Optical Detector Applications for Radiometric Measurements

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By

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PREFACE

Improved detector technology in the past two decades opened a new era in the field of optical radiation measurements. An increased number of calibration and measurement facilities and procedures could be developed with lower measurement uncertainties using the newly developed detector/radiometer standards instead of traditionally applied source standards (blackbodies and lamps). Shrinking of the traditional source-based calibrations and the large increase of optical detector-based calibrations motivated the writing of this book series.

The book series is a comprehensive description of optical detector based radiometric practices. Instead of giving the traditional lexical-type tutorial information, a research-based material is systematically organized and described. The large number of examples cover modern detector applications in the field of radiometry, photometry, colorimetry, and radiation temperature measurements. All the discussed devices and applications have been implemented, realized, tested, verified, and evaluated. These applications are described to obtain uniform results with low measurement uncertainties. They are described with enough details to successfully repeat them by the readers/users. The applications and evaluations follow the recommendations of international standardization. The described subjects are detailed and distributed in five volumes.

Properties of radiometric quality detectors, their use and selection for optical radiometers, design considerations of radiometers and detector-based standards, description of spectral and broadband detector-based calibrations and measurements using modern setups based on the new radiometer standards are described for practicing scientists, engineers, and technicians.

The book series includes many hundreds of designs, drawings, measurement schemes, a large number of detector-based measurement and calibration setups, measurement equations and results, calibration-transfer and measurement methods/procedures all tested in practical applications.

In addition to reference level detector/radiometer calibrations, measurement of radiometric quantities used in practice (secondary laboratory and field applications), are discussed. Such quantities are radiant power, irradiance, and radiance. Measurement of spectral and broadband (integrated) quantities are discussed from 200 nm in the ultraviolet to 30 μm in the infrared.

All discussed calibrations and measurements are traceable to the System International (SI) units through National Measurement Institutes (NMI) and/or the discussed intrinsic detector standards.

Linear and traceable measurement of detector output signals, including DC and AC photocurrent (sub-scale) and voltage measurements, detector-amplifier gain-calibrations, and gain-linearity tests are discussed in detail.

Uncertainty determination/calculation methods of detector-based measurements are described. It is a general rule for the discussed large number of design and application examples, to keep the calibration/measurement uncertainties low.

The author thanks all the colleagues listed in the references at the end of each volume for their help and contribution to perform the discussed large number of measurements and evaluations.

Dr. George P Eppeldauer, author

1. INTRODUCTION

The application of optical detectors for radiometric, photometric and colorimetric calibrations and measurements can be done after the detector properties are known. Detector applications include design considerations for the optical radiometers where the detectors can be used. The applications involve photovoltaic and photoconductive detector operations and their electrical signal measurements. Design of the radiometer input optics depends on the type of the radiometric quantity to be measured. The most frequently measured (input) radiometric quantities are radiant power, irradiance, and radiance. Modifications in the input optics of the radiometers makes it possible to measure their equivalent photometric quantities: luminous flux, illuminance, and luminance. The measurement mode can be direct current (DC), alternating current (AC), or pulse, depending on the specific measurement task. The detectors and their output-signal measuring circuits are to be matched to obtain optimum performance for a given measurement. A well-designed detector – preamplifier (matched) pair should produce an optimized first-stage for the radiometer resulting in a high signal-to-noise ratio, a wide signal range with linear operation, and a low uncertainty in the measurements. Temperature monitor or control is frequently needed for the input filters, detectors, and preamplifiers to further improve measurement uncertainty and long-term stability.

2. OPTICAL RADIATION MEASUREMENTS WITH DETECTORS

Radiometric quality detectors, discussed in the book of Optical Detector Properties (Volume 1 from the five-volume book series of George P Eppeldauer: Optical Radiation Detectors and Radiometers), are the fundamental building components of optical radiometers when accurate optical radiation measurements are needed. Figure 1 shows the scheme of optical radiation measurements. The complete instrument that measures a given radiometric quantity is an optical radiometer. In this example, the radiometer includes a photodiode detector, the input optics (that may include the shown shutter and chopper), the electronic circuits used to operate the detector, such as the biasing circuit (if needed) and the output signal (e.g. photocurrent) measuring circuits, the temperature monitoring or temperature control circuits for certain optical components (such as optical filters in front of the detector and a further temperature control for the detector itself when a constant and/or cold operational temperature is needed).

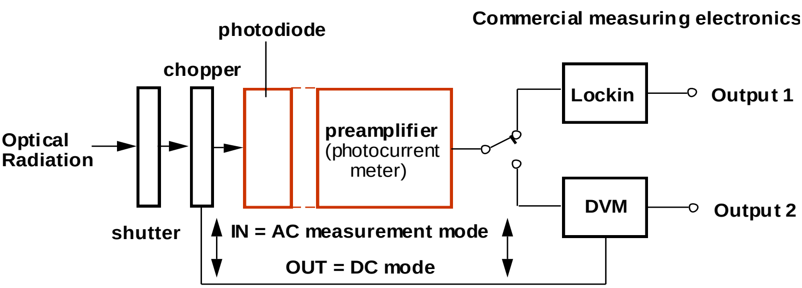

Fig. 1. Scheme of optical radiation measurements.

The measurements can be performed in either DC or AC measurement modes. In the shown scheme (as an example), the measurement mode selection can be made with a single-pole double-through switch. DC measurements can be performed in the lower position of the switch. In this mode, the chopper is removed from the incident radiation and the DC output voltage of the preamplifier is measured by a digital voltmeter (DVM). In AC mode, the switch is in the upper position, and a lock-in amplifier measures the chopped (or modulated) AC output signal of the preamplifier. In both DC and AC measurement modes a preamplifier is connected to the output of the detector. The first stage, that includes the preamplifier matched to the selected detector [1], will dominate the performance (signal-to-noise ratio) of the optical radiation measurement.

3. INPUT GEOMETRY FOR DETECTORS

The input geometry of an optical radiometer is determined by the applied input optics that may include a large number of different components. The selection of these components depends on the radiometric or photometric quantities to be measured.

3.1. Radiant power measurement

In radiant power measurements, the total power Φ in the incident radiation is to be measured. The unit of radiant power is watt (W). A practical example for radiant power measurement is measurement of laser beam power. The measurement geometry of laser power measurement is shown in Fig. 2. The sensitive area of the detector is underfilled by the incident beam. Accordingly, only large active-area detectors are suitable for radiant power mode measurements. The input optics in power mode is simple. Use of an aperture in front of the detector is not needed. Detectors with small non-uniformity of spatial responsivity are to be selected for power responsivity calibrations/measurements to obtain low responsivity uncertainty. Measurements using stabilized laser beams are common for power responsivity calibrations to obtain decreased responsivity uncertainty.

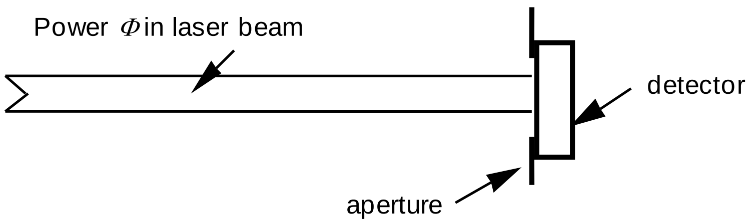

Fig. 2. Measurement geometry of laser power measurement.

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. These measurements are widely used in spectral responsivity scale transfers where test detector(s) are calibrated against a standard detector of known spectral power responsivity [2].

Figure 3 shows the design of the front-housing of a radiant power measuring Ge (or InGaAs) radiometer. The temperature controlled (cooled) photodiode is mounted in a TO-8 package which has a sealing window to avoid condensation. The package is plugged into the center hole of the threaded holder against a plastic ring. The threaded holder was designed to limit the field-of-view (FOV) to 60° for the photodiode to block radiation from the sides. This FOV is also called unvignetted FOV showing the angular range where the

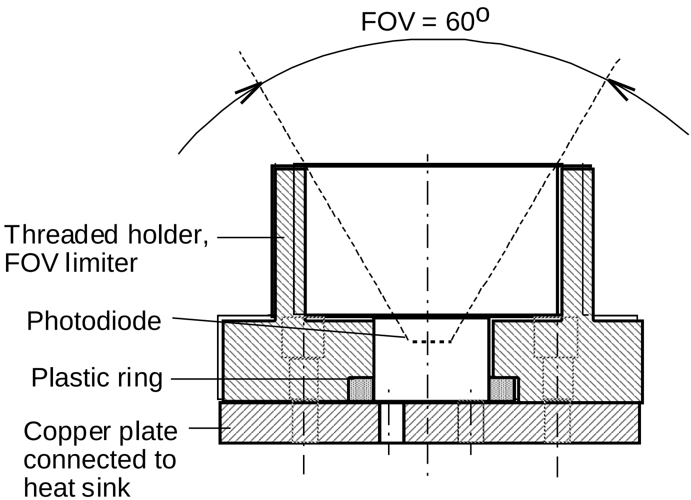

Fig. 3. Ge photodiode housing for radiant power measurements.

incident radiation can be measured without any beam clipping. This angular range is the acceptance angle of the radiometer. During radiant power measurement, the active area of the photodiode is underfilled by the incident radiation. The shape of the incident radiation can change from collimated (like laser) to an f/# which is limited by the FOV. The converging incident radiation should be focused onto the detector and the focused spot should be smaller than the active area of the detector. With this input geometry, the total power in the incident radiation will be measured. No aperture is needed in front of the photodiode for this measurement. If an aperture is applied, the focusing should be made to the aperture plane.

The non-uniformity of spatial response of a photodiode has to be matched to the required measurement uncertainty to get repeatable radiant power responsivities for different beam sizes and beam positions. The threaded holder in Fig. 3 is used to mount the input optics in front of the detector. The input optics can include different accessories, such as filter(s) and/or aperture in front of the photodiode. The heat from the bottom of the case of the thermoelectrically cooled photodiode is conducted by the copper plate to a heat sink where it is dissipated. An optical unit like this can be attached to an electronic unit and the two units together will be the measuring head (probe) of a radiometer.

The design of the input optics needs special attention when lasers are measured. Figure 4 shows an example for an input arrangement where no parallel surfaces are used in the incident radiation. In this example, a custom-made detector-case was built for a 5 mm diameter extended-InGaAs (EIGA) detector. The sapphire window has a 4º wedge angle and the detector-chip is tilted by another 4º as shown in circle C. In case of coherent radiation measurement, e.g., when measuring a 1 mm diameter laser beam, there will be no overlap on the detector surface between the reflected beams and the 0-order incident beam. Beam overlaps on the detector could cause interference fringes that should be avoided. However, most frequently non-coherent radiation is measured with the shown short-wave infrared (SW-IR) detector. The main advantage of the shown detector-case is that the front and side surfaces around the detector will not warm up because of the conducted heat dissipation from the illustrated 4-stage TE cooler and there will be no excess background radiation for the detector. In this example, the detector has a cut-off wavelength of 2.6 μm. When using traditional (such as 3CN) detector cans, the side walls can warm up. To avoid this problem, a cold FOV limiter (e.g. FOV=30º) can be mounted around the detector to keep the background radiation produced signal low.

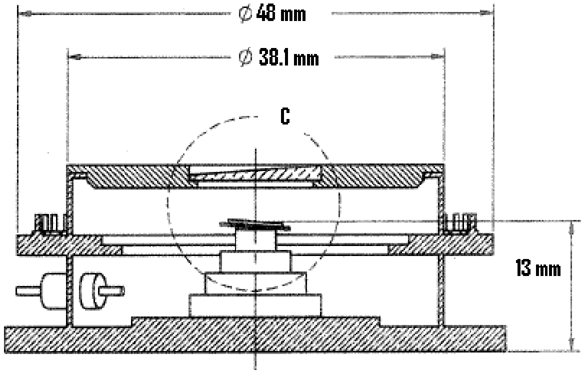

Fig. 4. A 5 mm diameter extended-InGaAs detector tilted with 4° behind the 4° wedged sapphire window to minimize interference fringes during laser measurements.

The photometric equivalent of radiant power is luminous flux [3]. In luminous flux measurements, a photopic filter is inserted into the incident radiation (in front of the detector) using similar measurement geometry as in power mode measurements. Luminous flux measurements are frequently used at monochromator setups to calibrate photometers for spectral responsivity. (Illuminance responsivity calibrations are discussed in Volumes 3 and 4.)

3.1.1. Optical filters

Optical filters can modify the spectral characteristics of detectors in optical radiometers. Two types of filters are commonly used: colored glass filters and multi-layer interference filters. Colored glass filters are used to block short or long wavelength radiation and to design instruments with a wide spectral band-pass, such as photometers and colorimeters. Interference filters are used in general when glass filters are not available or when a narrow spectral band-pass is required.

The color of filter glasses is determined by dissolving or suspending coloring agents in the glass. The optical density, or specific spectral transmittance of a filter, is controlled by the concentration of coloring agents in the glass or its thickness. Glass filters of different thickness that are cemented together are widely used in instruments such as photometers and colorimeters.

A large variety of filters with different spectral transmittance curves can be realized with custom-made interference filters. The stability of interference filters has been a long-standing issue. To improve their radiometric performance, the high-reflectance multi-layer coatings used in Fabry-Perot type filters [4] can be sealed to protect the coatings from moisture. Also, the filters can be constructed from hard, durable, non-hygroscopic materials. In addition, the stability of interference filters has improved in the last several years with the development of ion-beam-assisted deposition (IBAD) of the dielectric layers that comprise the filter. IBAD filters are less sensitive to humidity, UV exposure, and temperature changes than conventional multi-layer dielectric interference filters.

The transmission of interference-type filters depends on incident beam geometry. As the angle of beam incidence increases from the normal of the filter surface, the center wavelength shifts to shorter wavelengths. The lower the effective index of refraction, the greater the shift. Also, the filter transmittance is temperature dependent. It is important to keep the temperature coefficient of spectral transmittance low. The peak transmission wavelength increases and decreases with temperature in a linear fashion; nearly all optical filters exhibit a positive linear temperature coefficient.

The out-of-band transmission of band-pass filters can range from 10^{-3} to 10^{-7}. Consideration of the out-of-band transmission is very important when filters are used with broad-band sources and detectors. Flatness, parallelism, surface quality, and pinholes are important issues mostly for imaging applications. To keep measurement uncertainty low, high performance interference filters are to be purchased and parallel beams and temperature control for the filter(s) should be applied.

Inter-reflections between the aperture and filters or between the filter and the detector can result in a responsivity that is dependent on the measurement geometry. Inter-reflections between filter components is also a common problem. To avoid inter-filter reflections when more filters are used, the individual filters (filter layers) should be glued together using clear optical cement. As an example, Lens Bond [4] manufactured by Summers Laboratories, is a synthetic polyester adhesive optical cement. The refractive index of cured Lens Bond is approximately 1.55 at 25.0 ºC. From the six manufactured types, F-65 can be a good choice to glue glass filters together. This type of bond should always be cured at room temperature. The catalyst to bond ratio is 5:100. The mixture should have to be put in “vacuum” for 2-4 minutes to release bubbles. A thin layer should be applied on both sides of the layers to be glued together. Bonding should start from one side. Enough mixtures are to be applied on both sides before pushing them slightly together. Rotary motions can help to remove the bubbles. The glued filters should stay in “vacuum” with about 625 Hgmm pressure. The required time for pre-cure is 30 minutes and it is 1 day for full-cure.

Power mode calibrations and measurements are mostly used for responsivity scale transfer (with the exception of laser power measurements). Filters can be used in radiant power mode measurements to modify the spectral responsivity of detectors but they are more frequently used in irradiance and radiance meters which are widely used in different applications [5].

Frequently, the responsivity of a filter radiometer (such as a photometer) changes because dust (producing a gray-spot) can develop on the front surface of a filter. In spite of repeated calibrations, the responsivity of a dust-coated filter radiometer can decrease. As an example, the illuminance-responsivity change between two yearly calibrations can be about 0.2 %. Application of a simple cleaning procedure (using an optical-quality dry lens-cleaning tissue) eliminates the responsivity changes and the start-values of the illuminance-responsivities can be maintained. The reason of receiving a gray dust-spot is that the optical-radiation changes the electrostatic-state of the window (or filter) surface and that change attracts the dust particles. The window-glass charges up because the glass is a high insulator. This problem is well-known in UV radiation measurements where the UV content of the radiation amplifies the surface charge state changes. Regular cleaning of the front-surface of the filters eliminates the long-term responsivity changes.

At cleaning, the window or filter should not be touched with bare hands, especially in UV measurements, since foreign materials on the window can affect transmittance. Avoid using chemicals other than ethyl alcohol (using gentle wipe off) because they can cause changes in the filter transmittance and can also cause deterioration in the device's resin coating.

3.1.2. Input widows

Selection of windows in front of detectors is an important task in radiant power measurements. Selection of optical quality windows is important in applications where low measurement uncertainty is needed. For example, use of resin coating as a protecting window for photodiodes produces a rough surface that scatters the incident light. This light scatter should be avoided in many applications.

Different window materials have different spectral transmittances that will modify the spectral responsivity of the detectors. Borosilicate glass is used for silicon photodiodes for wavelengths longer than 320 nm. When spectral measurements are to be extended toward the shorter wavelengths range of about 190 nm, quartz glass windows are used. These are typically optical quality windows. The material of the window can restrict the spectral coverage of the detector. Sapphire glass windows widely used for extended-InGaAs and InSb detectors and ZnSe windows used for HgCdTe detectors have excellent optical quality and high stability. They are popular for the infrared range. Care should be taken when choosing a window material for the long infrared range because many of these IR window materials are hygroscopic.

The spectral transmittance of a selected window should be known unless it will be measured together with the spectral responsivity of the detector. As an example, Fig. 5 shows the measured spectral transmittance curves of two KBr windows from 2 μm to 20 μm. The average transmittance values are shown. The error bars show the transmittance measurement uncertainties. Both windows were selected from the same batch. The maximum-to-minimum deviations from a constant spectral transmittance are within +/- 1.5 %.

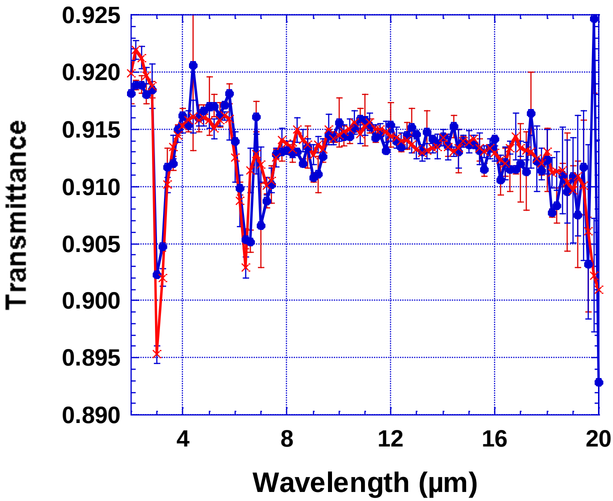

Fig. 5. Spectral transmittances of two KBr windows from the same batch.

3.1.3. Multiple input beam reflections

A detector responsivity (and external quantum efficiency) can be increased if the absorption of the detector to the incident radiation is increased. More radiation can be absorbed if the reflection losses are decreased using multiple input reflections on the detector or on a group of electrically connected detectors. If a detector (or detectors) used with multiple beam reflections were selected for high and spatially uniform internal quantum efficiency, an improved performance detector with spatially uniform and high responsivity can be obtained.

3.1.3.1. Trap detectors

Typically, trap detectors are used as transfer standards. They can measure radiant power. They can also measure irradiance if the input aperture is overfilled with the incident radiation. The scheme of a reflectance-type trap detector with an input aperture is shown in Fig. 6. The incident beam is reflected back from the trap-detector along the optical path of the entering beam after five reflections. Figure 7 shows the computer design of the trap detector illustrated in Fig. 6.

The scheme of a tunnel trap detector is shown in Fig. 8 [6]. The shown device was built from six photodiodes of two different sizes. The exiting (output) beam is trapped by a 30° conical shape light trap (not shown on the left side). This light trapping cover also keeps the trap detector light-tight since it rejects the ambient light from the inside. 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 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 must be large enough not to vignette the incident beam (e.g. from a monochromator).

The computer design of the tunnel-trap detector illustrated in Fig. 8 is shown in Fig. 9.

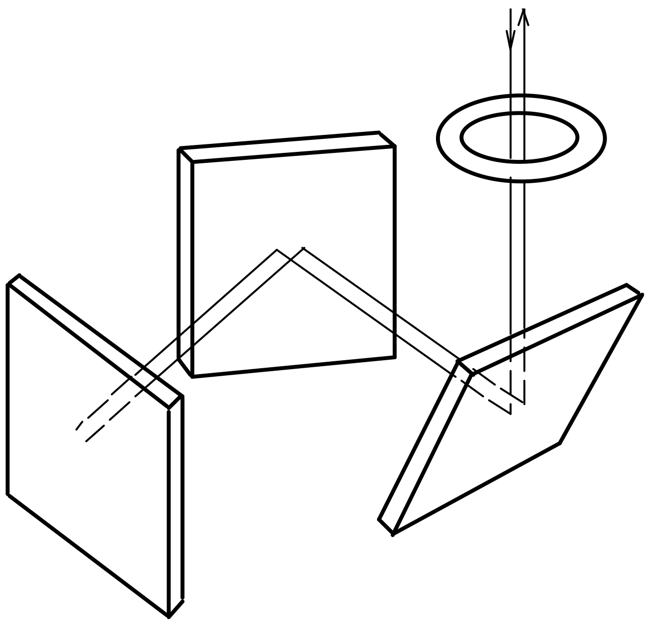

Fig. 6. Scheme of a reflectance-type trap detector.

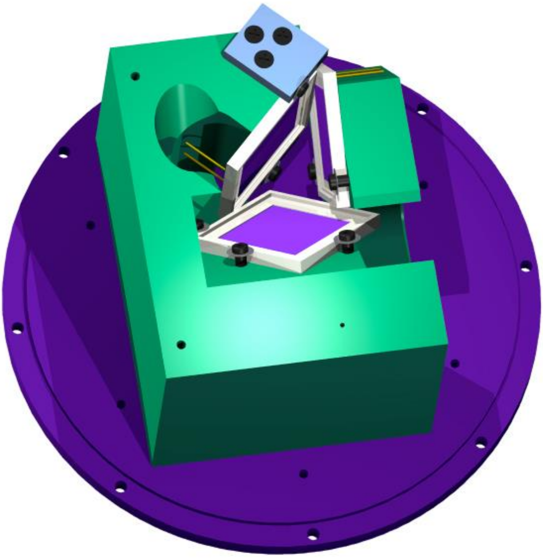

Fig. 7. Computer design of a reflectance-type trap detector illustrated in Fig. 6 using 18 mm by 18 mm Si photodiodes.

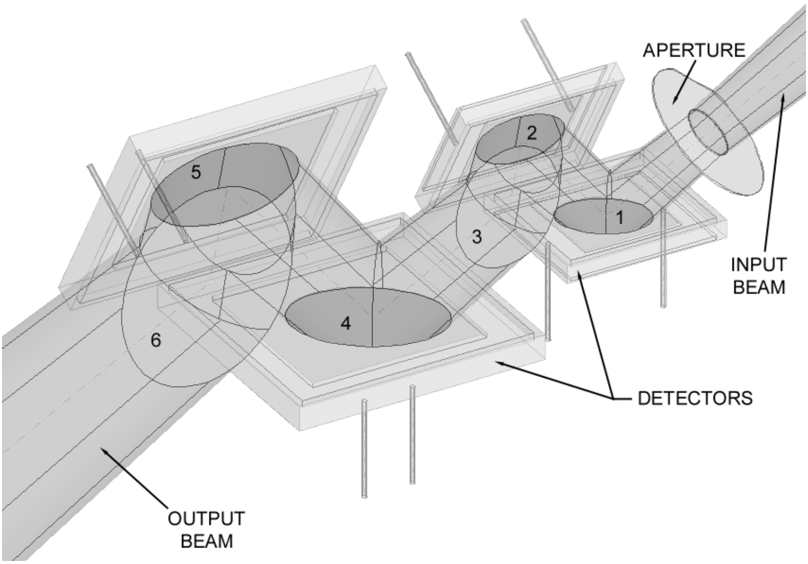

Fig. 8. Beam propagation in a triangular shape tunnel-trap detector using Si photodiodes of two different sizes.

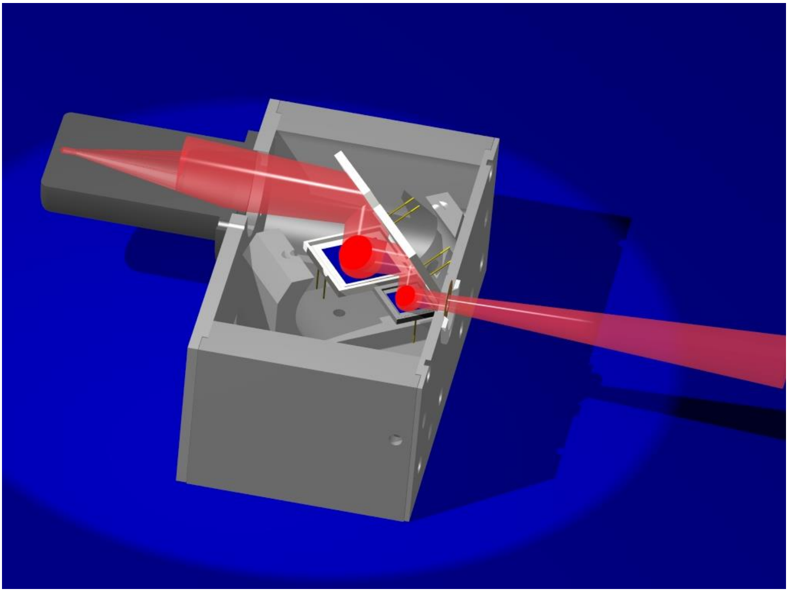

Fig. 9. Computer design of the tunnel trap detector illustrated in Fig. 8. The exiting beam (on the left) is absorbed by a conical shape light-trap.

A wedge type trap detector with several beam reflections is shown in Fig 10. In this example, the incident radiation (beam) hits the black coated pyroelectric crystal at an angle. To avoid obtaining large detector capacitance when using two parallel connected detectors (in wedge arrangement), the upper component of this wedge-trap is a gold coated mirror. The angle between the detector and the mirror determines the number of reflections. Similar wedge arrangements can be used with other detector types as well.

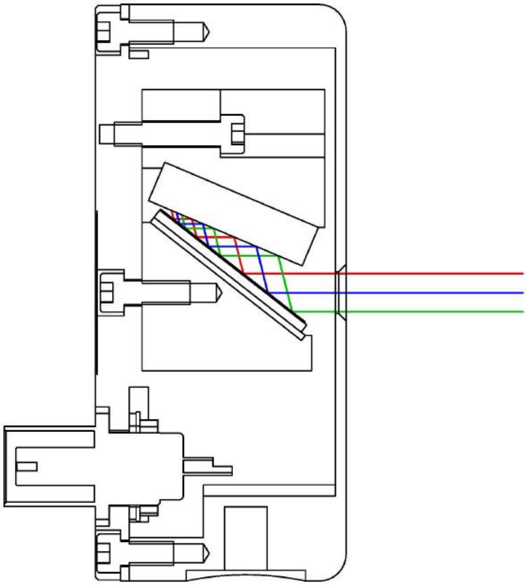

Fig. 10. Wedge arrangement of a pyroelectric detector and a mirror to obtain multiple reflections on the black coated detector.

Fig. 11. Picture of the wedge-input pyroelectric detector shown in Fig. 10.

3.1.3.2. Reflecting dome

A reflecting dome can produce multiple input beam reflections in order to increase detector absorption [7]. In the example, shown in Fig. 12, the detector is tilted by 20°. The incident radiation after the first reflection from the detector is reflected to the gold coated shiny dome that reflects the radiation back to the detector. The reflectance of the organic black coated pyroelectric detector (in the example) changes between 4 % and 5.5 % between 2 μm and 14 μm. The reflectance of quantum detectors can be higher, e.g. 35-40 % for Si photodiodes (as shown in Fig. 2 in Vol. 1). The reflecting dome is more efficient for detectors with high reflectance.

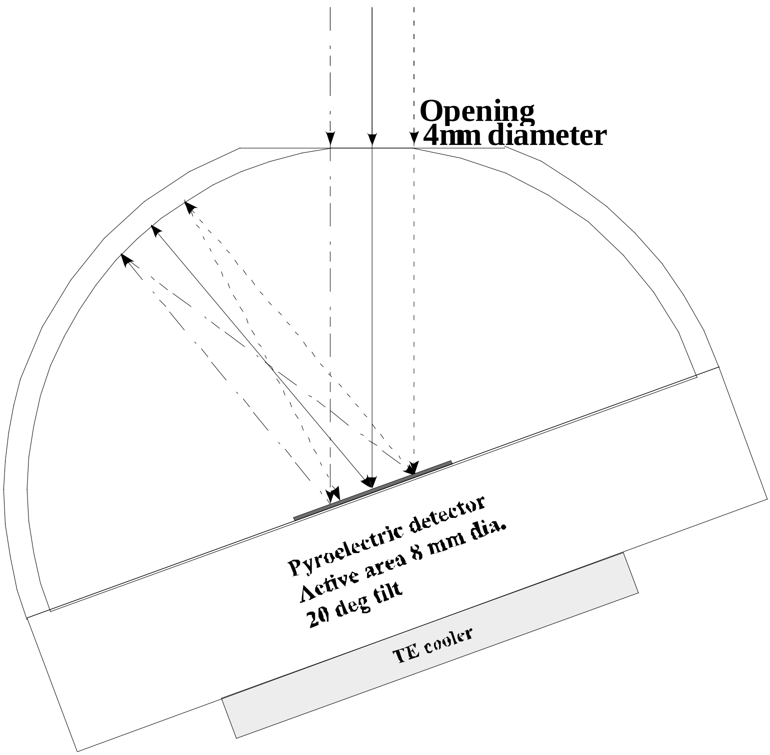

Fig. 12. Multiple beam reflections in a gold coated reflecting dome of 33 mm diameter when the detector is tilted by 20° for the incident radiation.

The picture of the reflecting dome is shown in Fig. 13. The inside wall of the pyrex dome is coated with a shiny gold layer. The computer design of the dome-input pyroelectric detector is shown in Fig. 14. The front picture of the dome-input pyroelectric radiometer is shown in Fig. 15. The front cover is removed for better illustration.

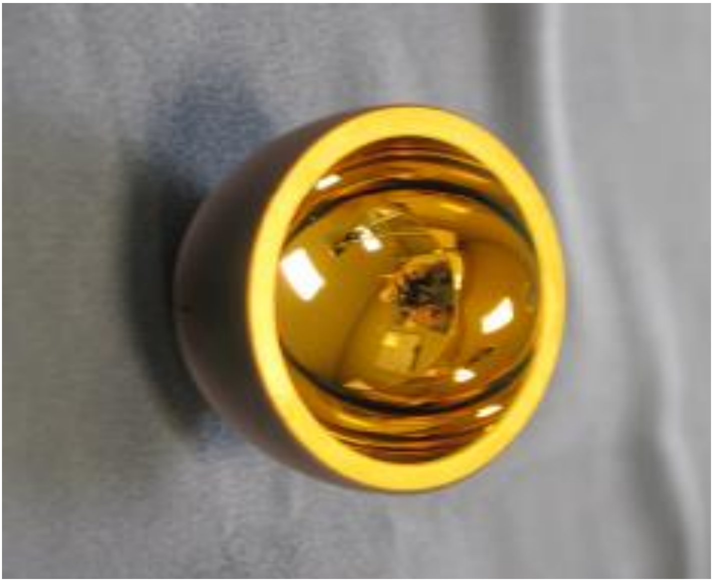

Fig 13. Gold coated reflecting dome

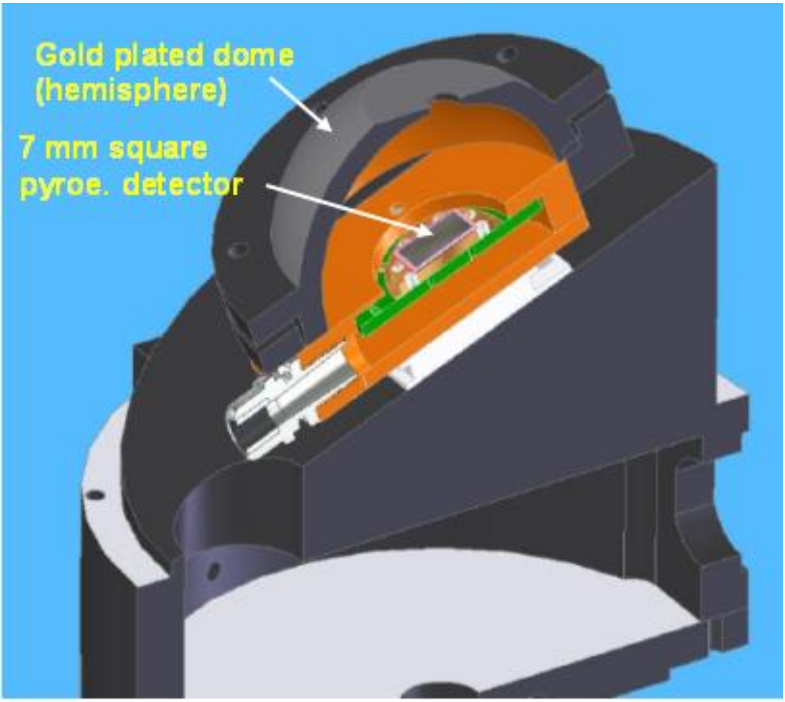

Fig. 14. Computer design of a dome-input pyroelectric detector.

Fig. 15. The front picture of the dome-input pyroelectric radiometer.

3.2. Irradiance measurement

Irradiance measurements are performed in many field applications. Irradiance and illuminance (the photometric equivalent of irradiance) are the most widely measured radiometric and photometric quantities. The unit of irradiance is watt divided by meter-square (W/m^2). The measurement geometry of applications is more complicated than the total-power measurement described above in radiant power measurements. The advantage of irradiance measurements is that even detectors with spatially non-uniform responsivity can be used for low uncertainty irradiance measurements [8]. The non-uniformity of the spatial responsivity is averaged out if a uniform incident beam of radiation overfills the active area of the detector.

Frequently, detectors with small active area cannot be measured in power mode because it is not possible (or very difficult) to underfill the detector with the incident radiation. Therefore, small detectors are usually measured and calibrated in irradiance mode.

The measurement geometry for irradiance measurements is shown in Fig. 16. Irradiance E (in the reference plane of the detector) is defined as radiant power Φ per unit area. Irradiance standard detectors are equipped with an aperture of area A_1. The radiation (with a total power Φ) leaving the overfilled detector-aperture must be entirely measured by the detector. The irradiance responsivity of an irradiance meter is equal to its own radiant power responsivity multiplied by area A_1 of the limiting aperture.

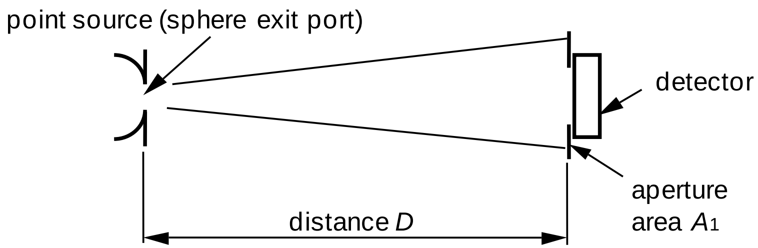

Fig. 16. Measurement geometry for irradiance mode measurement.

In irradiance responsivity measurements the aperture has to be overfilled by the incident optical radiation. In Fig. 16, the irradiating source is realized with an integrating sphere. A source like this can be considered as a point source if the distance D between the source aperture (exit port) and the detector aperture is much larger than the size of the apertures. Radiometers used as irradiance standards, to convert power responsivity into irradiance responsivity, must have apertures of known area.

3.2.1 Cosine law of detector irradiance measurements.

The operation of the cosine low in irradiance measurement mode is illustrated in Fig. 17:

The area before rotation of the detector surface is

$$A = 4a^2. \qquad (1)$$

After rotation of the surface (which is equivalent to changing the angle of incidence from zero to α) the (projected) area will be

$$A' = 2a \times 2a' = 4\,a^2 \cos\alpha = A \cos\alpha. \qquad (2)$$

The angle of incidence α is the angle between the normal of the aperture plane and the axis of the incident beam.

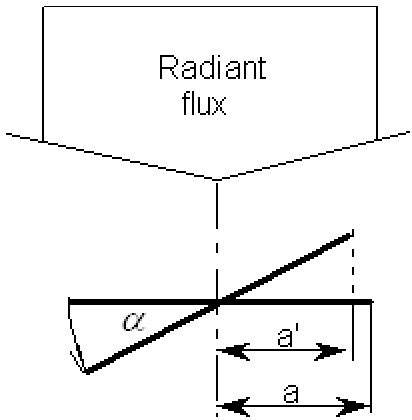

Fig. 17. Change of the aperture (or detector) area versus angle of incidence.

According to Eq. 2, the radiant flux collected by the rotated detector (or aperture) changes (decreases) by the cosine of the angle of rotation.

The angular response of a well-designed irradiance meter should match the cosine function within its FOV according to the law of detector irradiance measurements. This requirement can be achieved only if the input optics of the irradiance meter is properly designed.

The spectral irradiance responsivity, $s_E(\lambda)$, of an irradiance meter is derived from its own spatially averaged spectral radiant power responsivity:

$$s_E(\lambda, \alpha) = A_d \cos\alpha \; s_{avg}(\lambda) \qquad (3)$$

where A_d is the size of the aperture (or detector) area in m^2, α is the angle of the incident beam, and $s_{avg}(\lambda)$ is the spatially averaged spectral radiant power responsivity. Note that α = constant for all wavelengths in the equation. If the incident beam is not parallel, α is no longer a constant, but can take a range of values $0 \leq \alpha \leq \alpha_{max}$. In this case, the integral of $\cos\alpha$ will be measured for all incident angles (changing α) of the beam.

One of the main tasks in irradiance measurements is to maintain the cosine low for minimizing uncertainties of irradiance responsivity measurements.

3.2.2. Input optics design issues

The main goal of the input optics design of irradiance meters is to maintain the high accuracy of the cosine function realization in irradiance measurements. Without the right input geometry, the shape of the cosine function could be altered greatly, resulting in low measurement accuracy.

The stray light from the edge of the aperture and the aperture holder, that can reach the detector, should be kept at a low level. The size of the aperture and its distance from the detector has an influence for the uncertainty of the irradiance measurements. Figure 18 shows ideal and real beam shapes and different (simplified) detector input geometries for irradiance measurements. The advantage of a point source is that it produces a uniform irradiance with a collimated beam shape within the aperture of the irradiance meter. This geometry is shown in Fig. 18(b). When this irradiance measuring geometry is used, a separation is allowed between aperture and detector. The separation is needed when filters and/or a detector window are located between the aperture and the detector front-surface. For an ideal irradiance meter, a thin aperture should be positioned on the active area of the detector. In this ideal case, the shape of the beam that overfills the aperture can change from collimated (parallel) to a large angle β without any change in the irradiance responsivity. This