IR enhanced Si photodiode for spectral responsivity transfer between 300 nm and 1000 nm

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Introduction

- Si trap detectors have sub 0.1 % (k=2) responsivity uncertainties only within the 350 nm to 950 nm wavelength range.
- The trap photodiodes are exposed to the ambient (no windows)
- Traps cannot hold/maintain responsivity scales:
  - changes between 400 nm (~0.5 %) and 450 nm were measured
  - illuminance responsivity change of 0.35 % measured in 6 years
- Trap applications are limited to 950 nm because of:
  - Increased spatial non-uniformity of responsivity (internal quantum efficiency)
  - Increasing temperature coefficient of responsivity (0.2 %/^{o}C at 1000 nm).
- Small acceptance angles (beam clipping in monochromators)
- The trap limitations increase uncertainties for wavelengths shorter than 350 nm and longer than 950 nm.

IR enhanced Si photodiode
Hamamatsu Model S11499-01

- It can be used as a transfer/working standard: predicted years-long instabilities of less than 0.02 %
- 5 mm diameter, single element
- Peaks at 1000 nm
- Wavelength coverage down to 300 nm
- No temperature control is needed to 1000 nm
- Simple to use
- Inexpensive

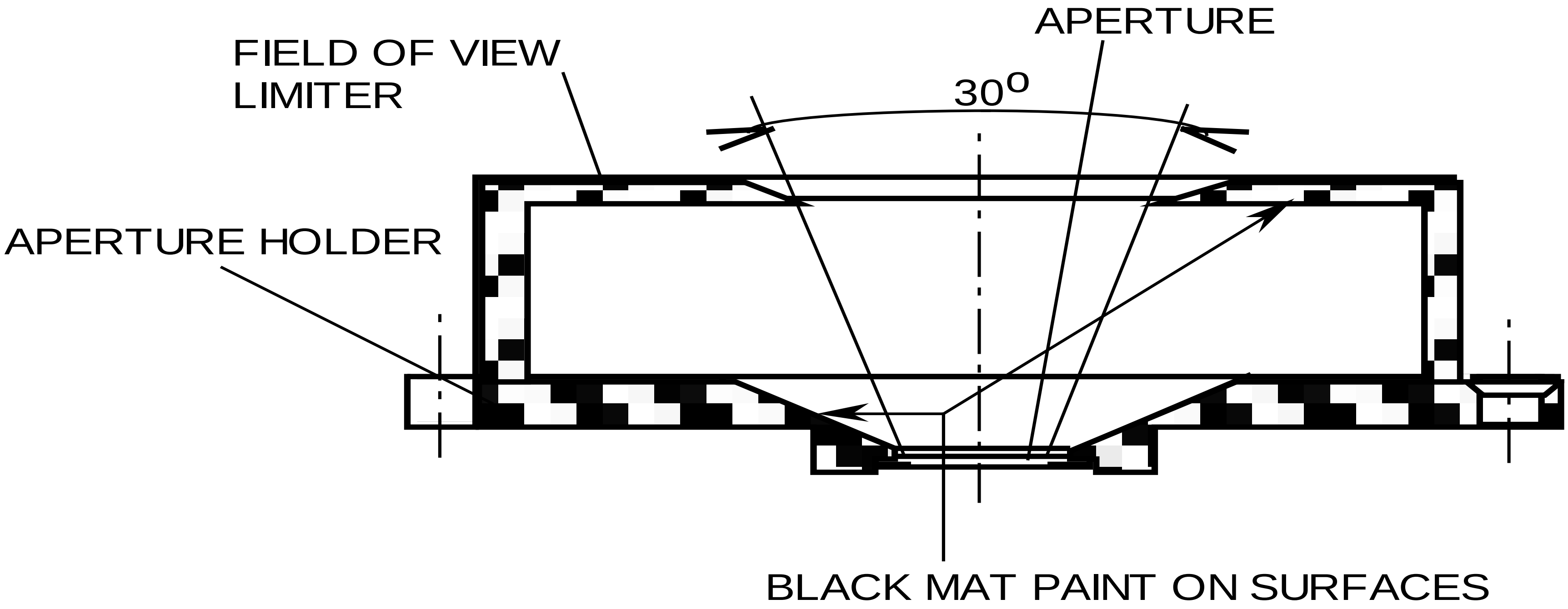
It was tested in this work if the responsivity uncertainty can be 0.1 % (k=2) between 300 nm and 1000 nm

Housing for enhanced Si

Temperature control was applied for characterizations only

Irradiance mode front-unit

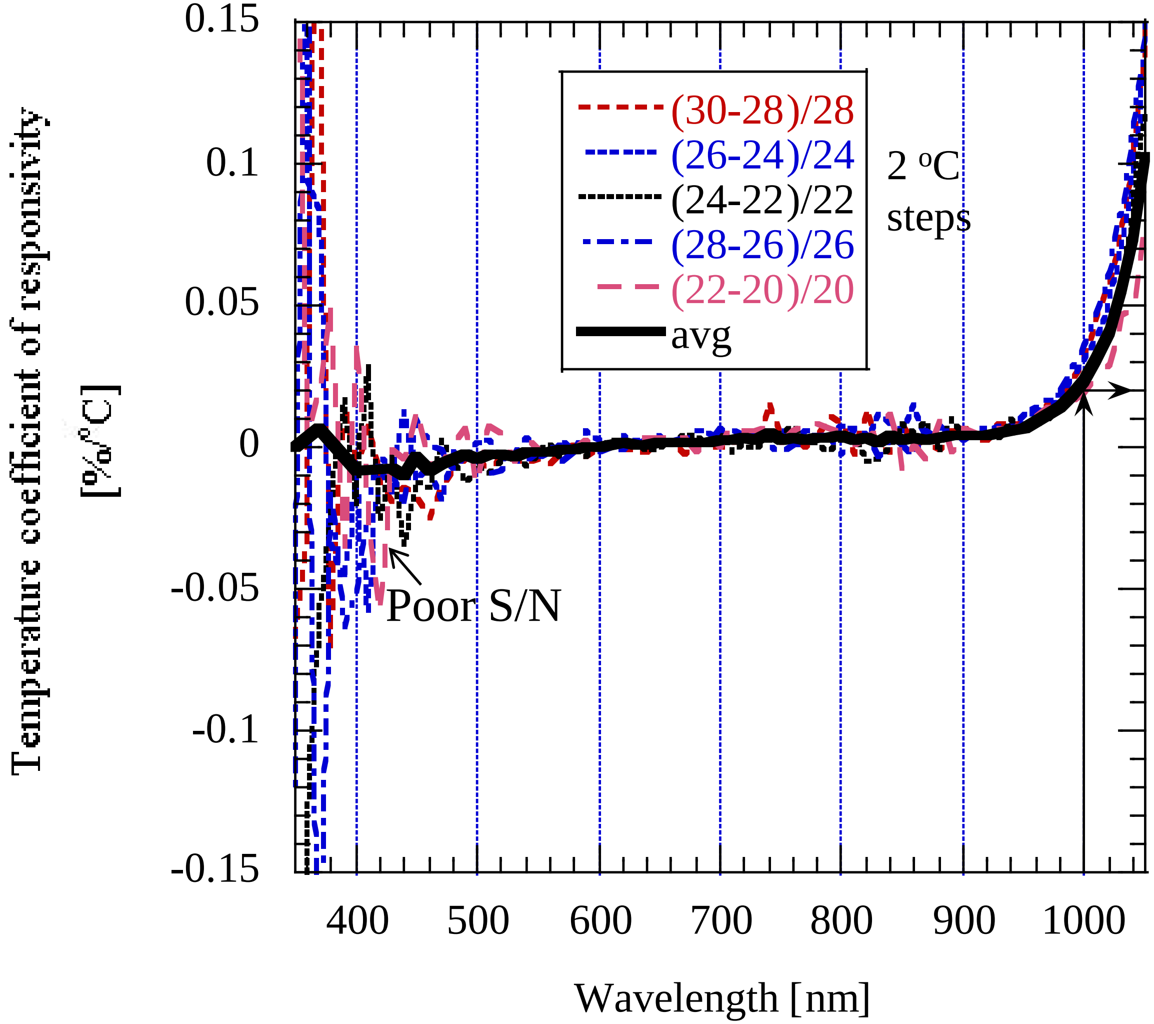
- It can measure the output beam from high throughput (e.g. using f/4) monochromators
- Using a precision aperture: **power-to-irradiance responsivity converter**



Characteristics of IR enhanced Si

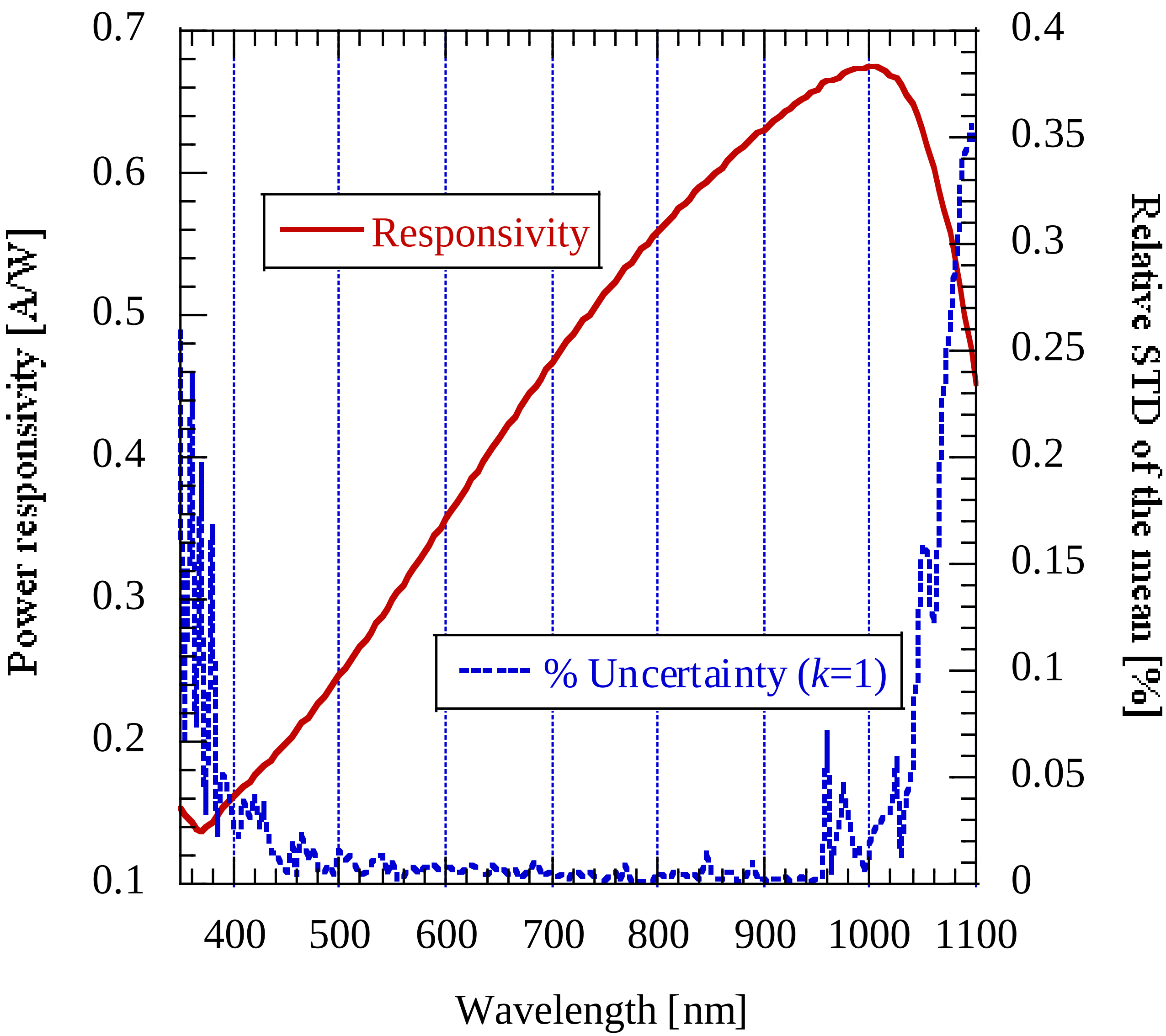
Temperature dependent responsivity

- The temperature coefficient of responsivity is close to zero to about 980 nm and it is 0.02 %/°C at 1000 nm.
- The temperature coefficient is a decade lower than that of the 1337 Si photodiodes (at 1000 nm) used in Si trap detectors.
- **Temperature control is not needed to 1000 nm!**



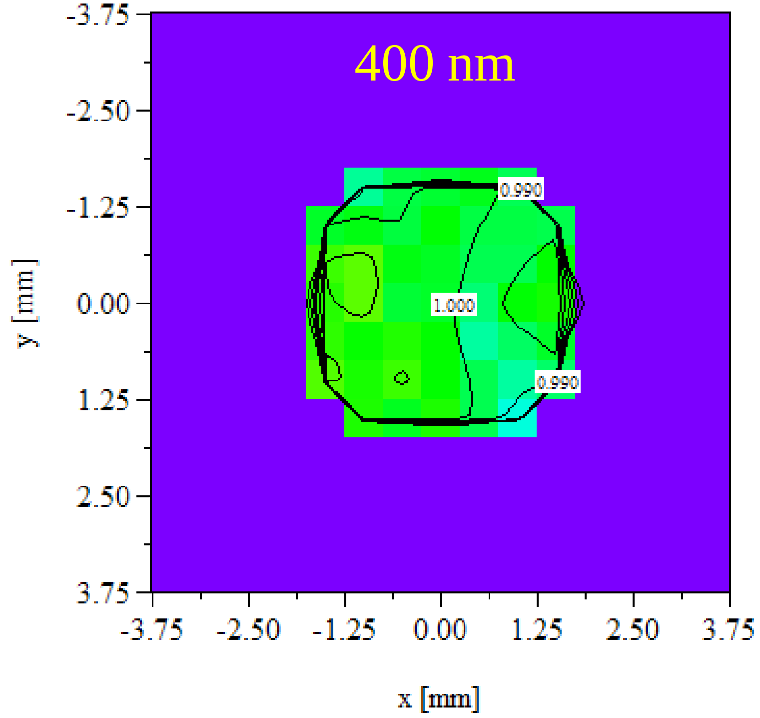
Characteristics of IR enhanced Si (cont.)

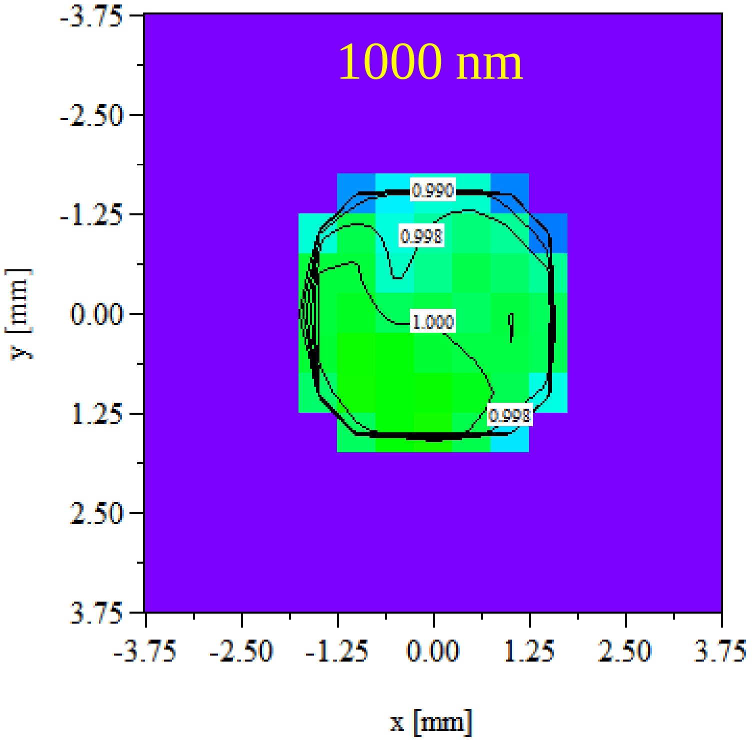
Spectral power responsivity



Characteristics of IR enhanced Si (cont.)

Spatial non-uniformity of responsivity at 400 nm and 1 μm

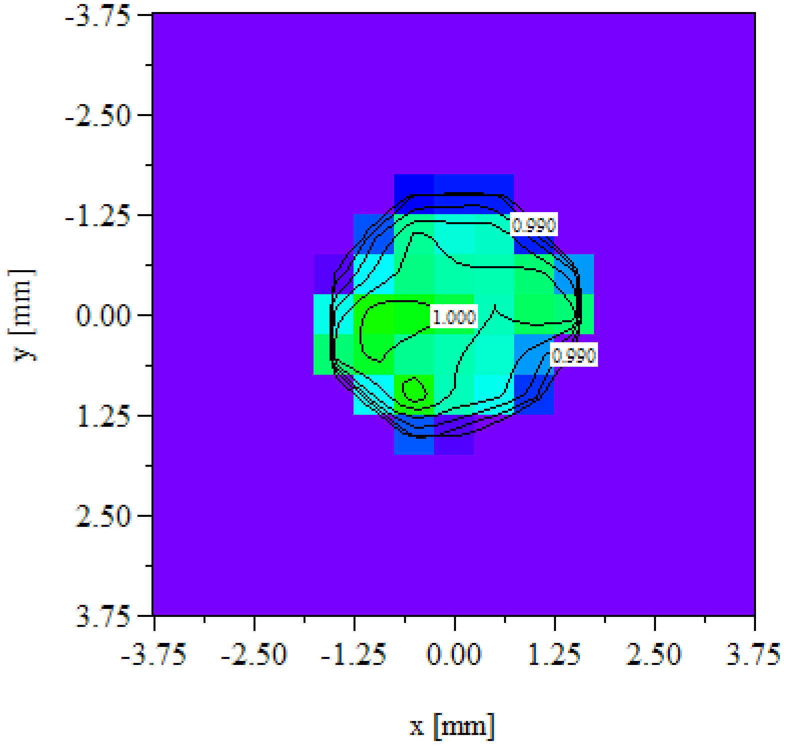


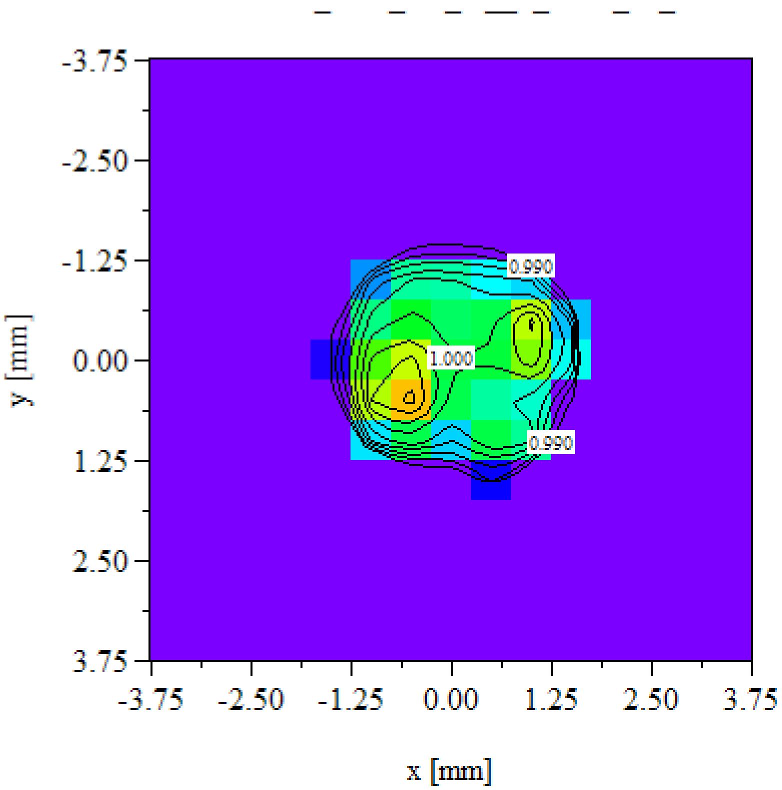


0.2 % max-to-min non-uniformity at 1000 nm makes it possible to perform power responsivity measurements with less than 0.05 % (*k*=2) uncertainty using incident beams centered to the detector. The beam diameter was 1.1 mm and the scan were made with 0.5 mm steps.

Characteristics of IR enhanced Si (cont.)

Spatial non-uniformity of responsivity at 1050 nm





These uniformity-scans suggest an upper wavelength limit of 1000 nm if responsivity uncertainty of 0.1 % (*k*=2) is required!

Electrical characteristics

- Most of the signal problems in the UV interval can be solved using the IR enhanced single-element Si photodiode
- It has a shunt resistance of 1 GΩ, thirty times higher than that of a Si tunnel trap detector.
- The 1 GΩ shunt resistance can result in a noise and drift equivalent current of about 3 fA at an electrical bandwidth of 0.3 Hz. This current corresponds to an NEP of about 7 fW/Hz^{½} which is more than a decade lower than the NEP=85 fW/Hz^{½} of a Si tunnel-trap transfer standard.

Present responsivity uncertainties at the SCF

- For the SCF, the scale is transferred from the cryogenic radiometer to Si trap and Ge transfer standards (TS)
- The **SCF** facility can measure between 350 nm and 1100 nm using sealed Si working standard photodiodes (calibrated against the TSs).
- SCF uncertainties:
  - 0.6 % (*k*=2) at 350 nm that decreases to 0.16 % (*k*=2) at 525 nm
  - 0.16 % (*k*=2) between 525 nm and 950 nm
  - increases to 1.2 % (*k*=2) at 1000 nm
  - increases to 2.6 % (*k*=2) at 1100 nm
- The **UV-SCF** facility is used between 200 nm and 500 nm (using UV-100 as TS) with an uncertainty of ~0.6 % (*k*=2) between 300 nm and 350 nm.

The present NIST responsivity-scale uncertainty between 300 nm and 1000 nm needs improvement!

Different detectors (InGaAs or ext-InGaAs) are needed above 1000 nm.

Expected uncertainty

- The IR enhanced photodiode can be used either as a transfer-standard or a working-standard.
- As a result of the 1-step scale transfer from the primary standard to test detectors :
  - the responsivity uncertainty is predicted to be 0.1 % (k=2) between 300 nm and 1000 nm, comparable to that of silicon trap detectors (but in this wider wavelength range).
  - the uncertainty improvement will be about an order of magnitude between 300 nm and 350 nm and similar between 950 nm and 1000 nm (over the existing NIST responsivity scale in these wavelength intervals).
- More radiometric characterizations are needed between 300 nm and 350 nm to better estimate the responsivity uncertainty in this range.

Conclusions

- The main radiometric and electronic characteristics of three 5 mm diameter IR enhanced Si photodiodes have been evaluated and compared to Si trap detectors.
- The IR enhanced Si photodiode can substitute Si trap detectors in an extended wavelength range between 300 nm and 1000 nm.
- It can measure both radiant power and irradiance with acceptance angles much larger than Si trap detectors.
- It can be used at the output of monochromators without any beam clipping.
- It does not need temperature control.
- It has an NEP=7 $fW/Hz^{½}$, more than a decade lower than that of Si tunnel-trap detectors.
- It can be calibrated directly against the primary standard cryogenic radiometer and then used as a reference detector to calibrate test detectors.
- The responsivity scale transfer can be performed in one step that adds a minimal increase to the spectral responsivity uncertainty of test detector calibrations.
- It eliminates the need to use the presently applied (at NIST) three detector transfer-standards to realize the spectral responsivity scale for routine calibrations from 300 nm to 1000 nm.
- It can decrease the uncertainty of the SCF scale at the spectral-ends by an order of magnitude.
- It will be used in the 2013 CCPR K2.b key inter-comparison where the SCF spectral power responsivity scale will be realized and maintained on a group of these detectors.
- The predicted responsivity uncertainty is 0.1 % (k=2) between 300 nm and 1000 nm.