Characterization of Silicon Photomultipliers

Photon number detection and high precision timing of SiPMs

Igor Shavrin, Helmut Fedder, Michael Schlagmüller and Markus Wick (Swabian Instruments GmbH)
Thomas Ganka, Christoph Berger and Florian Schneider (KETEK GmbH)

Silicon photomultipliers (SiPMs) have numerous applications in high precision single-photon timing measurements, including LIDAR, biophotonics, and Positron-Emission-Tomography. Their ability to detect the photon number of scintillation events is a key feature to achieve high fidelity signals with very low noise levels. The extraction of the photon number from the detector output pulse is traditionally achieved with a fast ADC or with multiple level analog discriminators (time-over-threshold approach). Here we demonstrate an alternative method where we use a single input threshold. By detecting both the rising and falling edge, we obtain an apparent pulse width, that directly encodes the photon number. This measurement capability is provided by Swabian Instruments Time Tagger Ultra. Its high timing precision enables exquisite characterization of the detector's timing jitter.

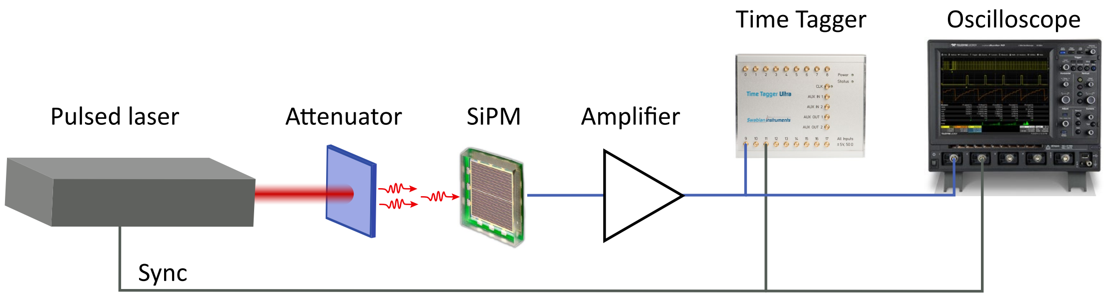

Figure 1. Illustration of the experimental setup.

EXPERIMENTAL SETUP

The experiment setup used for the SiPM (KETEK GmbH, PM1150T) characterization is shown in Fig. 1. Short laser pulses with a duration of 70 ps are attenuated and guided to the SiPM detector. The signal from the SiPM is amplified and connected to both, an oscilloscope and Swabian Instruments' Time Tagger Ultra. Both, the Time Tagger and the oscilloscope are triggered by the laser sync pulse. The oscilloscope is used to characterize the detector's output pulse shape distribution, while the Time Tagger Ultra analyzes all photon detection events in real time.

MEASUREMENT RESULTS

Typical detector output from SiPM is shown in the figure below. In here, the oscilloscope was set to the persistent mode such that multiple detected events are overlayed and the distribution of zero, single- and higher number photons are observed. The yellow line shows the laser sync pulse and the purple curves show photon detection pulses. Let's take a closer look at the SiPM response signals. The pulses that originate from the detection of laser photons are correlated to the trigger signal while the dark counts are uncorrelated and appear at random times. When the SiPM detects two or more photons simultaneously, the response pulse magnitude increases proportionally.

One way to identify the photon number from such signal is to use fast analog level discriminator. In this application note, we show an alternative approach using pulse width discrimination implemented as a custom measurement based on the Time Tagger's software engine. We discriminate photon numbers by analyzing the pulse width at the detector output and simultaneously obtain very precise timing information on the pulse arrival time. This method makes use of non-square pulse shapes and a change in apparent pulse width at a

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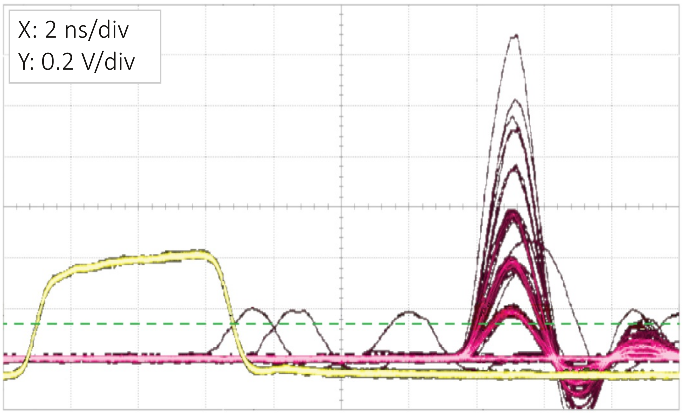

Figure 2. Persistent oscillograms of the laser sync (yellow) and the photon detection events (purple).

fixed threshold for pulses of various amplitudes. The Time Tagger input signal threshold level can be programmed such, that for all different photon numbers the threshold level is crossed twice, once for the rising and once for the falling edge, thus provides two timestamps. In the measurements presented here, every leading and trailing edges of the SiPM signal is captured as well as the laser sync pulse was captured and streamed to a computer for on-the-fly analysis.

PROCESSING OF THE TIME-TAG STREAM

With the Time Tagger, we capture laser sync pulse and both, leading and trailing edges of the detector pulses. The time-tags of the laser sync provide the reference time for the following photon-number detection event which is expected to occur after an arbitrary but constant delay. For every such detection event, we identify and store the arrival times for leading and trailing edges, from which we then calculate an apparent pulse width, as measured at a constant threshold level. This apparent pulse width is related to the detected number of photons. Figure 3(a) shows a pulse width histogram accumulated over a large number of multi-photon events. The histogram reveals separate peaks that correspond to the photon-number detected. In this measurement, the threshold level was chosen such that the lowest detected photon-number is n=1 and the photon-numbers up to n=5 are separable. In contrast, a histogram of the leading and trailing edges, shown in

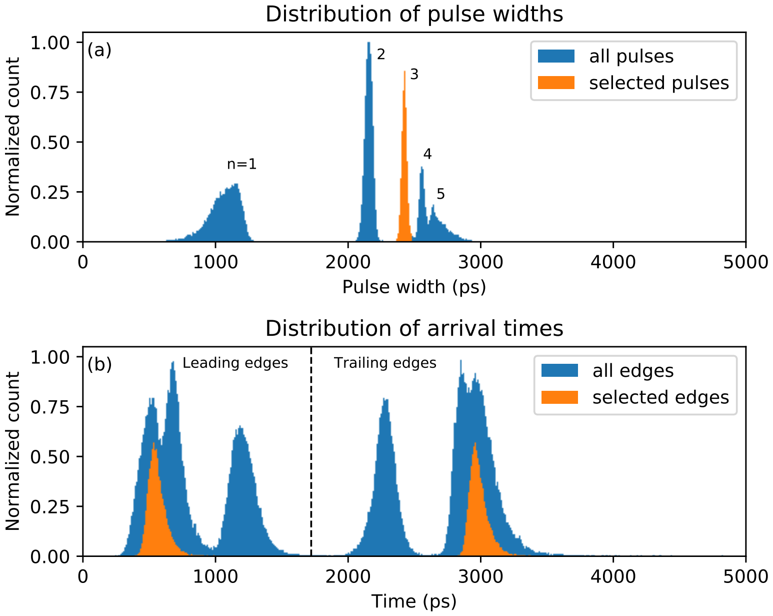

Figure 3. Histogram of the pulse widths of the captured multi-photon events (top) and a histogram of the corresponding leading and trailing pulse edges (bottom). Pulse widths histogram clearly resolves the photon numbers. By filtering time-tags for specific pulse widths (orange), we can determine precisely the timing information for the pulse edges.

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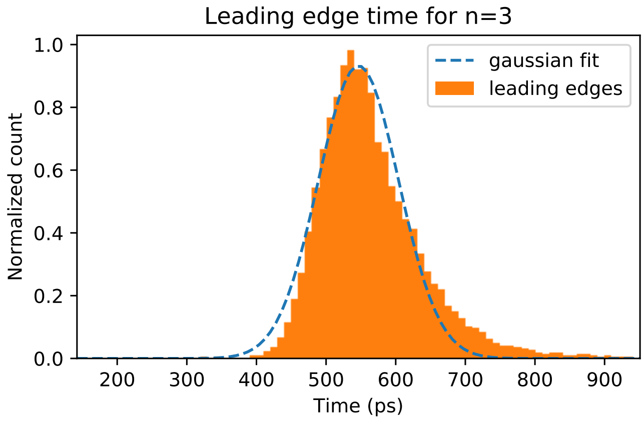

Figure 4. Histogram of the detected leading edges of SiPM pulses that correspond to three-photon detection event (orange area) and a Gaussian fit (dashed blue line).

Fig. 3(b), does not have such resolving power. It is, however, possible to access timing information of the pulse edges for each photon-number by selecting the pulses of a certain width within a convenient acceptance window.

For example, let's choose all the time-tags that correspond to the photon number n=3 and produce a histogram of their arrival times relative to laser trigger. The chosen widths and arrival times are highlighted with orange color throughout Fig. 3. The two orange peaks in Fig. 3(b) show that with the pulse width filtering we have gained access to the precise timing information of the chosen photon-number event. We can determine their mean arrival time as well as timing jitter, for example, by fitting a Gaussian function, as shown in Fig. 4. For this specific photon number, the FWHM timing uncertainty in the detected signal is about 130 ps.

CONCLUSIONS

The pulse width filtering method, presented in this application note, is capable of resolving the photon number and simultaneously provides precise timing information of the detected photon. The simultaneous access to the photon number and timing information, taking advantage of the streaming architecture of the Time Tagger, shows the versatility of the Time Tagger and its software engine. The Time Tagger proves to be a useful tool for multi-photon detector characterization and in the development of various applications like positron-emission tomography (PET).

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