this experiment and which we measured are: linearity, uniformity and window transmittance. The thermal detector was then used to measure the absolute spectral response of a photodetector (DRTIP) in the 350 to 1000 nm wavelength range using a monochromator and a xenon arc as the tunable source. Comparison with previous measurements of this detector's absolute spectral response in the 400 to 800 nm range showed an average difference of $-0.1 \pm 0.6\%$.

RESUMEN. En este trabajo describimos la calibración de la respuesta espectral absoluta de un fotodetector mediante un método que extiende el intervalo espectral de la técnica de autocalibración de fotodiodos de silicio. Se efectuó la autocalibración de un fotodiodo en la línea de 632.8 nm del láser de HeNe y posteriormente se usó para calibrar la respuesta espectral de un detector térmico de respuesta espectral plana (ECPR). Las otras características del detector térmico que son importantes en este experimento, y que fueron medidas, son: linealidad, uniformidad y transmitancia de la ventana. De esta forma, el detector térmico fue empleado para determinar la respuesta espectral absoluta de un fotodetector (DRTIP) en el intervalo de longitudes de onda de 350 a 1000 nm usando un monocromador y una lámpara de luz de arco de xenón como la fuente entonable. Al comparar nuestros resultados con mediciones previas de la respuesta espectral absoluta de este fotodetector en el intervalo de 400 a 800 nm, se observó una diferencia promedio entre ambos de $-0.1 \pm 0.6\%$.

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1. INTRODUCTION

The recent development of the silicon photodiode self-calibration (SPSC) technique [1,2] has opened a whole new era in high accuracy absolute radiometry. There are many different techniques that can be used to extend the SPSC method in order that it forms the absolute basis of radiometric measurements in a wider range of applications and over a broader spectral range. In this paper we demonstrate a method for extending the spectral range of the SPSC technique in the calibration of the absolute spectral response of a photodetector in the 350 to 1000 nm range.

The method begins with the self-calibration of a silicon photodiode at 632.8 nm according to the procedure described by Zalewski and Geist [1]. In addition to using an amplitude stabilized HeNe laser we also made measurements using simply a beam splitter and a monitor detector without the active feedback stabilization loop. The specular reflectance was measured in two ways; either using a second photodiode as a reflectometer or using a plane mirror to reflect the laser beam back onto the photodiode to be measured.

The self-calibrated silicon photodiode was then used to calibrate a gold-black coated thermal detector at the HeNe laser wavelength. The thermal detector was fitted with a quartz window in an evacuable housing. A correction therefore had to be made for the window transmittance. The linearity of response of the thermal detector was checked against a silicon photodiode. The uniformity of response over the surface of the thermal detector was also measured.

A monochromator based spectral comparator was used in the 350 to 1000 nm wavelength range to transfer the calibration from the thermal detector to another detector. We measured the absolute spectral response of a silicon photodiode in this way and compared the results with earlier measurements in the 400 to 800 nm range. The average difference between these two techniques was $-0.1 \pm 0.6\%$.

2. EXPERIMENTAL PROCEDURE

2.1. Silicon photodiode self-calibration

We followed the published SPSC procedure [1] with a few minor differences: pure water, instead of a dilute boric acid solution, was used as the oxide bias electrode and we did not paint over the anode ring to insulate it. The conductivity of distilled water is high enough to enable sufficient negative charge to build up in the drop, and the surface tension of the water is enough to keep the drop away from the anode electrode. We also measured the diffuse reflectance loss for our particular photodiode instead of assuming a value based on measurements with other detectors.

The diffuse reflectance was measured using a large area silicon photodiode with a hole in the center. This type of detector was previously described for use in the measurement of very small reflectance losses from cavity shaped thermal detectors [3]. The laser radiation passes through the hole in the reflectometer detector, is normally incident on the surface of the photodiode being measured and specularly reflected back through the hole. The distance between the photodiode and the reflectometer was varied in order to cover in two steps a solid angle of nearly 2π steradians. (See Ref. [3] for a more detailed description). The reflectometer readings were corrected to account for the area of its surface which is covered by the electrodes. In both reflectometer positions the specular reflection was, of course, not included. The reflections at angles approaching 90° from normal incidence were also not included in the measurements. The latter were assumed to be negligible and the former was measured in a separate experiment. To measure the amount of incident radiation the reflectometer was rotated by 180° and shifted laterally to intercept the laser beam. For the photodiode used in this study we obtained a diffuse reflectance factor (outside $\pm 1°$ of specular) of 0.0002. The specular reflectance at normal incidence was 0.1040.

The complete SPSC procedure was first carried out using an amplitude stabilized expanded laser beam [4]. The specular reflectance, reverse bias and oxide bias measurements were repeated using an unexpanded HeNe laser beam and a beamsplitter with a monitor detector to track the changes in laser amplitude. As expected, the second set of SPSC measurements were less precise than those obtained using the amplitude stabilized laser. We also estimated that the specular reflectance measurements were less accurate because of the non-collimated radiation (scattered light) around the laser beam. We attempted to reduce this extraneous radiation by aperturing the beam; however, we could not reduce it as much as when a spatial filter and beam expanding telescope were used as in the first set of SPSC measurements. The difference in the absolute spectral response values obtained with both sets of SPSC measurements was 0.8%.

In the above measurements the specular reflectance was determined with a second silicon photodiode acting as a reflectometer, following the same procedure of the published SPSC technique [1]. Then a second method of measuring specular reflectance was also tried in order to have a more reliable basis for the value that we used. This involved using a plane mirror to return the specularly reflected beam back to the photodiode being calibrated. In this case the silicon photodiode acts as its own reflectometer. With the mirror blocked the photodiode measures the incident radiation. Unblocked it measures the incident plus reflected radiation multiplied by the reflectance of the mirror. Because the reflectance of the mirror has to be measured, this technique is slightly less accurate than the one described above. We obtained a difference of 0.7% between values of specular reflectance measured by the two techniques. Since we did not use the amplitude stabilized laser, the difference may be due in large part to poor measurement precision. If this is indeed the case, then a significant improvement can be made by using a good quality analog divider circuit to obtain the ratio of the photodiode to monitor outputs in a simultaneous rather than sequential measurement. In our calculations we used the most accurate value of specular reflectance obtained with the stabilized laser beam.

2.2. Thermal detector calibration

The next step is the calibration of the absolute response of a thermal detector using the self-calibrated silicon photodiode as a standard. We used the most accurate value of the photodiode's absolute response; that is, the one we obtained using an amplitude stabilized laser beam that had been spatially filtered and expanded. The thermal detector we used was a gold-black coated, electrically calibrated pyroelectric radiometer (ECPR). Of course, the electrical calibration feature was not necessary for our measurements; however, it was convenient for checking the stability of response of the pyroelectric detector. The ECPR calibration was performed using the stabilized laser setup.

Since the laser beam underfilled the active area of the ECPR and since in subsequent measurements the active area was more nearly filled, it was necessary to measure the spatial uniformity of response of the ECPR. This was accomplished by translating the ECPR vertically and horizontally so that the laser beam scanned along these two diameters. Variations as high as 1.3% were observed, but in the average they led to only a 0.1% adjustment of the ECPR calibration factor.

The calibration of the ECPR was performed at a radiant power level of just under 2 mW. Since the ECPR was to be used in the 20 to 300 μW range, the calibration had to be constant over the range from 0.02 to 2 mW. Using the stabilized HeNe laser the ECPR response was checked against a silicon photodiode plus amplifier that was known to be linear [5,6,7]. The radiant power level was varied by means of neutral density filters. The lowest level measured was about 3 μW. The ECPR was found to be linear over this entire range with an offset of 0.4 ± 0.2 μW (ECPR measured too high). This offset was not detectable in the instrument zeroing steps; *i.e.* at zero radiant and electrical power no offset was apparent.

Finally, to improve the signal to noise ratio at the low radiant power levels the ECPR was fitted with a quartz window in an evacuable housing. The transmittance of the quartz window was measured with a monochromator/xenon arc source and a silicon photodiode. The measured values of the transmittance along with the values obtained from the calculated Fresnel reflection losses at normal incidence are presented in Table I. Note that the largest difference is 0.7% and the mean difference is slightly more than 0.1%. Judging from these results we decided to use the calculated transmittance values to obtain the spectral variation of the ECPR calibration factor.

The other spectrally variable parameter in the ECPR response is the reflectivity of the gold-black coating. The spectral reflectance has been measured [8]. Since the maximum variation in reflectivity is about 0.3% in the 350 to 1000 nm region, we used the literature values of the relative spectral reflectance of gold-black to obtain the spectral variation of the ECPR calibration factor.

2.3. ECPR Based spectral response calibration

Having the absolute spectral response of the ECPR over a large wavelength range and broad dynamic range enabled us to calibrate the absolute spectral response of other photodetectors. The photodetector we chose to calibrate was one of the NBS Detector Response Transfer and Intercomparison Packages (DRTIP) [7]. This is a silicon photodiode radiometer whose radiometric properties are well characterized. The absolute spectral response of the DRTIP was previously determined [9] by comparison to an electrical substitution thermopile radiometer (ESTR) [10]. The monochromatic radiation used in that calibration transfer was obtained from several laser lines that were amplitude stabilized, spatially filtered and expanded for maximum precision and accuracy [11]. The DRTIP reflectance was also measured using the same laser lines in order to calculate the internal quantum efficiency, which can be interpolated over the 400 to 900 nm range quite

TABLE I. Quartz window transmittance.

Wavelength (nm)	Measured Transmittance	Calculated Transmittance
363	0.934	0.929
405	0.934	0.930
436	0.931	0.931
546	0.928	0.932
577	0.927	0.933
633	0.926	0.933
697	0.929	0.934
750	0.931	0.934
812	0.932	0.934
882	0.934	0.934
912	0.933	0.934
922	0.934	0.934
966	0.932	0.934
992	0.936	0.934

accurately [12]; the reflectance can also be fitted [13] to a curve predicted by the physics of the reflectance of thin films [14]. Thus the absolute spectral response could be accurately obtained in the 400 to 900 nm range from measurements at relatively few wavelengths.

In the SPSC/ECPR based calibration of the absolute spectral response of the DRTIP detector, the source of monochromatic radiation was a xenon arc and a double grating monochromator; the experimental set-up used for this purpose is shown in Fig. 1. A double monochromator was used to reduce the possible errors due to out of band radiation. Appropriate spectral cut-off filters were used to eliminate diffracted radiation of second and higher orders. The wavelength accuracy was assured by setting the wavelength on either one of several mercury, argon or xenon emission lines. The xenon lines were obtained from the arc source itself, the mercury and argon lines from low pressure discharge lamps. A beamsplitter/monitor detector was used to adjust the data for fluctuations in the light source output. The difference in radiant power level for the light sources used in this task was accounted for by the ECPR linear characterization described above. The image of the output slit of the monochromator was focussed onto the detector surface and underfilled the active area. The approximate bandwidth was 15 nm and the radiant power in the slit image varied from 20 to 300 μW.

3. RESULTS AND DISCUSSION

The absolute responsivity of the DRTIP photodetector is presented in Table II. The responsivity values listed in the third column are the results of the present study and are based on the SPSC technique as the absolute standard. The calibration transfer was facilitated by a spectrally nonselective detector (the ECPR) and a monochroma-

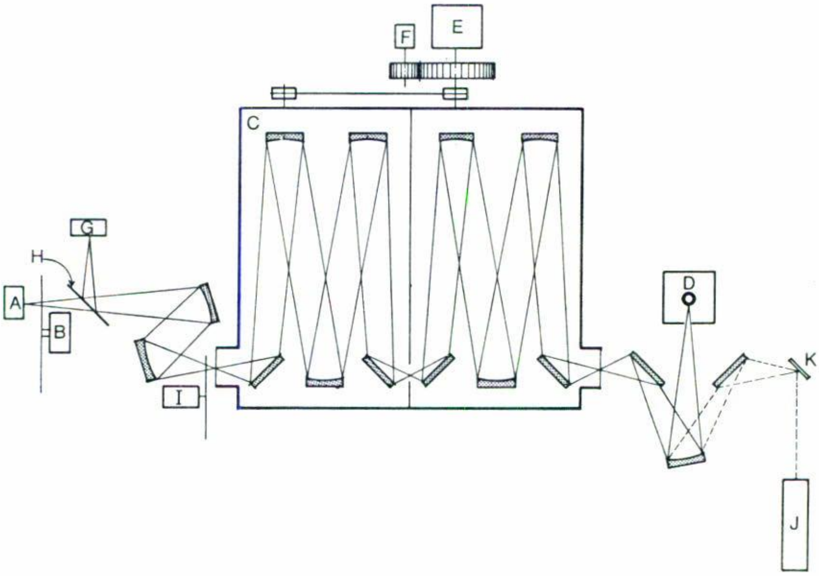

FIGURE 1. Experimental set-up for SPSC/ECPR based detector calibration: (A) reference or test detector; (B) chopper; (C) SPEX double monochromator; (D) 500 W supprassil window Xe arc lamp; (E) stepping motor wavelength drive; (F) shaft encoder wavelength read out; (G) monitor detector; (H) beam splitter; (I) motorized filter wheel and second-order diffraction filter set; (J) HeNe laser for system alignment; and (K) diffuser.

tor/xenon arc source. The fourth column is a list of responsivity values [9] based on an electrical substitution thermopile radiometer (ESTR) as the absolute standard [10]. Here the calibration was transfered from the ESTR to the silicon photodiode by means of amplitude stabilized laser lines. The values at the wavelengths listed were obtained by the interpolation procedure described in Ref. [9]. The ranges cited in columns three and four are the estimated uncertainties of the individual values. The last column lists the percent differences between the two measurement techniques from which we obtained a mean difference of $-0.1 \pm 0.6\%$. The differences are within the combined uncertainties (quadrature sum) except apparently for the ones at 546 and 633 nm. The combined uncertainty at 546 nm indicates a possible difference of 0.8% and at 633 nm of 0.6%. The observed differences are essentially equal to these values of the expected maximum difference.

The estimated uncertainties for the ESTR based responsivity values of the DRTIP photodetector are displayed in column four [9]. The estimates of the uncertainty for the values in the third column of Table II were obtained in the following way. The SPSC technique was reported [1] to have an uncertainty of less than 0.1%. However, some of our measurements did not have as high a precision as the earlier work so that we obtained a slightly larger uncertainty of 0.13%. We estimated from Table I, as was discussed in Sect. 2.2., that the correction for the window transmittance is between 0.1 and 0.2%.

TABLE II. Absolute responsivity of a silicon photodiode.

Wavelength (nm)	Monochromator Output (mW)	SPSC/ECPR Based Calibration (A/W)	ESTR Based Calibration (A/W)	Difference (%)
363	0.02	0.105 ± 0.002		
401	0.03	0.153 ± 0.002	0.154 ± 0.001	−0.6
405	0.03	0.157 ± 0.002	0.158 ± 0.001	−0.6
436	0.04	0.200 ± 0.002	0.200 ± 0.001	0
546	0.08	0.355 ± 0.002	0.352 ± 0.002	0.9
577	0.09	0.393 ± 0.002	0.391 ± 0.002	0.5
633	0.1	0.456 ± 0.002	0.453 ± 0.002	0.7
697	0.08	0.511 ± 0.003	0.514 ± 0.002	−0.6
750	0.06	0.555 ± 0.003	0.558 ± 0.003	−0.5
812	0.04	0.597 ± 0.005	0.600 ± 0.003	−0.5
882	0.3	0.640 ± 0.002	0.644 ± 0.003	−0.6
912	0.3	0.660 ± 0.002		
922	0.3	0.661 ± 0.002		
966	0.3	0.670 ± 0.002		
992	0.3	0.645 ± 0.002		

Also the calibration transfer uncertainty is of this order, so that the combined (quadrature sum) uncertainty for these three effects is 0.3%.

Although the spatial nonuniformity of the response of the ECPR led to only a 0.1% change in the calibration factor, the observed nonuniformity was much larger. The uncertainty arising from this effect is certainly less than 1.3% (the observed maximum nonuniformity) since the active area is nearly (but not completely) covered by the image of the exit slit of the monochromator. However, the irradiance across this image is not uniform so that the uncertainty is greater than the magnitude of the adjustment to the calibration factor. We estimated this uncertainty to be 0.3%.

The uncertainty in the offset correction to the ECPR readings is a function of the radiant power level being read. The second column of Table II is a list of the approximate radiant power in the monochromator output at each wavelength. The uncertainty varies from about 1% at the lowest power level to less than 0.1% at the highest levels (the xenon emission lines in the near infrared).

The uncertainty in the calibration transfer from the ECPR to the DRTIP detector is also a function of the radiant power level. It varies from about 1% at the lowest power level to about 0.2% at the highest. The most obvious way to get improvement in accuracy is to increase the radiant power in the monochromatic radiation source, perhaps by the use of interference filters instead of a grating monochromator, so that the signal to noise ratio would increase. Thus the uncertainty in both the offset correction to the ECPR readings and in the calibration transfer from the ECPR to the DRTIP detector would be reduced mainly in the near infrared region where the highest levels of radiation were obtained and where thermal detectors, like the ECPR, are more sensitive.

4. CONCLUSIONS

The technique for measuring absolute spectral response described in this paper is as accurate as other techniques based on electrical substitution radiometers but not as accurate as the interpolation of the SPSC technique reported by Geist, Zalewski and Schaefer [2]. The advantage of our technique is that it covers a broader spectral range than does the SPSC interpolation, but only at the cost of increasing the uncertainty and having less accuracy in the spectral response determination. Also accuracy is easier to achieve than with techniques based on electrical substitution radiometers.

The accuracy of this technique can probably be improved beyond what we have attained if we make some of the suggested changes to the procedure we followed in this paper: perform the SPSC procedure as well as the ECPR calibration using the amplitude stabilized expanded laser beam, increase the radiant power in the monochromatic radiation source for the ECPR to the DRTIP calibration transfer, etc. Also the wavelength range can be considerably extended by measuring the relative spectral variation of the reflectance losses of the coating used on the thermal detector and the spectral variation of the transmittance of any window material used.

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