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Absolute Photo Detection Efficiency measurement of Silicon PhotoMultipliers

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The absolute measurement of the Photo Detection Efficiency (PDE) of a silicon photomultiplier over the whole visible range using continuous light is not a straightforward task as it requires the accurate determination of the detector gain. We have developed at LAL a procedure to achieve an absolute PDE measurement with an accuracy of ± 6 %.

1.Introduction

Silicon photomultipliers (SiPM) are recent detectors studied by many groups. Their proprieties (compact form, insensitivity to magnetic fields, low voltage power supplies...) are promising for various scientific fields, from high energy physics calorimetry to medical imaging application. An accurate measurement of the SiPM parameters is needed to integrate these devices in experimentation. Absolute Photo Detection Efficiency over the visible range is a decisive parameter for most applications.

To measure the absolute SiPM PDE, we have carried out two methods at LAL: the “Counting method” using short laser pulses at fixed wavelengths and the “Current method”, using continuous monochromated light for a continous wavelength scan from 400 to 700nm.

After describing the experimental set-up and explaining in detail the two methods, we will show the absolute PDE measurement results for three SiPMs with different geometry.

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2. Experimental

2.1 Description of the tested devices and experimental set-up

The SiPMs studied are MPPCs (S10362-11) from HAMAMATSU Photonics with 1 mm² of active area. Measurements were performed in order to determine the working range of each SiPM: its breakdown voltage (V_{BD}), single pixel avalanche gain, dark count rate (DCR) and recovery time were measured. For more details about the employed set-up and the theory regarding measurements, refer to [1]. Breakdown voltage at 20°C for MPPCs of 25 µm, 50 µm and 100 µm of pixel size were measured at 69.9 V, 68.3 V and 68.7 V respectively.

Fig.1 presents the experimental set-up used for the PDE measurements. It is composed of a dark box of 1 m^3 that assures a high temperature stability (20± 0.1 °C).
The test bench was equipped with several light sources:

- a continuous source: a halogen lamp (100 W) followed by an ORIEL grating monochromator (350-800nm) with a wavelength accuracy of 2 nm.
- 3 pulsed Pilas laser diodes (405, 467 and 635 nm) driven at a repetition rate of 500 kHz with [1] Chaumat,Puill.spectral width below 3 nm and pulse timing width below 50 ps.

The incident flux is measured with a reference PMT (see 2.2) for continuous and pulsed light configurations. The light intensity is set by neutral density filters inside a motorized wheel.
The readout electronics consist of a 500 MHz MITEQ voltage amplifier (gain = 350, 50Ω). A SMA cable sends the signal to a Wavepro 750ZI LeCroy digital oscilloscope (40 GSamples/s, 4GHz of analog bandwidth). Polarization and current measurement of the SiPM are done by the Keithley source meter (2612).

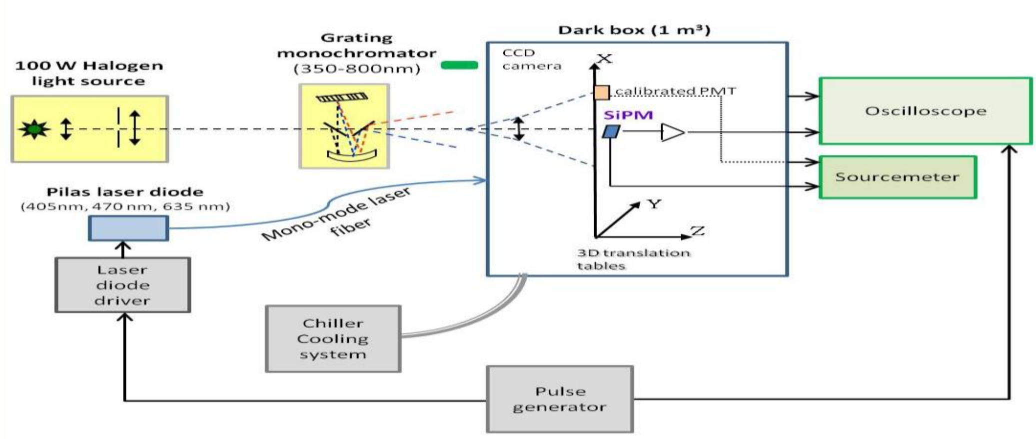


Fig 1*: experimental setup for the SiPM PDE measurement*

2.2 Test-bench calibration

We monitored the temperature with six Pt100 probes installed inside the dark box and readout by a Keithley acquisition unit and a thermo regulator (water chiller). A 20 ±0.1°C regulation is achieved. The light sources are placed at a stabilized temperature of 22 °C ± 1 °C.

Three reference photodetectors have been used to calibrate the light incident flux: 2 PIN Photodiodes (HAMAMATSU-S3590-18 and a Gamma Scientific-UDT 221) and a photomultiplier (PMT) (HAMAMATSU-R7400U-01). They are fixed on a rigid support on 3 axes translation stages, allowing movement in front of the light spot with an accuracy of 0.1 mm. The relative position between all the detectors is checked with a focusing CCD camera with an accuracy of 0.2 mm. The beam light is spreaded with lenses to achieve a 10 mm diameter surface whose homegeneity has been controlled with the PMT (with a 1mm² pin hole) to 2%.These precisions allow placement errors to be negleted. Although the PMT was supplied with a quantum efficiency curve, we had to correct these data to obtain a good agreement (5%) with the 2 PIN photodiodes. Once this correction has been made, the PMT is used as a unique reference detector.

The incident flux on the detector is defined as:

$$Flux_{incident}(ph/mm^2/s) = \frac{I_{PMT} \times \lambda \times q_e}{h \times c \times Rs_{PMT} \times G_{PMT} \times S_{PMT}} \quad \text{(Eq1)}$$

where q_e is the electron charge (C), I_{PMT} the photo generated current (A), Rs_{PMT} the PMT anode sensibility (A/W), G_{PMT} its gain and S_{PMT} its illuminated surface (mm²).

The main errors on the incident flux determination come from the errors on the illuminated surface (3% over 38.3mm²) and on the product of the gain by the sensitivity of the PMT (5%). After a one hour warming, the PMT current is measured with a Keithley source meter (2612) with around 1% accuracy (few nA over hundreds nA). The incident flux on the SiPM is then known with an accuracy of 6 %.

2.3 PDE measurement methods

The SiPM PDE [Eq2] is defined as the ratio of the number of converted photons ($N_{photoe-}$) to the incident number of photons (N_{photon}), it takes into account the quantum efficiency and the fill factor of the SiPM:

$$PDE(\%) = 100 \times \frac{N_{photo\bar{e}}}{Flux_{Incident}} \quad \text{(Eq2)}$$

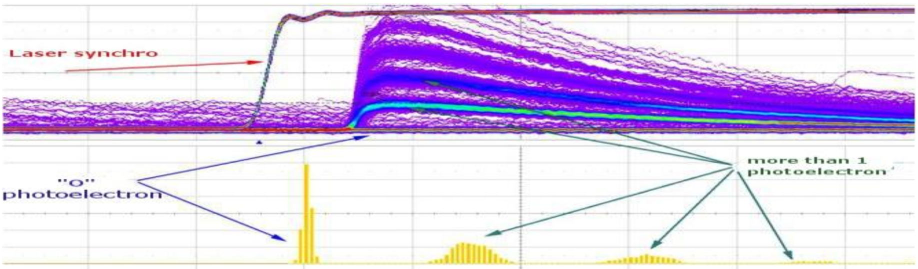
$Flux_{incident}$ is evaluated by the calibrated PMT whereas $N_{photoe-}$ is evaluated either by the "Counting Method", or by the "Current Method".

2.3.1 The "Counting Method"

The pulse coming from the Pilas laser diodes is short enough (50 ps) to be considered as a Dirac pulse. For low $Flux_{incident}$, below 5 photons per pulse, the obtained photoelectron distribution follows the Poisson probability (Fig. 2). Therefore the number of photoelectrons produced in the SiPM is defined as:

$$N_{photo\bar{e}} = -\ln((P0)) \quad \text{(Eq3)}$$

where P(0) is the probability of non converted events that are counted over 40000 events.



F*ig 2 : oscilloscope view of the SiPM answer to short light pulses with few photons*

The major error of the PDE measurement with this method comes from the measurement of the incident number of photons which had been estimated at 6%.

2.3.2 The "Current Method"

The number of photons coming from the monochromator that had been converted into photoelectrons by the SiPM ($N_{photoe-}$) is given by:

$$N_{photo\bar{e}} = 100 \times \frac{I_{pg}}{q_e \times G_{SiPM}} \quad \text{(Eq4)}$$

where I_{pg} is the photogenerated current (A) and G_{SiPM} the SiPM gain measured in dark conditions. The G_{SiPM} value directly affects $N_{photoe-}$ and therefore the PDE.

The determination of the gain of a SiPM has to take into account all the secondary effects (cross-talk, after-pulses) that affect it. To perform this measurement, we consider the SiPM signals in the dark (Fig 3): the oscilloscope is triggered on the rising edge of a primary avalanche signal. The signal is integrated (charge C) over a time window whose width represents around 5 times the recovery time of the device to take account of all its secondary effects. The pedestal charge (charge P), corresponding to the non-correlated signals, is determined by integrating the charge of these signals over a time window of the same length.

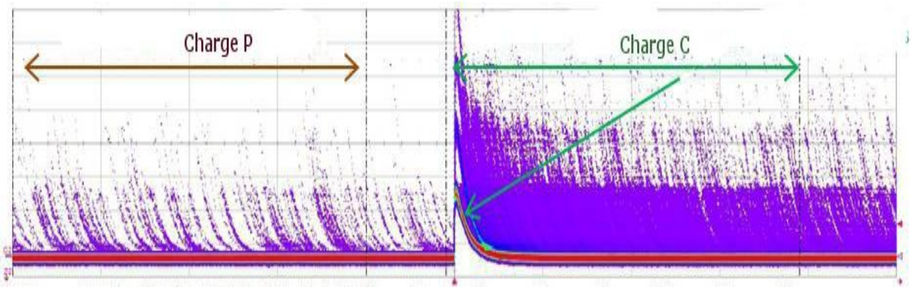


Fig 3*: SiPM dark signal and its correlated secondary effects integrated over the green window and the non correlated pedestal signals integrated over the maroon window*

The SiPM gain is then given by:

$$G_{SiPM} = \frac{(C - P)}{q_e \times Z_{Oscillo}} \quad \text{(Eq5)}$$

where $Z_{oscillo}$ is the impedance of the oscilloscope (50 Ω). The gain of the MPPCs measured as a function of the bias voltage is shown in Fig. 4.

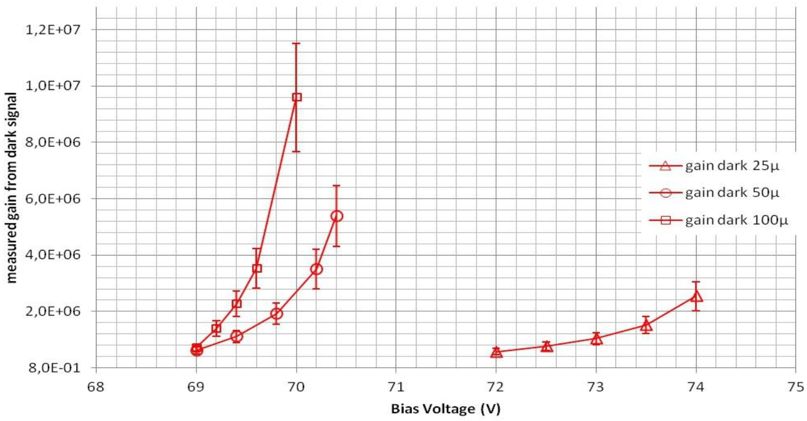


Fig 4*: gain of the S10362-11-25, 50 and 100 measured in dark at 20°C as a function of the bias voltage*

3 MPPC PDE measurements results

3.1 Comparison of the "Counting Method" and the "Current Method" results

Figure 5 shows the ratio of the "counting PDE" to the "current PDE" at 3 wavelengths (405, 467 and 635 nm) as a function of the bias voltage. We observe that the PDE measured by counting is larger than the one determined by current measurement for the MPPC with 25 and 50 µm of pixel size whereas this is the contrary for the 100 µm. For the 3 devices, the ratio increases with the bias voltage and reaches around 1.1 at high overvoltages. For a same MPPC, the ratio does not depend on the wavelength.
The difference between these two results can come from a bad determination either of the incident flux on the SiPM or of the number of converted photons. With the rigorous optical calibration of the test bench, the incident flux is known with 6 % accuracy. The most likely hypothesis is an incorrect SiPM gain measurement that distorted the number of converted photons determined with the current method. To check this hypothesis, we determine the PDE using the current method with the laser and the monochromator. With the ratio of two measurements, shown in Figure 6, the gain of the MPPC is no longer a variable of the equation. We observe that the PDE ratio is close to 1 and constant with the bias voltage. Therefore, we can conclude that the inaccurate measurement of the SiPM gain explains what we observed on Figure 5.

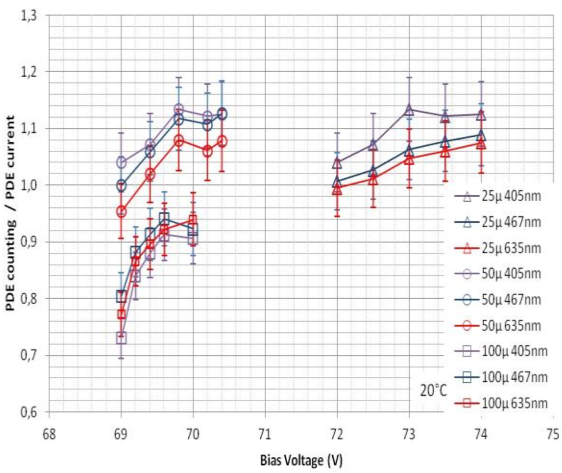


Fig 5: *counting PDE to current PDE ratio of the 3 MPPC S10362-11 as a function of the bias voltage and for 3 wavelength*

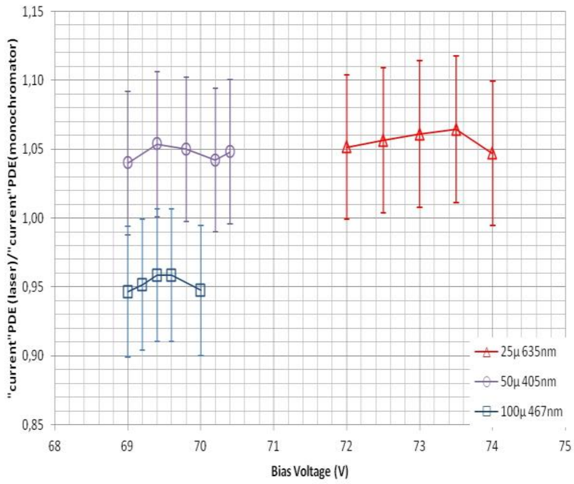


Fig 6: *ratio of the SiPM PDE measured when illuminated by the laser over the one when the light comes from the monochromator*

To determine the absolute PDE of a SiPM over the whole visible range of wavelengths with a high precision, the measurements with the current method have to be corrected. There are two ways to make this correction: either we normalize the "current PDE" curve with the "counting PDE" measurements at 3 wavelengths [3], or another method to determine the gain of the SiPM with the desire accuracy is developed. The latter method is explained afterwards.

3.2 The SiPM gain measurement using the "Counting Method"

As the determination of the gain of a SiPM is difficult to do very accurately with the method explained in 2.3, we calculate it from the PDE results obtained with the counting method.
The resultant gain is given by:

$$Gain_{\text{calculated}} = \frac{(I_{light} - I_{dark})}{Flux_{incident} \times PDE_{count} \times q_e} \quad \text{(Eq6)}$$

where I_{light} is the SiPM photo generated current (A), I_{dark} the SiPM dark current (A), $Flux_{incident}$ the number of photons at the SiPM surface (ph/mm²/s) and PDE_{count} the PDE measured with the counting method. Fig 7 shows that gain measured from the counting method is independent from the wavelength.

3.3 The absolute SiPM PDE over all the visible light range

To determine the absolute PDE of the MPPC S10362-11 at all the wavelengths from 400 to 700 nm, we have performed the measurements with the "current method" using the gain calculated from measurements of PDE at 3 wavelengths with the "counting method". The results for the 3 devices are shown on Fig 8. The agreement between the two PDE values is within 5 %.

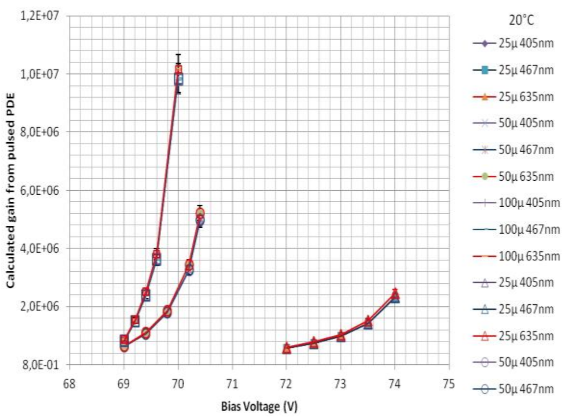


***Fig 7**: S10362-11-25, 50 and 100 gain measurement from pulsed light at 20°C*

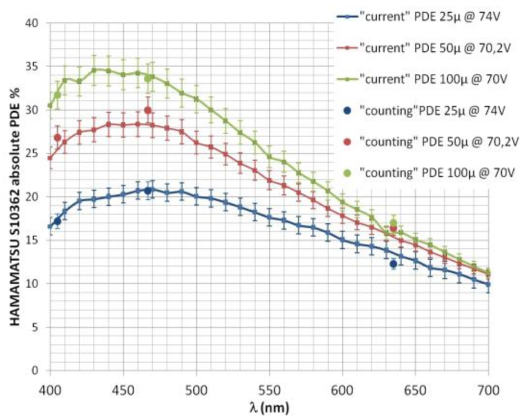


***Fig 8**: S10362-11-25, 50 and 100 absolute PDE as a function of the wavelength, at 20°C*

4 Conclusion and further work

After a long calibration process, we manage to obtain a 6% absolute PDE accuracy measurement over a wide spectral range from 400 to 700nm and at various polarization voltages. We develop a method which fits equally well for continuous light or pulsed light. We highlight the difficulty to measure the real SiPM gain with the dark signal. Despite our efforts, we did not achieve a direct gain measurement precise enough, only 10 to 20% accuracy, to realize a user friendly PDE measurement process. Owing to a very precise bench calibration (6%), we extract the SiPM gain from a calculation based on "counting" PDE measurement. Detailed analysis of secondary effects (after-pulses, crosstalk) and dark noise distribution is needed (ongoing study in collaboration with Fermilab) to perform a better gain measurement from the dark signal.

References

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