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Spatial non-uniformity analyses of radiometric detectors to identify suited transfer standards for optical radiometry

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Abstract. The non-uniformity of responsivity of photodiodes and thermal detectors limits the accuracy of their calibration. Spatial non-uniformity properties of a pyroelectric radiometer, a thermopile detector, silicon, germanium and indium gallium arsenide photodiodes are investigated in the scope of our work. Silicon type photodiodes showed best uniformity characteristics among the analysed photodiodes and detectors. Significant changes have been found in the spatial responsivity close to the band gap of silicon. The spatial responsivity of thermopile detector was measured at two different wavelengths and no wavelength dependence was observed.

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1 Introduction

Pyroelectric radiometers, thermopile detectors, silicon, germanium (Ge) and indium gallium arsenide (InGaAs) photodiodes are preferred transfer standards for optical measurements [1–5]. Due to the differences of production methods and internal structure of these detectors, they must be characterized carefully. For instance, silicon photodiodes are mainly used as the transfer standard of optical power within the region 300 nm to 1100 nm. These measurements were made against electrical substitution based cryogenic radiometers. In this type of measurements accuracies of better than 0.1% are desirable [6].

The progress in the development of optical communication techniques demands for more accurate optical measurements in the near infrared spectral range (NIR). The uncertainties of the primary standards of the national metrology laboratories to use optical radiant power is at the level of 0.01%. An accurate transfer of the optical radiant power to the applications in the NIR mostly is achieved with Ge and InGaAs photodiodes [7,8].

Pyroelectric radiometers and thermopiles are chosen in radiometry, especially in spectral broadband applications or radiant power measurements where sources of unknown spectral distribution function are used [9,10].

The detector should be under-filled in many applications [11]. If radiation hits an ideal, it should generate the same output signal at different locations on its sensitive surface. Because of the various effects such as structure of detectors, fabrication quality, heat conduction, radiation and convection heat losses, pyroelectric radiometers, thermopiles, silicon, Ge and InGaAs photodiodes suffer from spatial non-uniformity. Therefore, the non-uniformity of detectors' responsivity is very important when these detectors are utilised as transfer standards.

In order to choose suited transfer standard candidates in optical radiometry, spatial non-uniformity properties of various detectors are analysed in this work. In the first part of Section 2, the measurement method for silicon, InGaAs and Ge photodiodes is introduced. Then non-uniformity analyses of a thermopile at two different wavelengths are presented. Descriptions of pyroelectric radiometer structure and measurement technique for response non-uniformity are presented in Section 3.

2 Non-uniformity measurements for silicon, Ge, InGaAs and thermopile detectors

The schematic diagram of the measurement set-up to determine spatial non-uniformity properties of the detectors is shown in Figure 1. It is basically divided into two parts as laser power stabilizing system and high precision dual axis translation facility. A He-Ne laser with a wavelength of 632.8 nm and a Nd-YAG laser with a wavelength of 1064 nm were used as radiant sources.

The radiant powers of the lasers were stabilized to better than 0.004% by using an established system described previously [12]. Beam shaping optics were used to produce a Gaussian measurement spot having a $1/e^2$ size of 500 μm. The stability of the beam was monitored during the measurements with a beam splitter and a

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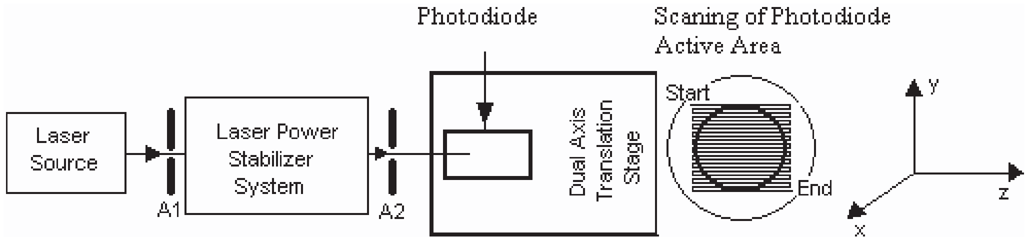

Fig. 1. Spatial non-uniformity measurement set-up.

monitor detector arrangement. The photodiode under test was mounted on a dual-axis translation stage and the perpendicular alignment to the optical axis was performed carefully. In order to eliminate interference effects the entrance window of the detector was made with 1.5° wedge-shape. The motion repeatability of the translation stage was analysed with an interferometer and it was found better than 3 μm in both axis. The spatial uniformity of detectors was investigated by scanning their entrance aperture with a step length of 0.5 mm. The beam size and shape on the detector were controlled by a CCD camera based beam-analyser before starting measurements. After each scan in the horizontal direction, the photodiode moved one step in the vertical direction and then another horizontal direction scan was started. The scans were continued in the reverse direction and average readings were recorded from the repeated measurements. The scans were started at the upper left corner and finished at the lower right corner of the photodiode. The uniformity of detectors was obtained by dividing their response at the selected point to the maximum responsivity value.

Current signals from the test and monitor detectors were measured with a current to voltage converter and a digital voltmeter. Signal drifts during the measurement period were corrected with the monitor detector.

Inhomogeneity of the photodiode material itself causes non-uniformity; inhomogeneity by bulk recombination centres at longer wavelengths [13] and by surface recombination centres at shorter wavelengths [14,15]. Therefore, spatial non-uniformity of responsivity for S1337-11 type silicon photodiodes was measured at the wavelengths 632.8 nm and at 1064 nm. All measurements were repeated 3 times and relative standard deviations were found to be 3×10^{-4} for 632.8 nm and 3.7×10^{-4} for 1064 nm. Figure 2 shows the non-uniformity map of the photodiode at two different wavelengths.

While the photodiode shows uniform responsivity at 632.8 nm, it reveals large non-uniformity at 1064 nm. The maximum relative variation in local responsivity at a 8×8 mm area is at the level of ± 0.02% at 632.8 nm. But the variation reached about ±1% at 1064 nm.

Ge and InGaAs photodiodes were measured at 1064 nm. Active areas of both detectors scanned with 250 μm steps. The temperature of the photodiodes was held constant within ±0.2 °C by placing them in a temperature controlled housing. While Ge photodiodes were produced by the monocrystal wafer preparation technique, InGaAs photodiodes are grown by Vapour Phase Epitaxy.

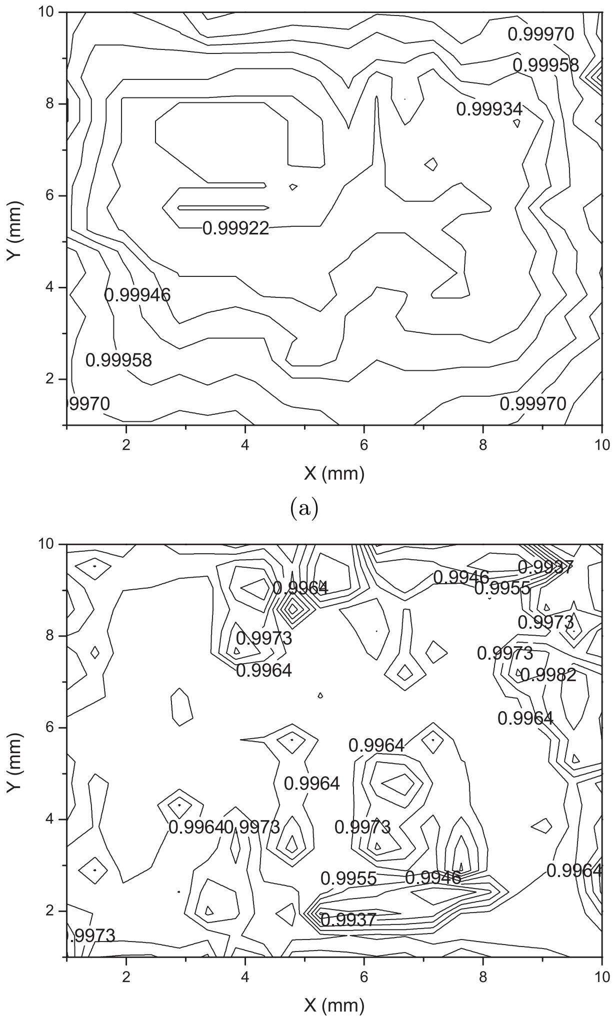

Fig. 2. Spatial non-uniformity of silicon photodiode at (a) 632.8 nm and (b) 1064 nm.

Graphical presentations of the measurement results for both photodiodes are shown in Figures 3 and 4, respectively. The comparison of their figures shows that the InGaAs photodiode has higher non-uniformity than the Ge photodiode.

Detectors that measure radiation by means of the change of temperature of an absorbing material are classified as thermal detectors. These types of detectors respond to any wavelength radiation that is absorbed and

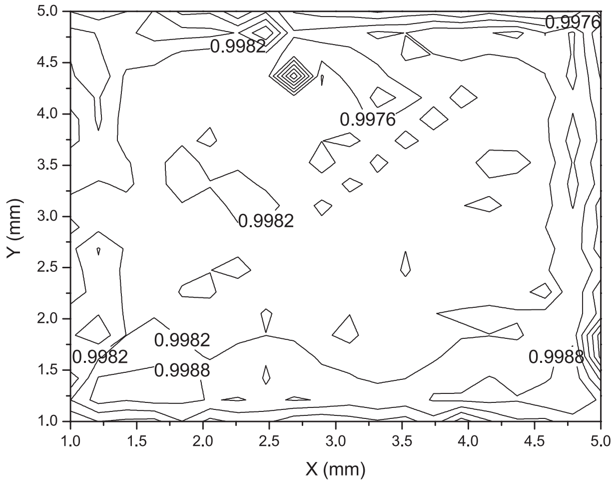

Fig. 3. Spatial relative responsivity of Ge photodiode (non-uniformity plot).

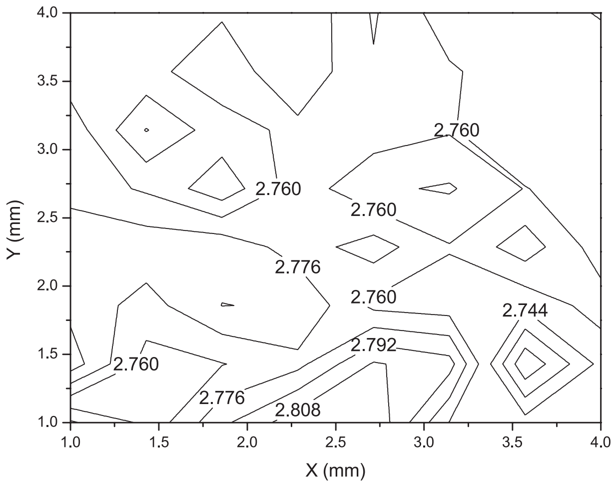

Fig. 4. Spatial relative responsivity of InGaAs photodiode (non-uniformity plot).

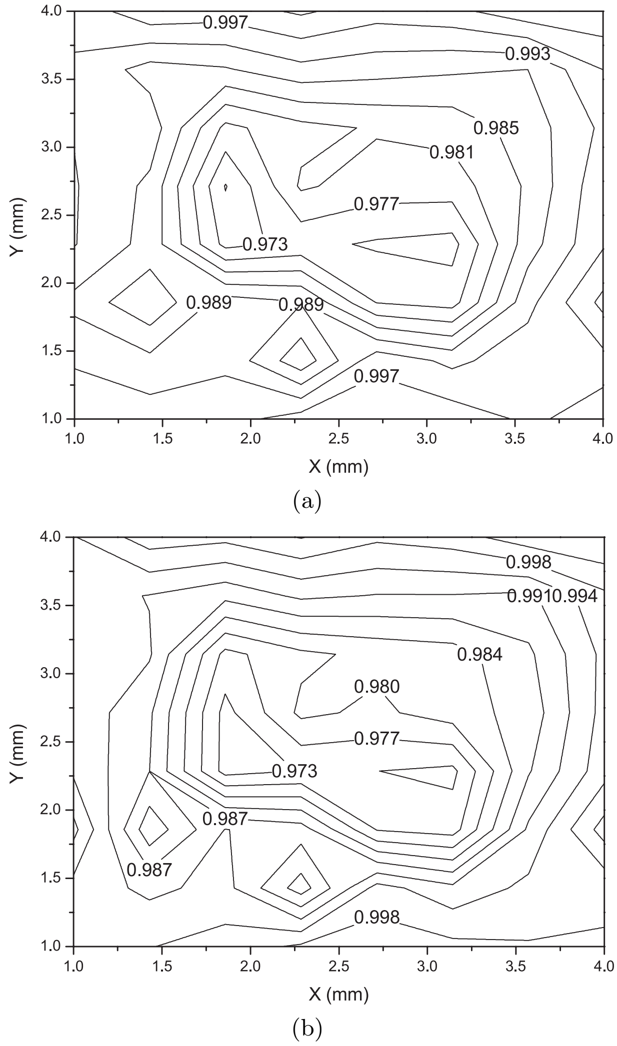

Fig. 5. Uniformity presentation of Thermopile detector at (a) 632.8 nm and (b) 1064 nm.

respond over a wide range of wavelengths. One of the most common thermal detectors used in the infrared (IR) applications is the thermopile. This kind of detectors differs from pyroelectric detectors in several important ways. The thermopile detectors are voltage-generating devices, which can be thought of as miniature arrays of thermocouple junctions. Thermopile detector output is proportional to the incident radiation while the pyroelectric detectors output is proportional to the rate of change of the incident radiation. In other words, the thermopile detector is DC coupled while the pyroelectric detector is AC coupled.

Spatial non-uniformity of a thermopile detector was measured at the laser lines of He-Ne at 632.8 nm and Nd-YAG at 1064 nm by using the set-up shown in Figure 1. These type of detectors are very sensitive to environmental temperature changes. Therefore, the laboratory was air-conditioned at (22 ± 1) °C. The active area of the thermopile, of 4×4 mm^2, was scanned with 500 μm steps in both directions. During the measurements the power level of the lasers was set to 650 μW. Graphical representations of the non-uniformity measurements of the detector are shown in Figures 5a, 5b for two different wavelengths.

The results show similar spatial uniformity for two different wavelengths. After analyses of several detectors it was shown that the responsivity has a minimum value at the centre and increases rapidly at the edge of the detector.

3 Measurement method for a pyroelectric radiometer

The pyroelectric radiometer, composed of a readout, a pyroelectric probe, and an optical chopper, has been used as a transfer standard from UV to mid-IR range. It is shown in Figure 6.

Tyrolectric probe has a pyroelectric detector and preamplifier in a common housing. The pyroelectric detector was made up of lithium tantalate ($LiTaO_3$). It has

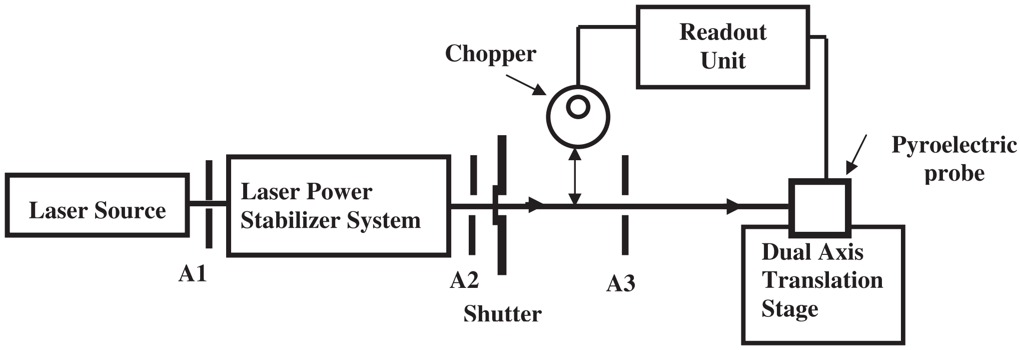

Fig. 6. Spatial uniformity measurement set-up for pyroelectric detector head.

a permanent electric dipole moment. A change in the temperature of the material changes the magnitude of this moment, requires a flow of charge. Moreover, the pyroelectric detector is coated with a gold-black which works as both a spectrally flat absorber for the incident optical radiation and a heating resistor for the electrical substitution servo-loop circuit.

The radiation to be measured is modulated by 15 Hz 50% duty cycle chopper. This should be placed as close as possible to the radiation source so that it minimizes the amount of chopped background radiation. When the chopped optical signal is aligned to hit the pyroelectric material, ultimately the resulting time variation in its temperature will produce a measurable ac current. This current can be detected using a lock-in amplifier, with the chopping frequency used as the reference.

While the chopper is open, the pyroelectric detector produces a thermal signal proportional to the optical power incident on the gold-black absorber material. When the chopper shuts the servo-loop generates electrical current pulses that pass through the gold-black, which now functions as a precision heating resistor. This electrical power (I × R) causes the pyroelectric detector to produce a thermal signal proportional to the electrical power. The servo-loop increases the magnitude of the current pulses until the null condition is reached at the output of the synchronous rectifier circuit. At this point the optical power is equal to the electrical power, and electrical power is digitised and displayed at readout.

Spatial non-uniformity of the detector response occurs primarily because of the thickness variations in the detector element [16]. This limits directly the accuracy attainable with a small illuminated area such as characteristic of laser measurements and when combined with the difference between electrically and optically excited areas, it leads to an overall correction factor. One approach to the problem is to map the optical response over the detector surface. The map can then be used to obtain a correction factor for a particular radiation distribution of interest.

The spatial non-uniformity in the response of ECPR is shown in Figure 7. The signals were normalized to a value obtained at the center of the detector to detect relative variations of responsivity. For the region within 5×5 mm^2 of the center, the maximum variation in the detector response is ±0.79%. This rather substantial non-uniformity

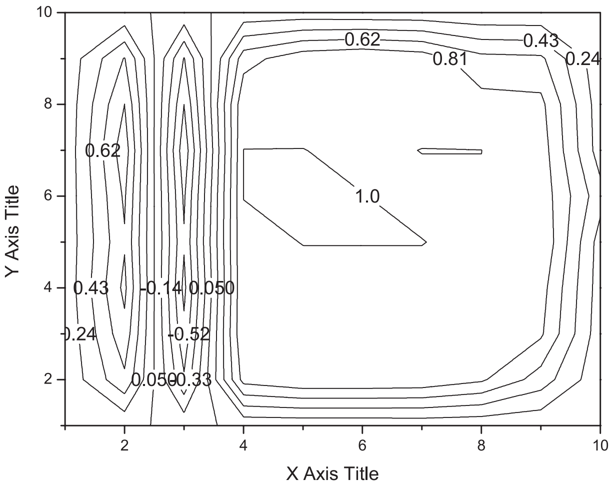

Fig. 7. Spatial response variation of the pyroelectric detector.

is likely to vary from detector to detector and could be improved with a better absorbing coating.

4 Conclusion

Silicon photodiodes with the spatial uniformities better than 0.03% in the area of 10×10 mm^2 have been identified to be preferentially used as transfer standard and in constructing trap detectors. It was found that spatial responsivity changes with wavelength, sometimes significantly as the wavelength approaches the bandgap. In order to identify this dependency spatial uniformity of the silicon photodiode was measured both at 632.8 nm and 1064 nm.

It was found that the non-uniformity of the Ge is approximately 0.1%. Compared to Ge photodiodes, InGaAs photodiodes showed higher non-uniformity (≈0.8%) characteristics. In order to diminish the non-uniformity problem an integrating sphere was constructed which contains a 4 mm InGaAs photodiode. The non-uniformity of the detector's local responsivity is an important selection criterion. Moreover the non-uniformity of the detector essentially determines the requirements on the calibration set-up with respect to positioning, the size and homogeneity of the beam used.

In order to obtain a correction factor to compensate the effects arisen from the illuminated area for each laser wavelengths, the optical response was mapped over the surface of the thermopile and the pyroelectric probe. For a 16 mm^2 region of the thermopile the relative variation in local responsivity was found to be less than 0.49%. This variation was less than 0.79% in the area of 0.25 cm^2 for the pyroelectric detector. It was deduced that the spatial non-uniformities of both the thermopile and the pyroelectric detector are proportional to the square of the distance to the detector centre.

There was no wavelength dependence detectable for the thermopile detector. Therefore, the spectral responsivity of these kinds of detectors can be determined if spectral reflectance values are known.

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