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COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

TECHNICAL REPORT

SPECTRAL RESPONSIVITY MEASUREMENT OF DETECTORS, RADIOMETERS AND PHOTOMETERS

CIE 202:2011

UDC: 535.24
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Descriptor: Photometry
Quantities related to photometric and other
measurements
Calibration

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3. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
4. De préparer et publier des normes, rapports et autres textes, concernant toutes matières relatives à la science, la technologie et l'art dans les domaines de la lumière et de l'éclairage.
5. De maintenir une liaison et une collaboration technique avec les autres organisations internationales concernées par des sujets relatifs à la science, la technologie, la normalisation et l'art dans les domaines de la lumière et de l'éclairage.

Les travaux de la CIE sont effectués par 7 Divisions, ayant chacune environ 20 Comités Techniques. Les sujets d'études s'étendent des questions fondamentales, à tous les types d'applications de l'éclairage. Les normes et les rapports techniques élaborés par ces Divisions Internationales de la CIE sont reconnus dans le monde entier.

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2. Grundnormen und Verfahren der Messtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
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This Technical Report has been prepared by CIE Technical Committee 2-48 of Division 2 "Physical Measurement of Light and Radiation" and has been approved by the Board of Administration of the Commission Internationale de l'Eclairage for study and application. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

Ce rapport technique a été élaboré par le Comité Technique CIE 2-48 de la Division 2 "Mesures Physiques de la Lumière et des Radiations" et a été approuvé par le Bureau de la Commission Internationale de l'Eclairage, pour étude et emploi. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire.

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SPECTRAL RESPONSIVITY MEASUREMENT OF DETECTORS, RADIOMETERS AND PHOTOMETERS

Summary

This Technical Report gives recommendations for spectral radiant power, irradiance and radiance responsivity measurement of single element detectors in the 200 nm to 2 500 nm wavelength range. It covers measurement setups and methods, summarizes the types and basic properties of typical detectors, radiometers and photometers and gives guidance on how to choose a reference detector. Spectral considerations for source and radiometer applications, detector amplifier application issues and measurement uncertainties are described. Primary detector standards and procedures for the realization of units and responsivity functions are the responsibility of national metrology institutes and are not discussed in this report. This Technical Report was written to update Technical Report CIE 64-1984 "Determination of the Spectral Responsivity of Optical Radiation Detectors" with respect to device and measurement technology, and to include spectral irradiance and radiance responsivity measurements for radiometers and photometers from the ultraviolet wavelength range up to 2 500 nm.

MESURE DE LA SENSIBILITÉ SPECTRALE DES DÉTECTEURS, DES RADIOMÈTRES ET DES PHOTOMÈTRES

Résumé

Ce rapport technique fournit des recommandations pour la mesure de la sensibilité spectrale des détecteurs, que ce soit en puissance rayonnante, en luminance énergétique ou en éclairage énergétique, dans le domaine spectral compris entre 200 nm et 2 500 nm. Il présente les différentes installations et méthodes de mesure, ainsi que les différents types de détecteurs, de radiomètres et de photomètres et leurs propriétés de base, et il fournit des conseils pour choisir un détecteur de référence. Les aspects spectraux des sources et des détecteurs, les difficultés liées à l'amplification des signaux issus des détecteurs et les incertitudes de mesures sont décrits. Les détecteurs étalons primaires et les méthodes qui permettent la réalisation des unités et des courbes de sensibilité spectrales sont du ressort des instituts nationaux de métrologie et ne sont pas abordés dans ce rapport. Ce rapport technique a été écrit pour actualiser le rapport technique CIE 64-1984 "Determination of the Spectral Responsivity of Optical Radiation Detectors" ("Détermination de la sensibilité spectrale des détecteurs de rayonnements optiques") pour prendre en compte les développements de nouveaux instruments et des nouvelles technologies, et pour l'élargir aux mesures de luminance et d'éclairage énergétique pour les radiomètres et les photomètres, dans le domaine allant de l'ultraviolet à 2 500 nm.

MESSUNG DER SPEKTRALEN EMPFINDLICHKEIT VON DETEKTOREN, RADIOMETERN UND PHOTOMETERN

Zusammenfassung

Dieser technische Bericht gibt Empfehlungen zur Messung der spektralen Strahlungsleistungs-, Bestrahlungsstärke- und Strahldichte-Empfindlichkeit von Einzeldetektoren im Wellenlängenbereich zwischen 200 nm und 2 500 nm. Er beschreibt Messaufbauten und Messmethoden, fasst Typen und grundlegende Eigenschaften von typischen Detektoren, Radiometern und Photometern zusammen und leitet an, wie ein Empfänger zur Verwendung als Referenznormal ausgewählt werden kann. Weiterhin werden spektrale Überlegungen zur Verwendung von Strahlungsquellen und Radiometern, Belange bei der Verwendung von Photostromverstärkern und Beiträge zu Messunsicherheiten beschrieben. Dagegen werden primäre Empfänger-normale und Verfahren zur Realisierung der Einheiten als Aufgabe nationaler metrologischer Institute in diesem Bericht nicht betrachtet. Dieser Bericht wurde zur Aktualisierung des

technischen Berichtes CIE 64-1984 "Determination of the Spectral Responsivity of Optical Radiation Detectors" verfasst unter Berücksichtigung der veränderten Technologien von Messobjekten und Messungen, und um die Messung der spektralen Empfindlichkeiten für Bestrahlungsstärke und Strahldichte von Radiometern und Photometern vom ultravioletten Wellenlängenbereich bis zum Infrarot um 2 500 nm mit einzubeziehen.

1 Introduction

Responsivity standards and measurement techniques have changed significantly in the past 20 years. In addition to relatively simple single element detectors, more complex radiometers with multiple-reflection input geometries (trap, wedge, and sphere), filters, windows, diffusers, and apertures are now widely used. Also, small field-of-view and/or narrow band-pass elements are frequently used in modern radiometers. In addition to radiant power, many applications require irradiance and/or radiance responsivity measurements. This document describes how to perform spectral radiant power, irradiance, and radiance responsivity measurements. Measurement methods are described for detectors, radiometers and photometers to determine the relative spatial, angular and spectral variations of their (absolute) responsivities. The document describes measurement geometry, measurement setups, typical types and properties of different detectors, radiometers and photometers, and measurement methods. The measurement methods include procedures to obtain traceability to National Metrological Institutes (NMIs) and guidance on selecting standards. Evaluation of measurement uncertainty and state of the art measurement uncertainty values are discussed. Common problems in all of the above three radiometric quantity measurements, such as spectral issues, DC and AC measuring instruments are also discussed. Details of the primary standards and the procedures for the realization of units (the tasks of NMIs) are not discussed in this report. Also, multi-element devices, such as two dimensional array detectors, spectrographs, and imaging devices, including hyper spectral instruments, are not discussed here. Multi-element devices are discussed in other documents such as the TC 2-51 Technical Report¹.

The responsivity s of an optical radiation detector (radiometer or photometer) is the ratio of its output electrical signal Y to its input radiometric quantity Q . In general, responsivity is the ratio of two integrals:

$$s = \frac{Y}{Q} = \frac{\int_{\lambda} s(\lambda) S(\lambda) d\lambda}{\int_{\lambda} S(\lambda) d\lambda} \quad (1)$$

where $s(\lambda)$ is the absolute spectral responsivity (the responsivity at a specific wavelength λ) and $S(\lambda)$ is the spectral power distribution of the input radiometric quantity to be measured (e.g. spectral flux in radiant power measurement) at wavelength λ , expressed as either an absolute or relative value.

The responsivity of a detector is determined during a measurement (calibration) transfer. After calibration, the detector can be taken as a standard and can measure the same radiometric quantity for which it was calibrated. The magnitude of the radiometric quantity to be measured will be equal to the measured electrical signal of the device divided by the responsivity. The three fundamental radiometric quantities can be determined from three different measurement equations. The radiant power is

$$\Phi = \frac{Y}{s_{\Phi}} \quad (2)$$

where s_{Φ} is the radiant power responsivity.

The irradiance (radiant power per area) is

$$E = \frac{Y}{s_E} \quad (3)$$

¹ In preparation by CIE TC 2-51 *The Calibration of Multi-Channel Spectrometers*.

where s_E is the irradiance responsivity.

The radiance (radiant power per solid angle per projected area) is

$$L = \frac{Y}{s_L} \quad (4)$$

where s_L is the radiance responsivity.

For all three cases, Y is the output electrical signal from the detector, which can be expressed as the result of an integration as shown above.

For a perfect radiometer that can measure radiant power, irradiance, and radiance, the responsivities may be interrelated:

$$s_\phi = \frac{s_E}{A} = \frac{s_L}{A\Omega} \quad (5)$$

where A is the detector active area and Ω is the viewing solid angle of the radiometer.

A test device can be calibrated against the detector standard if it can be substituted for the detector standard. The responsivity of the test device will be the ratio of its electrical output signal (current or voltage) to the magnitude of the measured radiometric quantity determined by the detector standard.

Responsivity measurements can be made broadband or spectrally (versus wavelength). This document is mainly focused on spectral responsivity measurements. Even in the case of broadband responsivity measurements it is often necessary to measure the spectral responsivity of the detector (radiometer) as well e.g., a broad-band UV source can be measured with a broad-band UV-A detector only if the spectral responsivity of the detector and the spectral power distribution of the source are known, so that any spectral mismatch corrections can be determined (see Section 3.7). The relative standard measurement uncertainty of the test device will be always larger than that of the standard device because of the increased number of the calibration steps (during the measurement transfer).

Responsivity related calibrations are:

- relative spectral responsivity (in power, irradiance, and radiance modes),
- absolute spectral responsivity (in power, irradiance, and radiance modes),
- uniformity:
 - relative variation of the spatial responsivity (typically varies with wavelength),
 - relative variation of the angular responsivity (typically varies with wavelength),
- aperture effective area measurement,
- linearity (typically varies with wavelength),
- temporal characteristics,
- temperature coefficient of detector responsivity (typically varies with wavelength).

Responsivity measurements can be utilized in the field of:

- optical radiometry,
- photometry,
- colorimetry,

- temperature measurements of blackbody radiators,
- optical pyrometry,
- solar photovoltaic quantum efficiency measurements.

2 Definitions

The optical radiation related quantities and units as well as the terms related to radiometric, photometric, and colorimetric measurements, including physical detectors, are defined in the International Lighting Vocabulary (ILV) [1]. More definitions are given in the International Vocabulary of Basic and General Terms in Metrology (IVM) [2]. These definitions will be used in this Technical Report (TR) where applicable.

In this report near infrared (NIR) is taken to mean the wavelength band from 700 nm (approximately the upper limit of the visible range) to 1 800 nm, determined by the wavelength coverage of the widely used InGaAs and Ge detectors.

3 Spectral Radiant Power Responsivity Measurements

Radiant power is the fundamental radiometric quantity measured by primary standard radiometers. The optical power Φ in a beam can be measured if the beam is totally detected by an optical radiation detector. The radiant power responsivity of a power meter is equal to the detector (radiometer) output electrical signal divided by the incident (input) optical power. Spectral radiant power responsivity is determined by making measurements of monochromatic radiation at different wavelengths with the radiometer, using equally spaced wavelength increments. Spectral radiant power responsivities can be used as reference functions to propagate calibrations to radiometric, photometric, colorimetric, and pyrometric measurements.

3.1 Measurement Geometry

Power mode measurement geometry is illustrated for a laser beam in Figure 1. Underfilling of the detector sensitive area by the incident beam is a widely used radiant power measurement technique. The use of an aperture in front of the detector is not necessary for power measurements. The uniformity of the spatial responsivity of detectors, calibrated in underfilled mode, has to be good to keep the relative standard uncertainty for power measurement low. Measurements using stabilized laser beams are common for responsivity calibrations in situations where the reference detector is a cryogenic radiometer or a Si trap-detector.

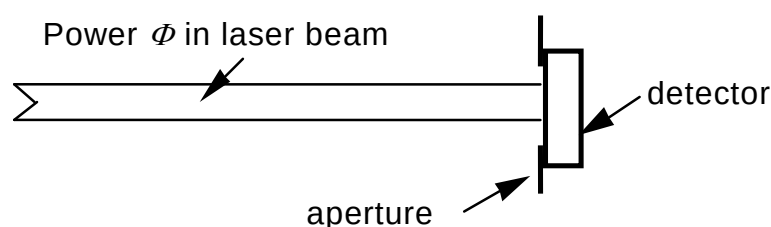


Figure 1 – Measurement geometry of laser power measurement

In spectral radiant power responsivity measurements, where broadband-sources are used with either narrow-band filters or monochromators, the incident beam is usually convergent onto the detectors. Test detector(s) can be calibrated against a standard detector of known spectral power responsivity. Figure 2 shows a typical arrangement for this type of measurement using a lamp-source and a series of narrow-band interference filters in a filter wheel. The field stop restricts the viewing area of the source to obtain a uniform source image. The radiation emerging from the field stop is collimated by a plano-convex lens with the flat side facing the

source. The interference filters are mounted in a filter wheel and each of them converts the broadband parallel radiation into a quasi-monochromatic beam. This beam is then re-focused on the detectors. The optimal position of the lenses depends on the wavelength, due to chromatic aberration effects. The detectors in this example are single element detectors and the beam spot on the detector has to be smaller than the sensitive area of the detector. When filters are used, their temperature should be controlled. They may need to be recalibrated at regular intervals to minimize ageing effects, using the same geometry. Often corrections need to be applied to allow for changes in the effective bandpass and centre wavelength of the individual filters when used with the test and standard detectors, depending on the spectral responsivities of these detectors.

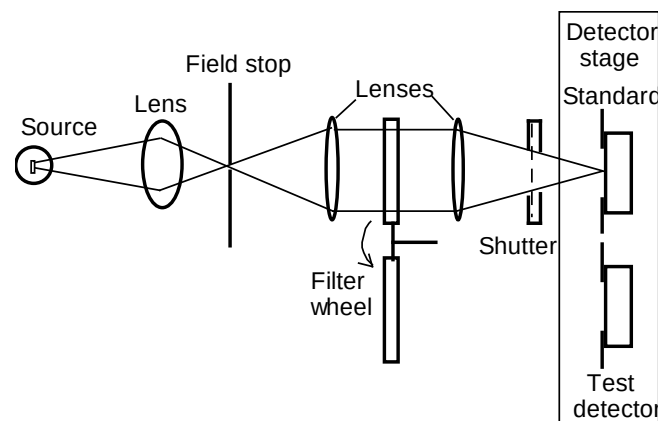


Figure 2 – Converging beam geometry for spectral radiant power responsivity measurement using a broadband-source with interference filters in filter wheel

When photodiodes are used very close to light sources, the incident radiation can be oblique to the detector surface or may have significant angular divergence, and as a result the detector responsivity can change. Angular response and/or polarization dependence of responsivity will be discussed in 3.4.1.

3.2 Measurement Setup

3.2.1 Monochromator-Based Measurement Setup

Most commonly, spectral responsivity measurements are monochromator based. The complexity of a spectral responsivity measurement setup depends on the measurement uncertainty level and the wavelength range needed for the test detector. For instance, if the spectral responsivity function has to be transferred from a high accuracy silicon (Si) trap detector (which has low noise floor) to a pyroelectric detector (where the noise floor is high), the setup has to be more versatile than for a calibration in which the test and working standard detectors are of similar types.

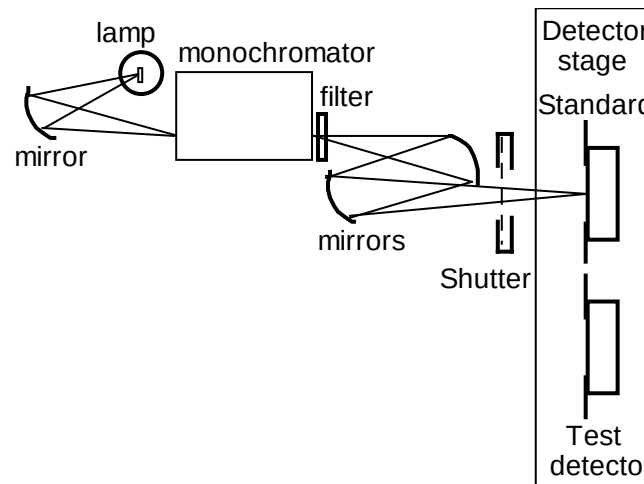


Figure 3 – Spectral responsivity measurement setup using a monochromator

A typical monochromator-based responsivity measurement setup is shown in Figure 3. A broadband lamp is imaged onto the input slit of the monochromator using a lens or mirror imaging system. Mirrors have no internal reflections, unlike lenses and are preferable for wide spectral range applications because they show no chromatic aberrations. Spherical mirrors are most commonly used for imaging, operated at near-normal angles of incidence to reduce off-axis aberrations. Spherical aberration is usually negligible for 'slow' mirrors (i.e. $f/8$ or greater, $f/\#$ being the so-called f -number which is the ratio of the image distance (or focal length), f , to the aperture (diameter) of the imaging optics). Double monochromators are used in high accuracy applications where high stray light rejection is needed. Single monochromators have higher throughput but lower performance in terms of spectral stray light. The dispersing elements in the monochromator are either prisms or gratings. The dispersion of prisms is highly non-linear. Therefore, when constant spectral bandpass is needed, elaborate cams have to be used for both the wavelength and the slit-width drives. It is difficult to find prism materials that have high enough transmission and dispersion in a wide wavelength range. Prism monochromators are more complex, hence, more expensive than grating versions. Gratings have anomalies that render their spectral efficiency highly irregular and they need order sorting (cut-on) filters. (See more detail on monochromators in 6.1.) The output slit is imaged at the surface of the detectors. A light shutter can be used to subtract both the background radiation and the output offset voltage of the detector-amplifier from the output signal.

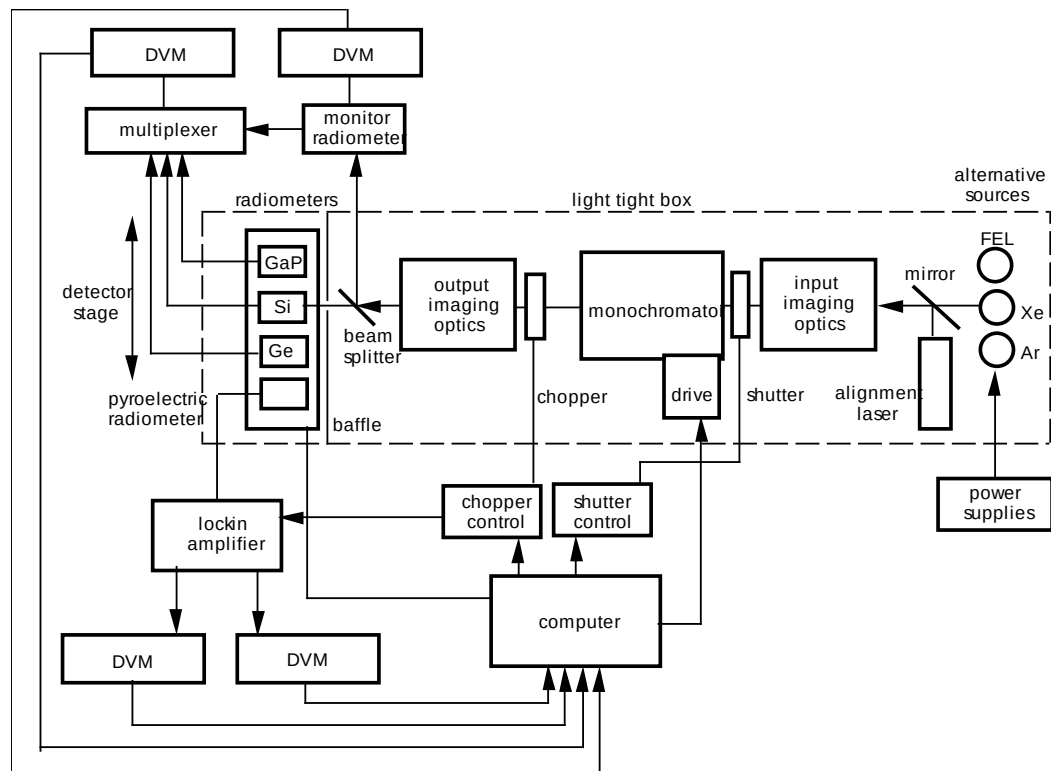


Figure 4 – A versatile monochromator-based setup to measure spectral responsivity

A versatile monochromator-based measurement setup is shown in Figure 4. This setup has a computer controlled detector stage where test detectors can be calibrated against the standard detector. All detectors are operated in underfilled mode and measure the same total power of the monochromatic beam leaving the output imaging optics of the monochromator. Different broad-band sources can be imaged onto the input slit of the monochromator through the input imaging optics. The power level and the spectral purity of the monochromatic beam (imaged on a detector) depend on the properties of the monochromator, the related optical system, and the type of the illuminating source. Usually, a combination of tungsten halogen lamps, Xenon lamps, and/or Argon arc sources is used to cover a wavelength range from 200 nm to 2.5 μm . The detector stage is optically shielded from the source related components of the setup using a baffle inside the light-tight box. The baffle is used to minimize the stray radiation seen by the detectors. Stray and background radiation be further decreased through the use of a shutter. This should be placed far from the detectors in order ensure that the dark signal measured with the shutter closed is the same as that superimposed on the signal when the shutter is open. If a monitor detector measures a (constant) part of the monochromatic beam simultaneously with the signal of the measured detector, the ratio of the two output signals (signal to monitor) can be used to decrease the effect of the source fluctuations in the measured data. The ratio method will be efficient only if both the spatial and the temporal changes are equal (or very similar) in both channels. All detectors, the monitor, the test, and the standard detector, need short-circuit current-to-voltage converters to obtain linear operation in case of photovoltaic detectors. The output voltages of the converters are measured by digital voltmeters (DVMs), usually under computer control (as is the data acquisition).

When pyroelectric detectors are used (e.g. to extend the spectral responsivity measurements to a wider wavelength range), the optical radiation must be chopped. Either voltage mode or current mode preamplifiers can be used. In voltage mode preamplifiers, field effect transistors (FETs) are used to amplify the voltage drop on the detector. Here, the total input stray capacitance, including the detector, is typically 10 to 100 times the stray feedback capacitance of a current mode preamplifier circuit. Therefore, the frequency response of current mode preamplifiers (current-to-voltage converters) is much broader than that for voltage mode types.

The output of the preamplifier is measured by a synchronized lock-in amplifier, with the X and Y vector components of the lock-in output signal being converted into digital signals using linear analog-to-digital converters or digital voltmeters (DVMs). The responsivity of pyroelectric detectors is low (about six orders of magnitude lower than Si) therefore their noise-equivalent-power (NEP) is high. The NEP is a ratio of the output noise to the responsivity. High NEP needs high beam power from the monochromator. Using traditional pyroelectric detectors with a NEP of $40 \text{ nW}\cdot\text{Hz}^{-1/2}$, $4 \text{ }\mu\text{W}$ or higher beam-power is needed to achieve a relative standard measurement uncertainty of 1 % (i.e. a signal-to-noise ratio of 100). Recently, the NEP of pyroelectric detectors has been decreased by an order of magnitude as a result of frequency compensations performed by the organic black paint coating [3] and also by decreasing the LiTaO_3 crystal thickness. This means that traditional monochromators (with relatively low beam-power) can be used with these new low-NEP pyroelectric detectors for spectral power responsivity measurements in a wide wavelength range. In spectral responsivity measurements where traditional pyroelectric detectors are used, the power of the source, the efficiency of the imaging optics (including flux collection from the source), and the power throughput of the monochromator have to be high. Also, it is important to note that the responsivity of the lock-in amplifier can depend on the shape of the chopped input signal. This can be an issue if the standard detector and the test detector have different response times. Sine-wave measuring lock-in amplifiers that measure the fundamental frequency component of the input signal can be less affected by changes in the AC signal shape than square-wave measuring lock-in amplifiers.

Where pyroelectric detectors are not used, AC measurements are generally not needed unless the detector measures up to $2\text{ }500 \text{ nm}$, where it can be advantageous if the background (DC) signal is separated from the modulated (chopped) useful signal. When pyroelectric detectors are not used, the spectral instrument and related optics typically do not have to be optimized for power throughput. Also, in many cases, full automation is not necessary.

3.2.2 FT-Based Measurement Setup

For infrared spectral radiant power responsivity measurements, one could consider replacing the monochromator in Figure 3 with a Fourier-transform infrared (FTIR) spectrometer, as shown in Figure 5. FTIR spectrometers in principle have several advantages over dispersive systems in the infrared spectral region. First, the interferometer in an FTIR spectrometer modulates the entire spectral band defined by the source, beamsplitter, and other optical components simultaneously. If the signal-to-noise ratio (SNR) of the power responsivity measurement is limited by detector or amplifier noise, rather than by photon or source noise, then for a given observation time the FTIR can improve the SNR by a factor equal to the spectral bandwidth divided by the resolution. This advantage may apply for pyroelectric detectors, but is not relevant for Si or InGaAs detectors at shorter wavelengths. Second, the aperture of an FTIR spectrometer is naturally circular instead of slit-shaped, and thus the beam has a larger etendue than a monochromator for a given spectral resolution. This produces an optical throughput advantage. Third, an FTIR spectrometer typically uses a stabilized single-mode laser to measure the optical path difference in the interferometer. This yields excellent wavelength accuracy and stability; it is not difficult to achieve a relative wavelength uncertainty of 10^{-6} .

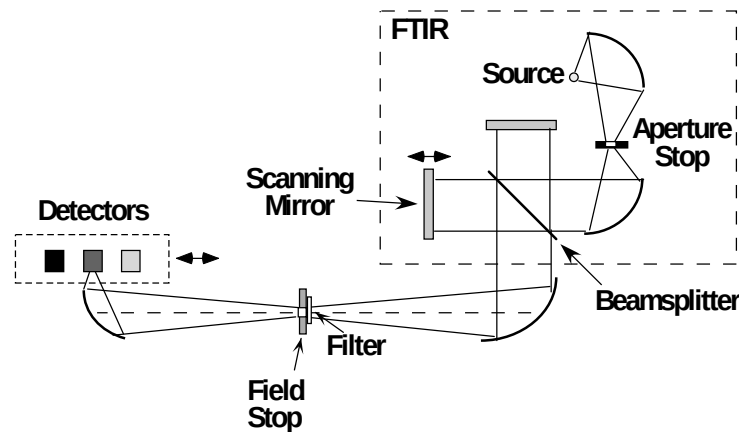


Figure 5 – Spectral responsivity measurement setup using an FTIR spectrometer

However, these theoretical advantages may not necessarily lead to improved spectral radiant power responsivity measurements. The most troublesome issue for detector calibration with FTIR spectrometers is linearity. The power output of a typical FTIR spectrometer configured for near-infrared spectroscopy with a 3 000 K tungsten halogen lamp and quartz beamsplitter can be ≈ 200 mW for an f -number of $f/3$ and a 3 mm focal spot. This is enough power to cause changes in responsivity of several percent in many pyroelectric detectors (compared with the responsivity at lower power levels), and can completely saturate high-sensitivity InSb detectors. Nonlinearity in the measured interferogram is transformed into harmonic distortion over the entire spectrum. For the most accurate measurements, the power output from the source must therefore be attenuated e. g. with filters or stops, and much of the multiplexing and throughput advantages mentioned above are lost. Also, it is not possible to assess linearity using the dual shutter method that works well with the monochromator approach. The amplitude and phase of the modulated FTIR output beam vary spatially in such a way as to make this scheme impractical. It is possible to use an integrating sphere and vary the input beam power using a set of apertures, such that the uniformity of modulated irradiance at the detector plane is negligibly affected. The integrating sphere attenuation (typically 100x or more) also can bring the power level down to the linear regime for cooled photoconductive detectors.

Another possible complication in making FTIR-based power responsivity measurements is the frequency response of the detector. Most FTIR spectrometers operate in a continuously-scanning mode in which the modulation frequency for a given spectral component is given by twice the scanning mirror velocity divided by the wavelength. For typical spectrometers this is in the audio frequency range. If the detector under test and standard reference detector have different frequency responses, the measurement will be more difficult to analyze. Even without this complication, the results of the responsivity measurement would need to be reported at a different frequency for each wavelength in the spectrum. Some FTIR spectrometers can be used in a step-scan mode, and the output beam sent through an optical chopper so that the frequency is fixed for each wavelength. However, this mode is often less stable than the continuously-scanning mode.

The FTIR output beam also contains an unmodulated DC power level that can be larger than the modulated AC component. This must be accounted for in the measurement, especially if linearity of detector response is important. Unfortunately, its spectral content cannot be easily determined. Further, by its nature a scanning FTIR system modulates a fraction of all of the radiant power present within the optical extent of the instrument, not just the output of the source. This includes ambient background radiation as well as possible emission from the detector itself. These components become more significant at longer wavelengths in the IR spectral region. It may necessary to perform a background measurement with the source blocked, or to use multiple sources (e.g., variable temperature blackbodies) to properly account for the background signal.

It is possible to achieve low uncertainty spectral power responsivity measurements of detectors with an FTIR spectrometer, but only with appropriate care taken to address the error sources

mentioned above. Also, there are more sophisticated 4-port FTIR designs that can be used to directly compare two detectors at the output ports, without moving them in and out of the beam as in Figure 5. This approach can produce faster and more stable data output. In general, FTIR spectrometers should be considered alongside laser, filter, or monochromator-based systems for spectral radiant power responsivity measurements in the infrared spectral region. Even where other methods may produce lower absolute uncertainties at given wavelengths, the FTIR may be very useful for interpolating between these points.

3.3 Detector Standards

All spectral responsivity calibrations, regardless of the measurement setup, involve the use of a reference detector, which is a standard detector with low measurement uncertainty whose spectral responsivity values are traceable to SI unit(s). Traceability is usually obtained by purchasing a standard calibrated by a National Metrological Institute (NMI) or by sending a high quality detector to a NMI for calibration. The relative uncertainties associated with the spectral responsivity values of reference standards can be different depending on the type and performance of the device. They will also depend on the number of steps required to derive the reference values.

3.3.1 Reference Radiometers

The detector standards with lowest measurement uncertainty are electrical substitution cryogenic radiometers (ESCR) [4], Si trap detectors [5], and sphere-input InGaAs [6] detectors. A radiant power value measured with an ESCR typically has an associated relative standard measurement uncertainty of about 0,01 %. The QED-200 Si trap detector, which is made from three UDT UV-100 n-on-p inversion layer photodiodes, can measure radiant power with a typical relative standard measurement uncertainty of about 0,03 % between 440 nm and 460 nm without applying any bias voltage to the photodiodes [7]. The UDT QED-150 and several other trap detectors on the market are made from Hamamatsu S1337 p-on-n silicon photodiodes. These photodiodes are “quantum-flat” meaning they have external quantum efficiencies (EQE) that are constant to within 0,1 % from 550 nm to 860 nm. The spectral responsivity of quantum detectors is proportional to their EQE and wavelength. The quantum flatness of these trap detectors can be extrapolated to 400 nm using the silicon photodiode self-calibration technique [7]. The spectral responsivity of the S1337 trap-detectors can be calibrated against either a UDT QED-200 (between 440 nm and 460 nm) or an ESCR. The quantum efficiency curves of three Si tunnel trap detectors (calibrated against an ESCR) are shown in Figure 6. The measurements were made using stabilized tuneable lasers.

NOTE Usually, these trap detectors are used as standards at NMIs and they are often optimized for operation with intensity-stabilized laser sources.

Example: Transfer standard Si trap detectors can be calibrated against ESCRs or reference trap detector standards at selected wavelengths using intensity-stabilized laser sources. The spectral responsivity of the transfer standard trap detectors at intermediate wavelengths can be determined by utilizing the physical model of the internal quantum efficiency for Hamamatsu S1337 silicon photodiodes [8] [9]. For radiant power responsivity, a relative standard measurement uncertainty of about 0,03 % can be achieved for Si trap detectors between 405 nm and 920 nm where the model can be applied. These are the highest-level transfer standards for the silicon wavelength range that can be calibrated by NMIs.

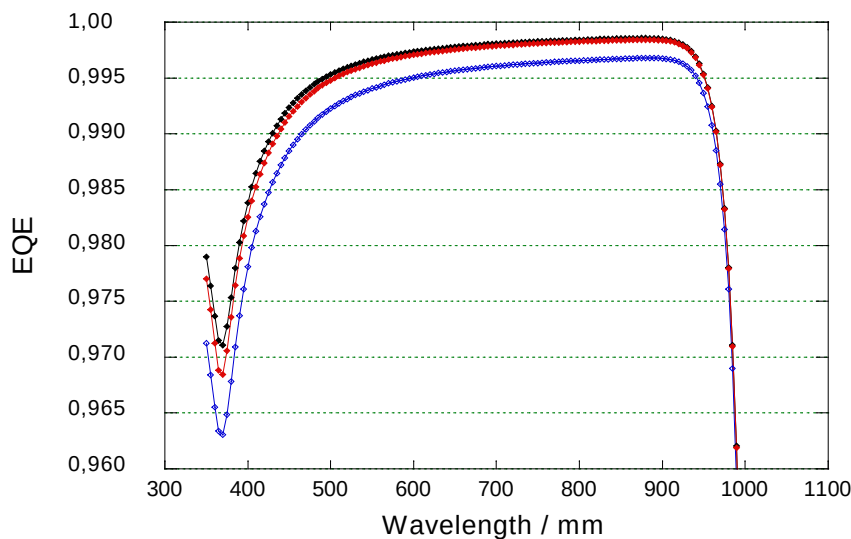


Figure 6 – Quantum efficiency curves of three Si tunnel-trap detectors

Both reflectance and transmission (tunnel) type trap detectors are suitable for use as reference standards [10]. The scheme of a reflectance-type trap detector is shown in Figure 7. The incident beam is reflected back from the trap-detector along the optical path of the entering beam after five reflections. Figure 8 shows the scheme of a tunnel-trap detector [11] built from six photodiodes of two different sizes. The advantage of tunnel-trap detectors is that the incident beam is entirely transmitted and there are no back reflections at the input. Stable optical components (such as glass filters) can be located at the front of the tunnel-trap detector that can be calibrated (e.g. for spectral transmittance) separately from the trap detector. The shown tunnel-trap device has an aperture at the input. The aperture and the photodiodes in this example were packed tightly to increase the field-of-view (FOV) to 8°. Usually, trap detectors have a FOV of only a few degrees. If a source other than a laser beam is to be measured, the FOV of the trap-detector has to be large enough not to vignette the incident beam (e.g. from a monochromator).

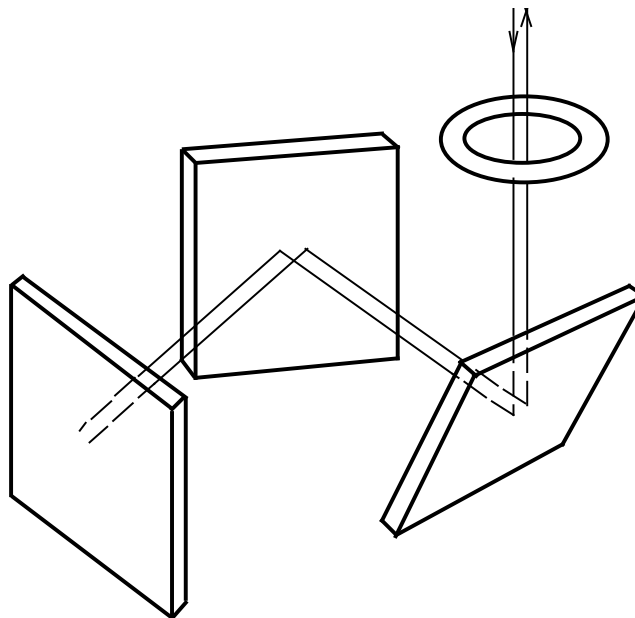


Figure 7 – Scheme of a reflectance-type trap detector

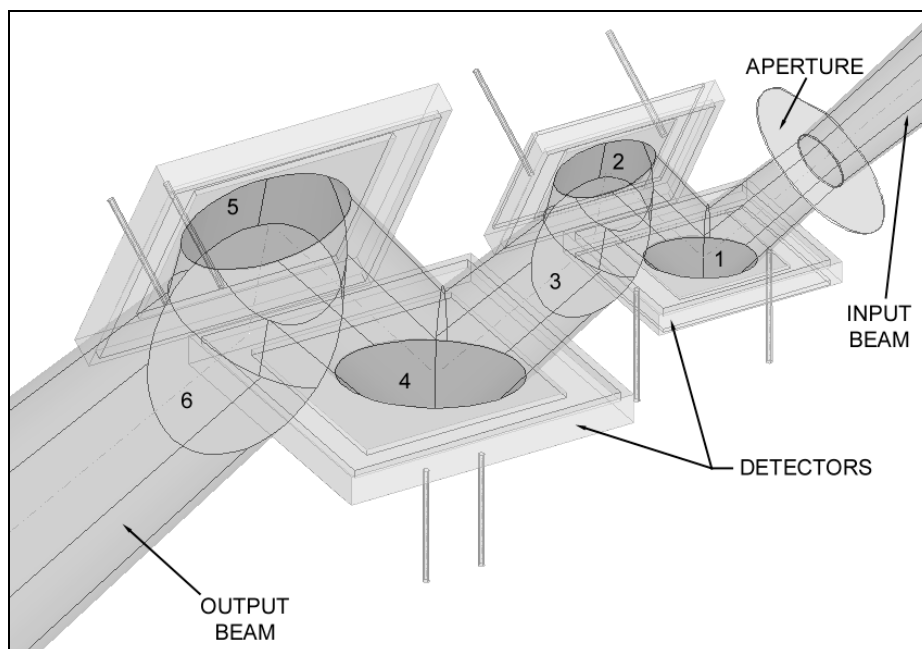
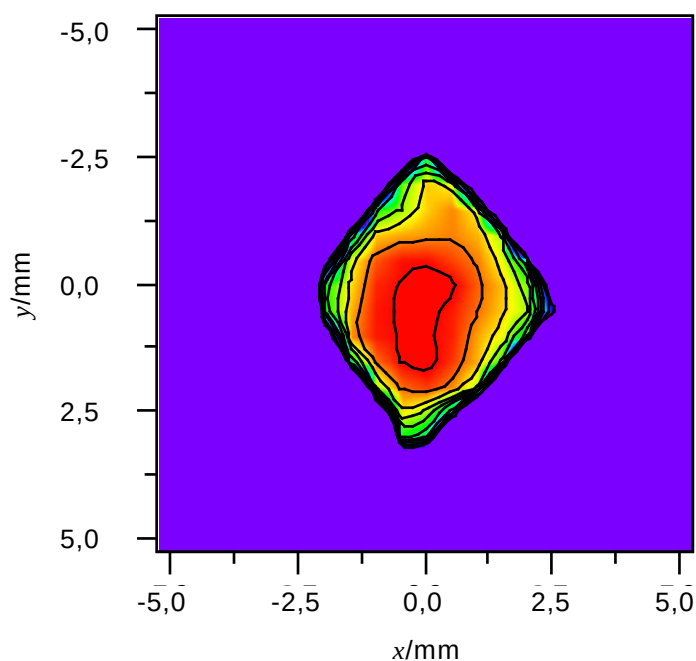


Figure 8 – Tunnel-trap detector using Si photodiodes of two different sizes

The trap arrangement improves the uniformity of the spatial responsivity compared to a single element photodiode, which is an important issue in radiant power mode measurements where the incident beam underfills the detector. The spatial responsivity map of a well-designed reflectance-type trap-detector (built from three Hamamatsu S1337 photodiodes) is shown in Figure 9.



NOTE The 0,01 % contours shown (solid curves) were obtained when the device was scanned by a 1,1 mm diameter spot of 500 nm wavelength.

Figure 9 – Spatial responsivity map of a reflectance-type S1337 trap-detector.

Sphere-input InGaAs transfer-standard detectors with a tilted input aperture (relative to the sphere axis) and a symmetrical photodiode arrangement (relative to the sphere axis and the incident beam spot) can have radiometric and electronic characteristics similar to silicon trap detectors. They can be used for absolute responsivity calibrations with around 0,05 % uncertainty in the 950 nm to 1 650 nm wavelength range [6]. The cross-section of a sphere-InGaAs detector is shown in Figure 10.

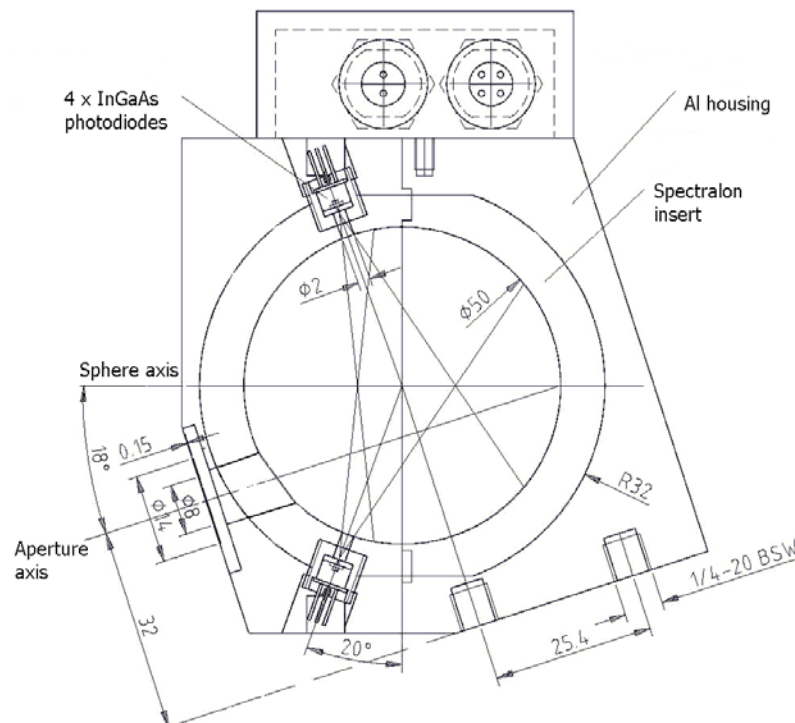


Figure 10 – Cross section of a sphere-InGaAs detector

3.3.2 Radiometers for Extended Wavelength Range

The reference radiometers described in 3.3.1 can be used with other types of transfer detectors in order to extend spectral responsivity measurements to the UV and IR ranges. These transfer detectors usually have spectrally flat (constant) responsivities across a wide wavelength range. The transfer device can be calibrated for absolute radiant power responsivity against a Si trap detector (or other reference standard detector) and provided that the relative spectral responsivity of the transfer device is known (or can be determined) in a spectral range wider than that of the reference standard, it can then be used to extend the spectral responsivity range beyond that of the reference. Thermopiles or pyroelectric detectors are the most commonly used wavelength-extending transfer standards.

Example 1: A thermopile calibrated with an ESCR using a visible laser beam was used to extend the responsivity scale to the IR [12]. The spectral reflectance of the thermopile coating was measured and the relative spectral radiant power responsivity was determined, correcting for the reflectance loss. The thermopile was coated with black velvet paint. The thermopile temperature coefficient was $-0,2 \text{ }^{\circ}\text{C}$. The contribution to the combined relative standard uncertainty of the spectral radiant power responsivity originating from the thermopile non-uniformity of spatial responsivity was $0,1 \text{ } \%$. In order to eliminate effects of non-linearity of response, the thermopile was always used at the same power level. The sensitivity of thermopiles is poor, therefore they can be used only for laser beam or high-power measurements.

Example 2: The spectral power responsivity of a single element gold-black coated LiNbO_3 pyroelectric detector was determined [13]. The device had an overall spectral responsivity variation of about 1 % between 250 nm and 2 500 nm. This variation was determined with a maximum 0,34 % relative standard measurement uncertainty from spectral reflectance measurements. Absolute responsivity (tie) points were used to convert the relative spectral responsivity into absolute spectral responsivity. The absolute tie point was obtained by substituting the pyroelectric device for a Si trap detector when both measured the same 442 nm (stabilized) laser beam. The disadvantage of pyroelectric detectors is a relatively high noise floor. The signal power has to be high to get a high signal-to-noise ratio. The noise floor was about $40 \text{ nW} \cdot \text{Hz}^{-1/2}$ for the LiNbO_3 pyroelectric detector [14]. A radiant power of $4 \text{ } \mu\text{W}$ or higher is needed for this device to achieve a relative standard measurement uncertainty (with 1 Hz electrical bandwidth) of about 1 %. Longer measurement time (averaging) is needed to obtain smaller uncertainties at $4 \text{ } \mu\text{W}$. In this case, the measured laser beam could usefully be power stabilized.

Example 3: A sphere-input near-infrared radiometer has been reported [15] to measure radiant power with a non-uniformity in the spatial responsivity of less than 0,1 %. The radiometer incorporated a small integrating sphere and three 5 mm diameter InGaAs detectors. The peak responsivity was close to $0,3 \text{ A} \cdot \text{W}^{-1}$ at 1 600 nm. This type of device can be calibrated against low sensitivity standards, such as cryogenic radiometers, pyroelectric detectors, or thermopiles. At the same time, the device has a wide dynamic signal range that extends the radiant power range of near-infrared responsivity calibrations.

Example 4: Another sphere-input radiometer was developed for an extended-InGaAs radiometer. The transfer standard was calibrated against a cryogenic radiometer in radiant power measurement mode. The spatial non-uniformity was again 0,1 % but the upper wavelength limit was 2 500 nm [16].

3.3.3 Working Standards

Working standard detectors/radiometers are day-to-day reference devices for spectral responsivity calibrations that can be calibrated by NMIs or secondary standard laboratories. These devices have spectral responsivity values with slightly higher relative uncertainty than trap detector standards. They can be less expensive than reference standards and usually they are easy to use. Different types of working standard detectors are required if wide wavelength coverage is needed. The best choice is one where the working standard and the test detectors have similar characteristics. In this case, systematic errors will be similar during a responsivity transfer in both the reference and test channels. The most important characteristics of working standard and test detectors for spectral responsivity measurements will be discussed (together) in the following section.

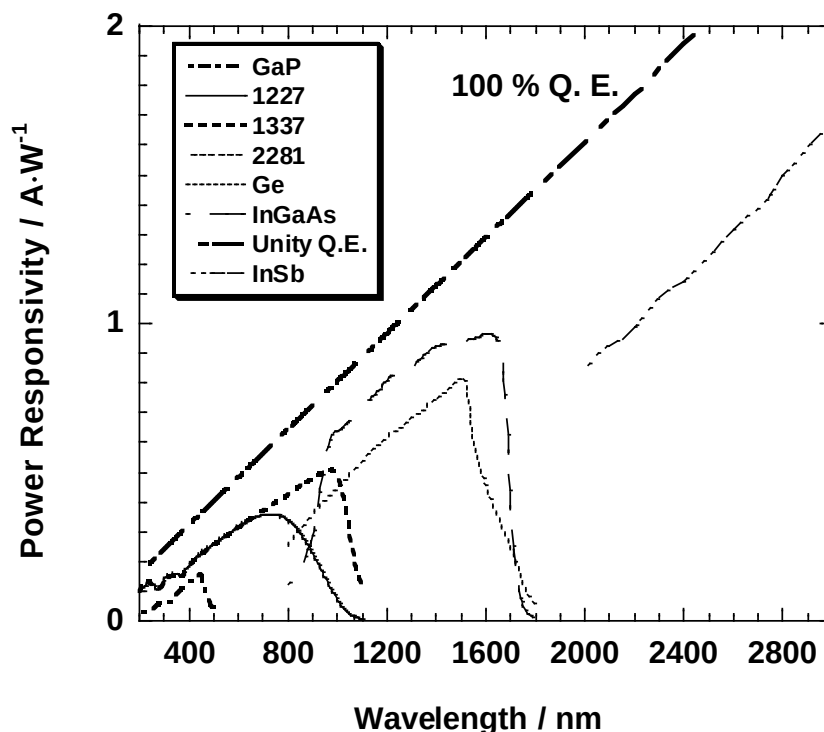
3.4 Selection of Detectors

A test detector is also called the detector under test (DUT). In order to obtain the lowest relative uncertainties associated with the spectral responsivity values, careful selection of the test detectors is important. It is suggested that customers consult the intended calibration laboratory before choosing a test detector for calibration. The basic characteristics of photoelectric detectors (photodiodes) that are the most suitable devices for spectral responsivity measurements will be discussed below. The spectral responsivity function can be transferred to selected photodiodes with only a minimum increase in the relative standard measurement uncertainty compared with that of the reference detector.

3.4.1 Basic Characteristics of Photodiodes

Photodiodes are photovoltaic detectors that usually have advantageous electronic and radiometric characteristics. They are the work-horses of routine spectral responsivity measurements. Single element Si, PtSi, Nitrided Si, Ge, InGaAs, extended InGaAs, and InSb photodiodes can be utilized as reference and test detectors in the 200 nm to 2 500 nm wavelength range. Photodiodes made from different materials have different energy-bands.

Incident photons, with energy $h\nu$ greater than the energy band gap, will create electron-hole pairs in the semiconductor at or near the junction to generate a photocurrent. Typical spectral radiant power responsivity characteristics of several photodiodes are shown in Figure 11. The 100 % external quantum efficiency line shows the theoretical maximum of the device responsivities. (Quantum efficiency is the ratio of the number of generated electron-hole pairs to the number of incident photons.) The responsivity curves are below the 100 % quantum efficiency line because of the external reflection loss and internal losses that reduce the quantum efficiency. (Note the surface reflectance loss and internal losses are included in the actually-achieved external quantum efficiency for the device.) Surface coatings are often applied to reduce reflectance losses so that a device may more closely approach the theoretical maximum responsivity in a given spectral range. These photodiodes are available in different sizes. In radiant power responsivity calibrations, the detector active area always has to be larger than the spot of the beam incident (focused) on the detector. Two frequently used silicon photodiodes are shown as an example. The Hamamatsu Model 1337 silicon photodiode is made by planar diffusion technology. The Model 2281, which is shown but cannot be seen on the graph (the curve of the 1337 covers it), is fabricated with the same technology. This model has a very high and spatially uniform internal quantum efficiency (quantum efficiency excluding the reflectance loss) and it is the most frequently used photodiode in the realization and propagation of spectral responsivity scales. The Model 1227 is a PNN⁺ type silicon photodiode with a thick N⁺ layer that brings the N-N⁺ boundary close to the depletion layer resulting in suppressed infrared responsivity. This model has about two orders of magnitude higher shunt resistance than the 1337. The 1227 is very suitable for photometric and colour measurements (due to the low IR responsivity) and also for very high sensitivity applications. The extra thin P layers in both silicon models produce high ultraviolet responsivity.



NOTE The dotted straight line shows the 100 % external quantum efficiency (100 % Q.E.).

Figure 11 – Spectral responsivity characteristics of photodiodes

Photodiodes are usually hermetically sealed in a case. The window should not be removed, to protect the photodiode against slow degradation of responsivity.

The non-uniformity of spatial responsivity of these devices has to be matched to the uncertainty requirement of a radiant power responsivity measurement. The spatial non-uniformity of responsivity (ratio maximum-to-minimum) of high radiometric quality Si photodiodes with 10 mm² or larger area is between 0,3 % and 0,5 %, that of InGaAs photodiodes is 0,5 % or higher, and that of Ge and InSb photodiodes is about 1 % or higher. The use of photodiodes that have been specially selected for good spatial uniformity of responsivity can be necessary if radiant power responsivity measurements are needed with reduced relative uncertainties. For broad-band applications, the spectral dependence of the spatial uniformity should be tested.

Angular response and/or polarization dependence of responsivity should be considered if the incident radiation is oblique to the detector surface or has angular divergence. Most photoelectric detectors can be well-modelled optically [17-19] as an absorbing substrate with a (semi-) transparent overlayer as shown in Figure 12. Since reflectance for p-polarization, ρ_p , is generally different from reflectance for s-polarization, ρ_s , transmittance through the overlayer into the sensitive volume (which is proportional to the responsivity) differs between s- and p-polarization. Since the optical indices are functions of the wavelength, the angular dependence of responsivity or polarization sensitivity is wavelength-dependent. Calculation results for a silicon photodiode with a 27 nm thick silicon dioxide layer simulating Hamamatsu Model 1337 (1227) at the wavelengths of 506 nm and 182 nm are shown in Figures 13 and 14, respectively [20]. Note that optical properties can be very different because of the layered structure.

Because of the above mentioned polarization property, responsivity for a divergent beam, in general, is different from that for a parallel beam. Responsivity for a divergent beam can be obtained by integrating the angular responses for the two polarization components over the appropriate angle of divergence, and taking the average.

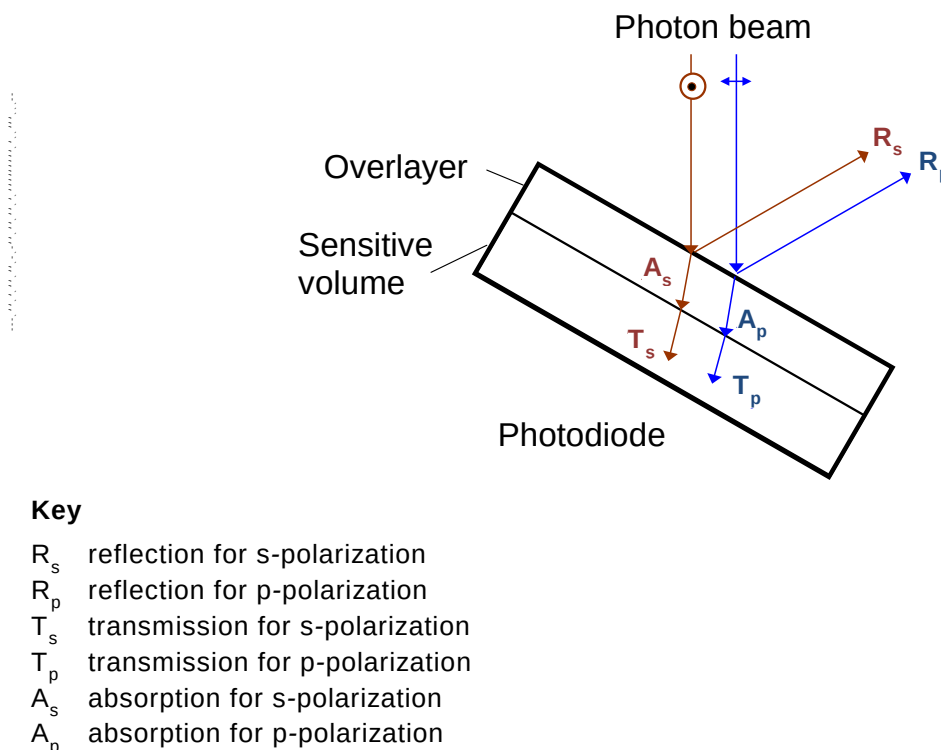


Figure 12 – Simplified detector model and possible paths of incident photons