# Si-SPAD quantum efficiency calibration


Salvatore Virzì[1], Elisa Redolfi[1,2,3], Alice Meda[1], Giorgio Brida[1], Marco Gramegna[1], Ivo Degiovanni[1,3] and Marco Genovese[1,3]

[1] Istituto Nazionale di Ricerca Metrologica (INRiM), Torino, Italy

[2] Università di Torino, Torino, Italy

[3] Istituto Nazionale di Fisica Nucleare (INFN), Torino, Italy

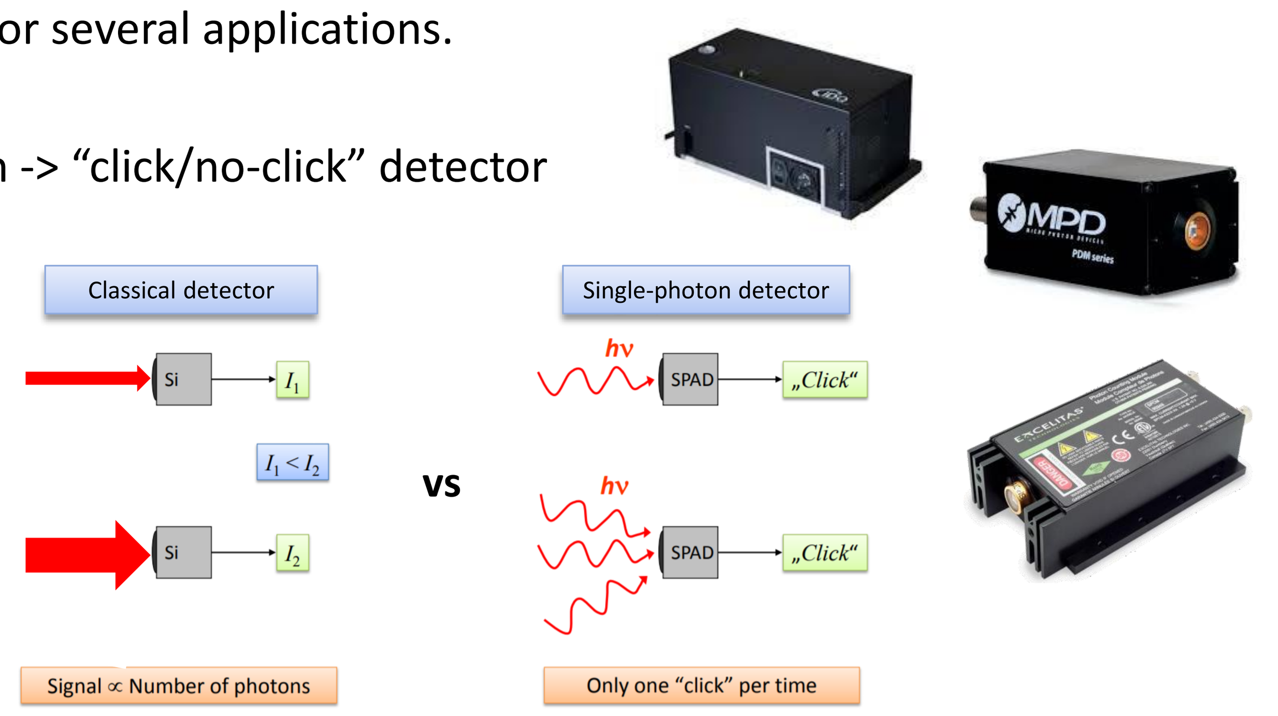
s.virzi@inrim.it


## Introduction

Single photon detectors are essential for photon-based Quantum Technologies.

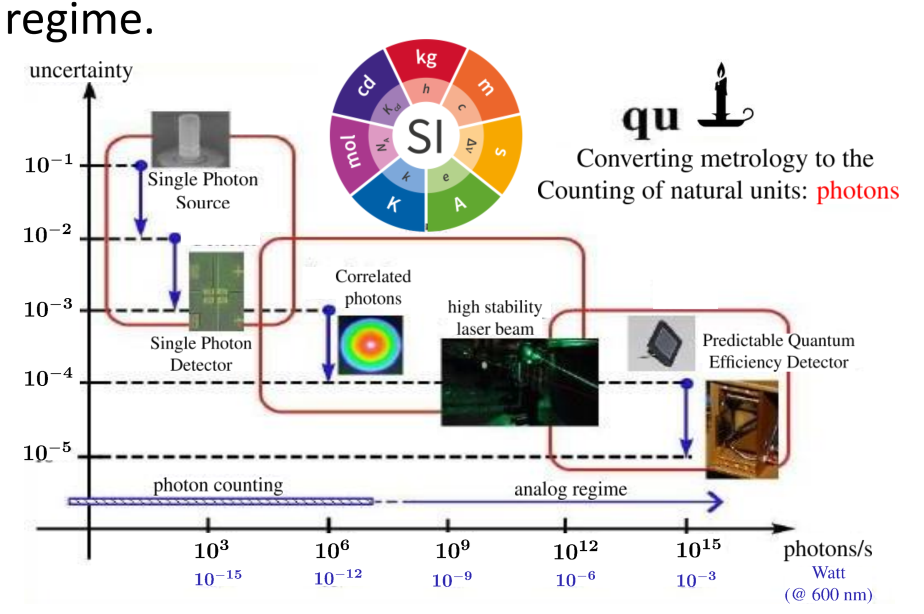
Single-Photon Avalanche Diodes (SPADs) are the most commonly used, so their characterization is necessary for several applications.

SPADs parameters
- photon number resolution -> "click/no-click" detector
- detection efficiency, $\eta$
- dark count probability
- after-pulse probability
- dead-time, recovery time
- jitter
- linearity of response
- maximum exposure level




Our goal: Efficiency calibration of Silicon SPADs at 850 nm wavelength

**Quantum Radiometry:** link between typical optical power measurement regime of conventional radiometry and photon counting regime.




Possible application

Free-space QKD

## Detection efficiency model

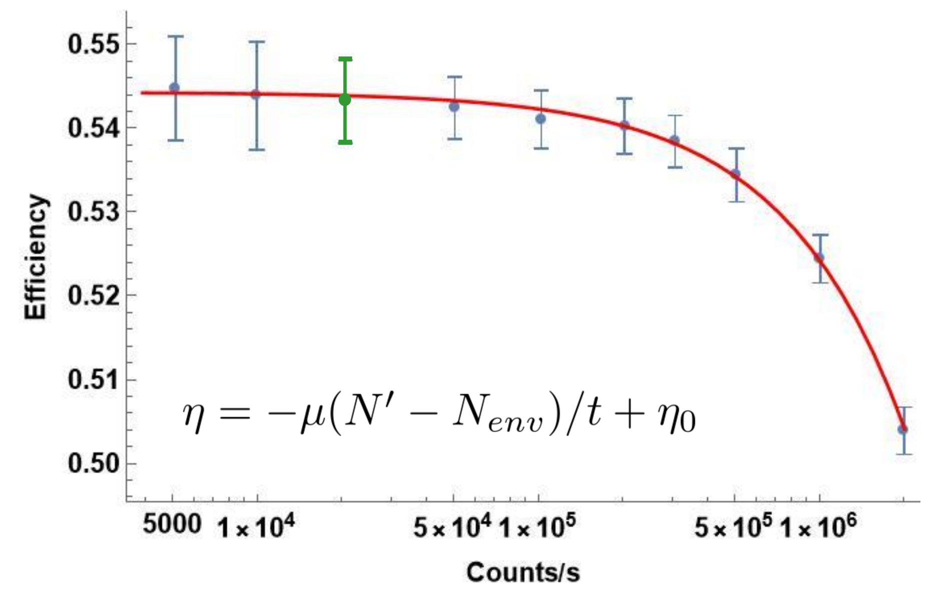
The Device Under Test (DUT) detection efficiency $\eta_{DUT}$ is estimated by comparing the optical power, corresponding to the effective number of photons per second registered by the SPAD detector, with the incident mean optical power, SI-traceable measured by a reference detector (substitution method [1,2]).

$$\eta_{DUT} = \frac{hc}{\lambda t}\frac{s(N'-N_{env})}{\tau C(A'\cdot\epsilon - A_{env})T} \qquad N' = N\cdot\rho_{DUT} \quad A' = A\cdot\rho_{ph}$$

$h$ = Planck constant, $c$ = speed of light, $\lambda$ = wavelength, $t$ = acquisition time, $N_{(env)}$ = DUT (environmental) counts, $A_{(env)}$ = Si-ph (environmental) current, $s$ = responsivity [W/A], $\rho$ = fluctuation normalization factor, $C$ = current meter calibration factor, $T$ = focusing lens transmittance, $\tau$ = attenuation factor, $\epsilon$ = average statistical normalization factor.

## Efficiency measurement

The DUT detection efficiency at different count rates has been measured at 850 nm.



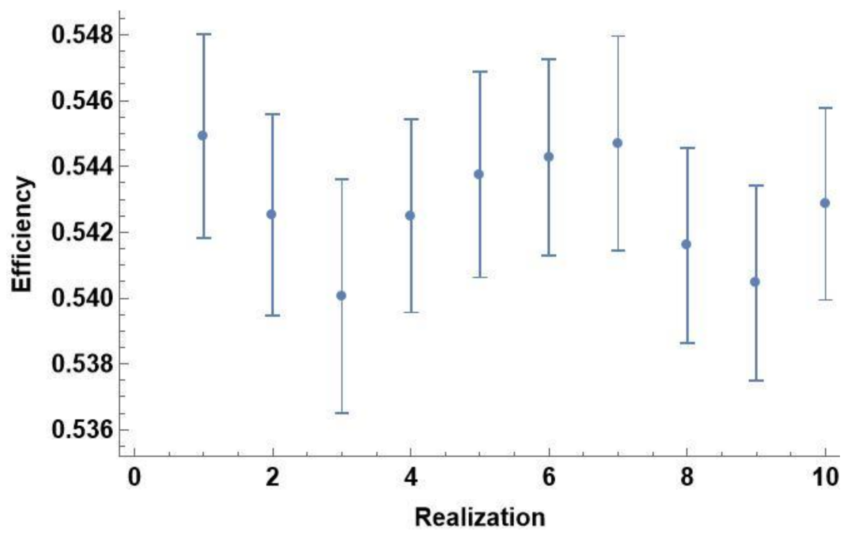

From the linear regression the detection efficiency results: $\eta_0 = (0.544 \pm 0.003)$

$\eta_0$ uncertainty budget

| Measurand | Symbol | Type | Value | Standard Uncertainty | Contribution* (%) |
|---|---|---|---|---|---|
| DUT counts | $N'$ | A | 20655 | 27 | 61.87 |
| DUT environmental counts | $N_{env}$ | A | 28 | 1 | 0.14 |
| Si-photodiode current [A] | $A'$ | A | $1.92807 \cdot 10^{-8}$ | $4.9 \cdot 10^{-12}$ | 0.68 |
| Si-photodiode environmental current [A] | $A_{env}$ | A | $4.88 \cdot 10^{-14}$ | $1.3 \cdot 10^{-15}$ | $1.7 \cdot 10^{-7}$ |
| Wavelength [nm] | $\lambda$ | B | 850.711 | 0.006 | $6 \cdot 10^{-5}$ |
| Acquisition time [s] | $t$ | B | 1 | $10^{-3}$ | 1.22 |
| Sensitivity | $s$ | B | 0.4766 | 0.0019 | 19.45 |
| Attenuation factor | $\tau$ | B | $2.1601 \cdot 10^{-7}$ | $7.0 \cdot 10^{-10}$ | 12.77 |
| Current meter calibration factor | $C$ | B | 1.000023 | $1.0 \cdot 10^{-5}$ | $1.0 \cdot 10^{-3}$ |
| Focusing lens transmittance | $T$ | B | 0.985000 | $3.0 \cdot 10^{-5}$ | $3.0 \cdot 10^{-3}$ |

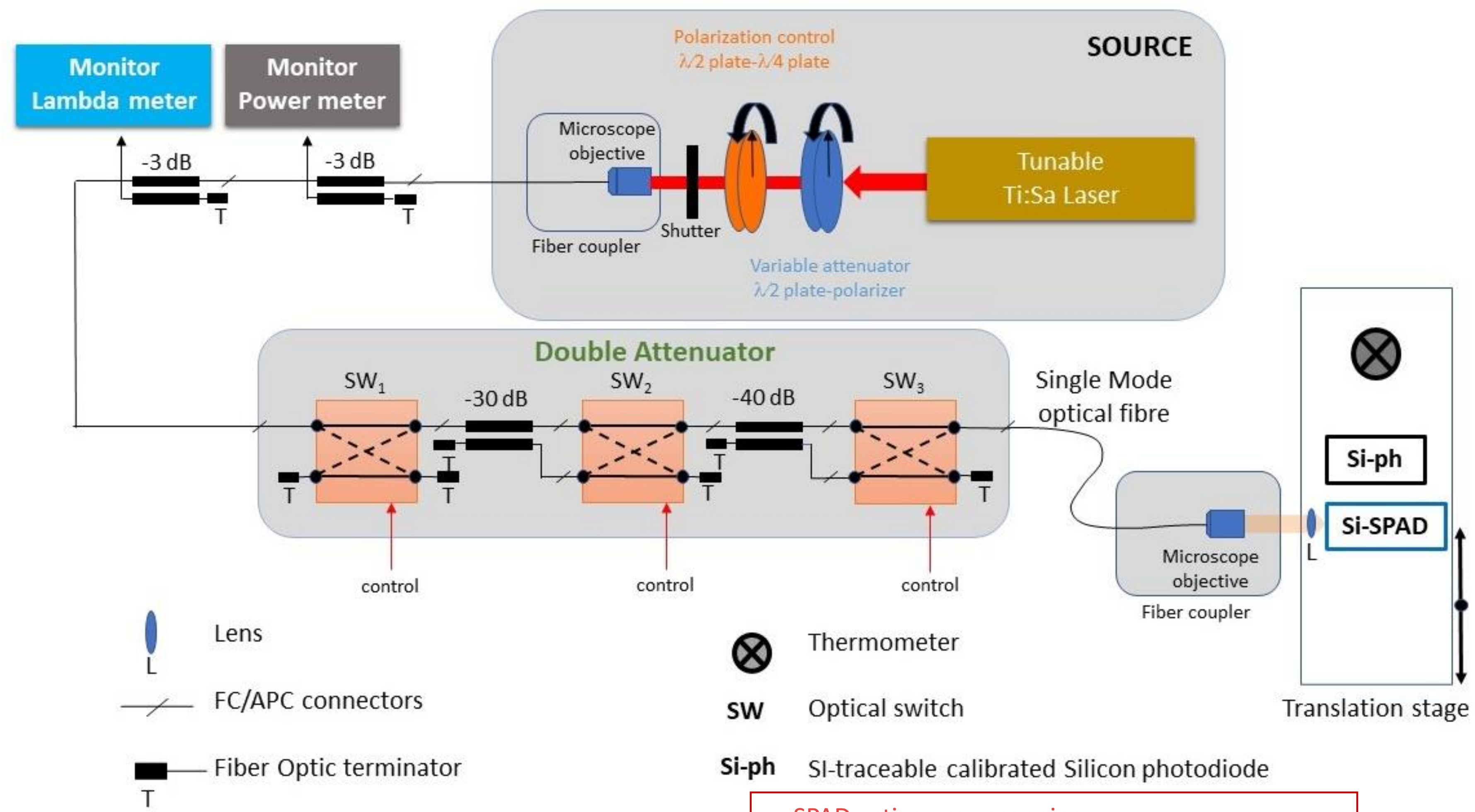
*The contribution of each measurand is obtained considering the variance. The correlation contribution is not taken into account in this table.

With this apparatus, we obtained good repeatability.



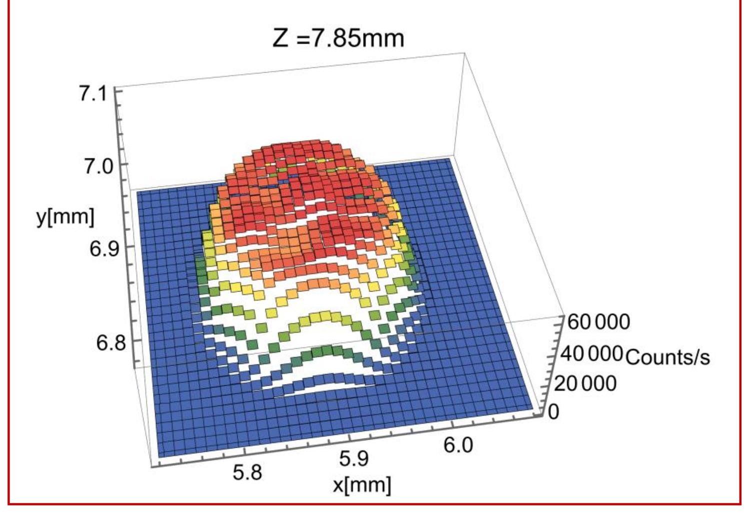

$< \eta_0 > = (0.543 \pm 0.003)$

## Experimental setup



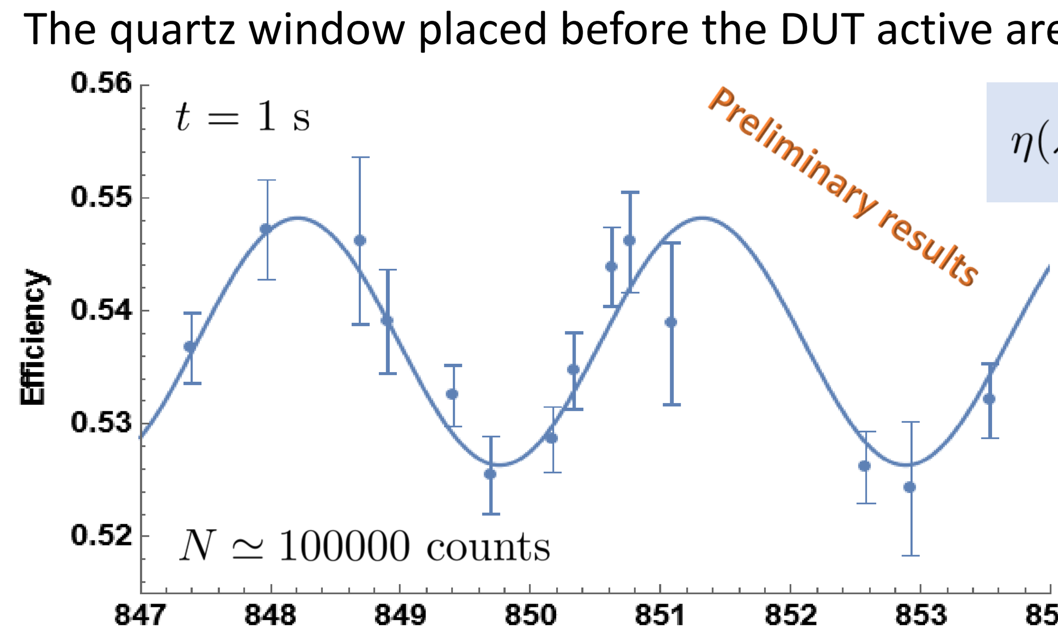

Optimizations:
- Horizontal polarization
- Attenuation value
- Wavelength value
- Temperature = (23 ± 1) °C
- SPAD active area scanning

SPAD active area scanning
- Motorized stage with variable step size
- Laser beam diameter ~ 40 µm
- SPAD active area diameter = 200µm




## Spectral characterization

The quartz window placed before the DUT active area induces an efficiency variation:




$$\eta(\lambda, n, L, N) = \eta_N\left(1 - |\Gamma(\lambda, n, L)|^2\right)$$

$$\Gamma = \frac{\gamma\cdot(1 - e^{-2i\cdot\frac{2\pi}{\lambda}\cdot n\cdot L})}{1 - \gamma^2\cdot e^{-2i\cdot\frac{2\pi}{\lambda}\cdot n\cdot L}}$$

Where:
$\eta$ = detection efficiency,
$\Gamma$ = transmissivity,
$\lambda$ = wavelength,
$n$ = quartz refractive index,
$\gamma = (n - n_{air})/(n + n_{air})$,
$L$ = quartz thickness ($\sim 100\,\mu$m),
$t$ = acquisition time.

Manuscript in preparation…

## Conclusions

- Metrological characterization of free-space Si-SPADs at the INRiM facility
- Innovative automated setup to estimate the quantum efficiency $\eta_0$ of commercial Si-SPADs at a fixed wavelength with standard uncertainty less than 1 %, exploiting the double attenuator technique
- Evaluation of the effect induced by the quartz window on the DUT efficiency

## References


[1] M. López, H. Hofer & S. Kück , Detection efficiency calibration of single-photon silicon avalanche photodiodes traceable using double attenuator technique, *Journal of Modern Optics* **62**, 1732-1738 (2015)

[2] M. López, A. Meda, *et al.*, A study to develop a robust method for measuring the detection efficiency of free-running InGaAs/InP single-photon detectors, *EPJ Quantum Technol.* **7**, 14 (2020)



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