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SensL New Fast Timing Silicon Photomultiplier

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In this paper we report on a new silicon photomultiplier (SPM) architecture with additional signal output. This additional output has very fast single photo electron response (~2 ns FWTM). This new device can be easily integrated into legacy systems by providing the ability to operate as a normal SPM with Anode readout or in new designs with an additional fast output. As result the rise time of timing signal for LYSO scintillator coupled to this new fast SPM is about 2ns, compared with typical 20-40ns for SPM's anode signal. This enables coincidence-timing performance improvements for SPM devices, from 300 ps (Coincidence Resolved Time – CRT - FWHM) to better than 250ps (CRT FWHM) coincidence timing resolution for SM series devices. Furthermore, use of the fast terminal allows for a wide range of leading thresholds without large degradation of CRT as compared with standard terminal. In this paper we will demonstrate that providing ability to detect first photon events provides significantly better CRT, comparable to large PDE improvement.

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1. Introduction

Silicon Photomultipliers (SPMs) are a favourite candidate for timing applications such as PET [1], Hazard and Threat detection or LiDAR because of their low cost and continually improving performance compared with Photomultiplier Tubes (PMTs). One of the major challenges in SPM is improving high performance timing performance. While photon detection efficiency is a key parameter in improving the timing performance of SPMs, another key ingredient is the rise time of the signals from the individual microcells and the ability to timestamp at the earliest photoelectron signal in the scintillation burst [2]. An effective way to improve timing in devices is to make the leading edge of the signal as steep as possible. In this paper we show that, using this route, a significant improvement in timing performance can be achieved over a wide range of time-stamp thresholds.

2. New SPM Architecture

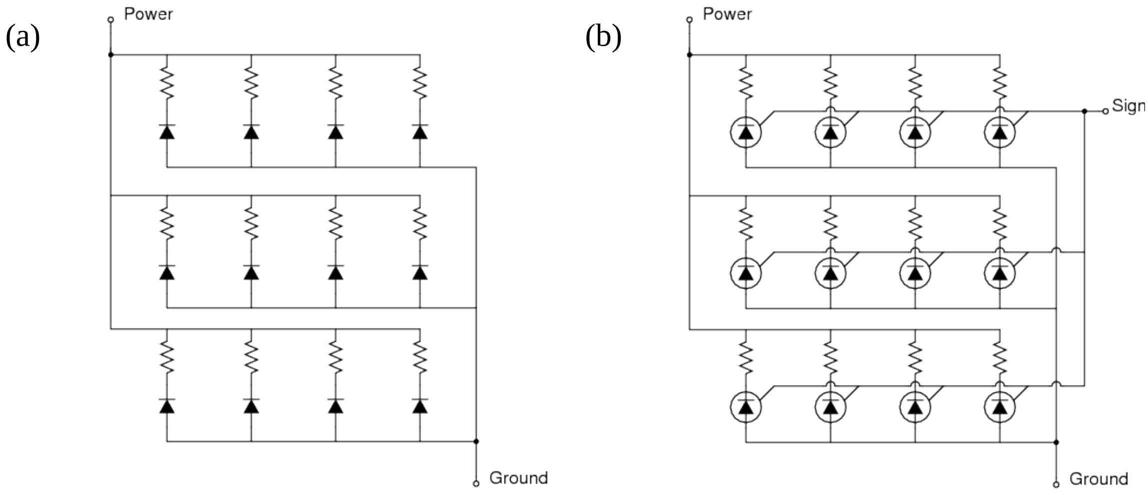

Figure 1: (a) traditional SPM architecture; (b) SPM architecture with inclusion of fast signal terminal.

The traditional SPM consists of a parallel array of avalanche photodiodes each in series with a quench resistor, as shown in Figure 1(a). In this configuration both bias and readout must occur on the same electrode. The introduction of a derivatively coupled electrode to each APD-resistor pair creates single-purpose signal line which delivers steeper rise-time pulses than the traditional SPM discharge which is inherently limited by the large output capacitance of each APD [3].

3. Measurements

All measurements were made using 3mm SPM devices with 35µm width microcells. Each SPM consists of 4774 microcells in parallel.

3.1 Signal Shape

The signal shape properties of the fast signal terminal compared with the standard terminal response are shown in Figure 2. The response to a fast pulsed laser signal

(Photek LPG-405 [4]) in Figure 2(a) show that the signal terminal is capable of very fast rise time (<1ns) and very short pulse widths (2ns). The benefit of this to timing applications such as TOF-PET are demonstrated in Figure 2(b), in which the electrical response to a scintillation event in 3x3x15mm^3 LYSO crystal of a fast signal terminal is compared to the standard terminal response. The fast terminal demonstrates much steeper rising edge (10%-90% rise time 1.5ns) than the standard terminal(10%-90% rise time 46ns).

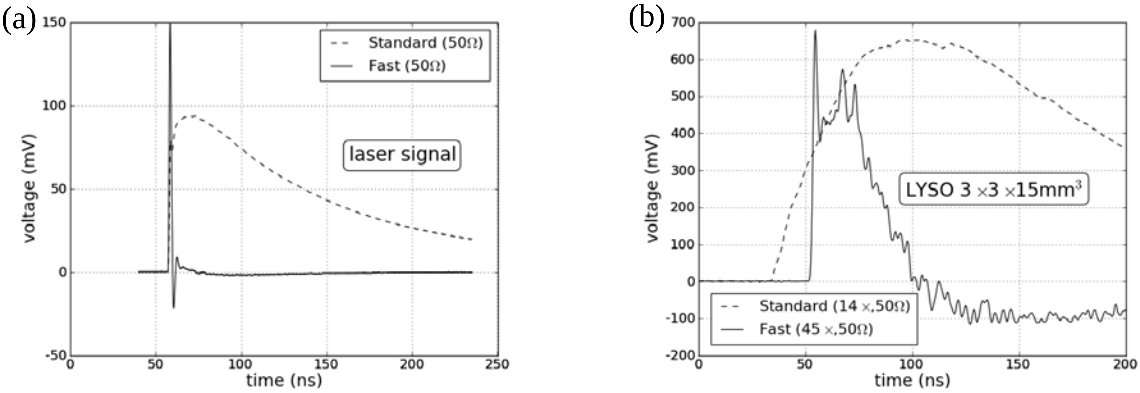

Figure 2: (a) electrical pulse shape response of FM and S series detector using a pulsed laser; (b) electrical pulse shape response from a LYSO scintillation crystal.

3.2 Coincidence Timing Resolution

Coincidence resolving time (CRT) was measured in a side-by-side configuration using the 511keV emission of a ^{22}Na source and a 3×3×15mm^3 LYSO crystals. Measurements were made using a 12bit 3.2GS/s digitizer [5]. Leading edge triggers were used to validate and timestamp the traces. Energy filtering was performed on all data around the 511keV photon peak, from 461keV to 561keV.

The timing characteristics of the fast terminal are shown in Figure 3(a)-(d). Figure 3(a) shows the CRT at the optimum bias setting of 4.5V over break-down, achieving a FWHM folded CRT of 226ps.

Figure 3(b) compares the fast terminal and standard terminal CRT obtained as a function of threshold voltage, at 2V over breakdown. We note that the fast terminal shows a shallow dependence on the threshold compared to the standard terminal, rising from 300ps at 5mV threshold to approximately 500ps at 100mV threshold. Over the same threshold range, the S series CRT rises from 350ps to 1.35ns.

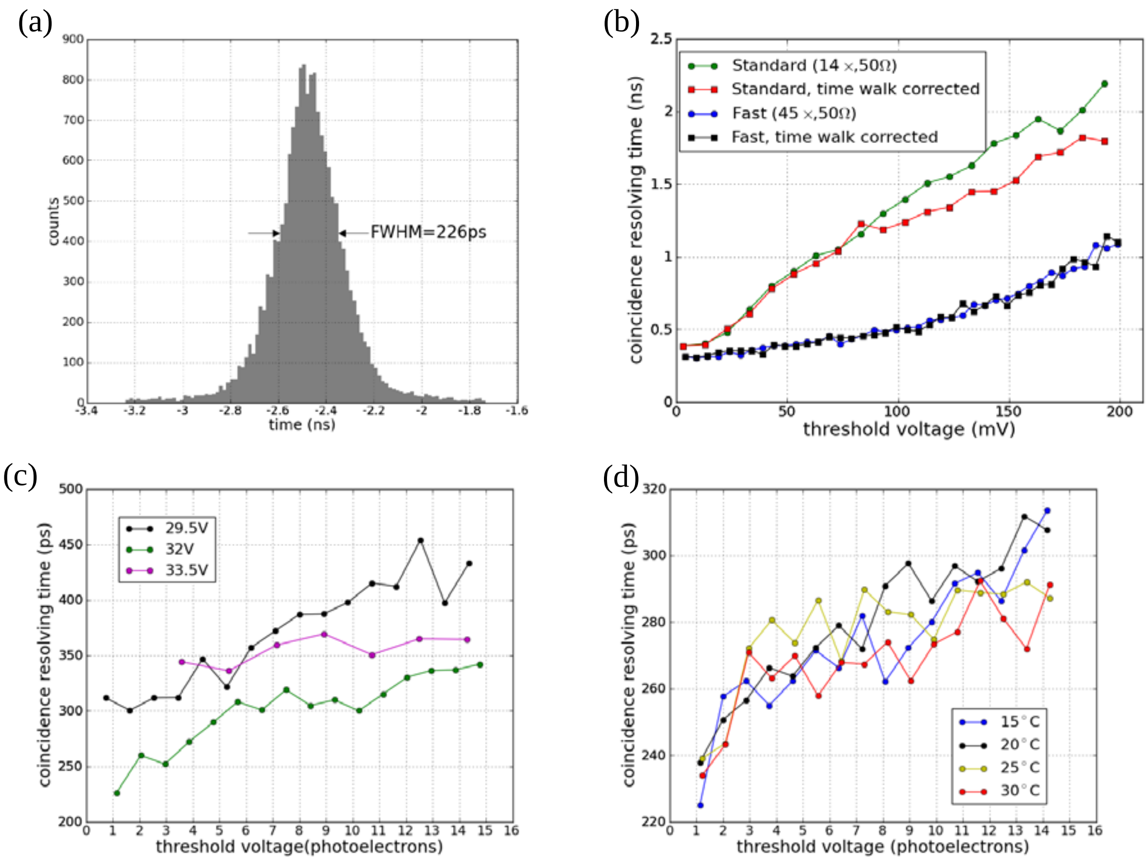

Figure 3: (a) the coincidence resolving time (CRT) of the detector using the signal outputs; (b) the variation of CRT with threshold voltage, comparing fast (blue) and standard (green) outputs (time walk corrected data are shown as crosses); (c) variation of CRT with applied bias, demonstrating an optimal bias of 4.5V over breakdown (27.5V); (d) variation of CRT with different temperature.

Figure 3(c) shows the fast terminal CRT dependence on threshold, expressed as photoelectron amplitude, for three different over-bias conditions: 2V, 4.5V and 6V (corresponding to absolute voltages 29.5V, 31V and 33.5V). Here we observe that the optimum over-bias condition for CRT using the fast terminal is 4.5V. This may be due to increased PDE available while at higher voltage noise dominates the variability of the signal, resulting in deteriorated CRT.
Figure 3(d) show the CRT dependence on threshold, expressed in terms of photoelectron amplitude, for a variety of temperatures around room temperature. We note that there is no statistically meaningful variation of the CRT in the temperature range 15ºC-30ºC.

3.3 Energy Resolution

Enegy resolution can be determined from either standard or fast terminal. For 3mm detectros with 35µm width microcells and at 2V over-bias, the average energy resolution of the 511keV peak using a 22Na source and a LYSO crystal with dimensions is 13% using the standard terminal, and 14% using the fast terminal. When determining the charge integral from the fast mode traces, only the positive part of the trace over the baseline is taken into account.

(a) (b)

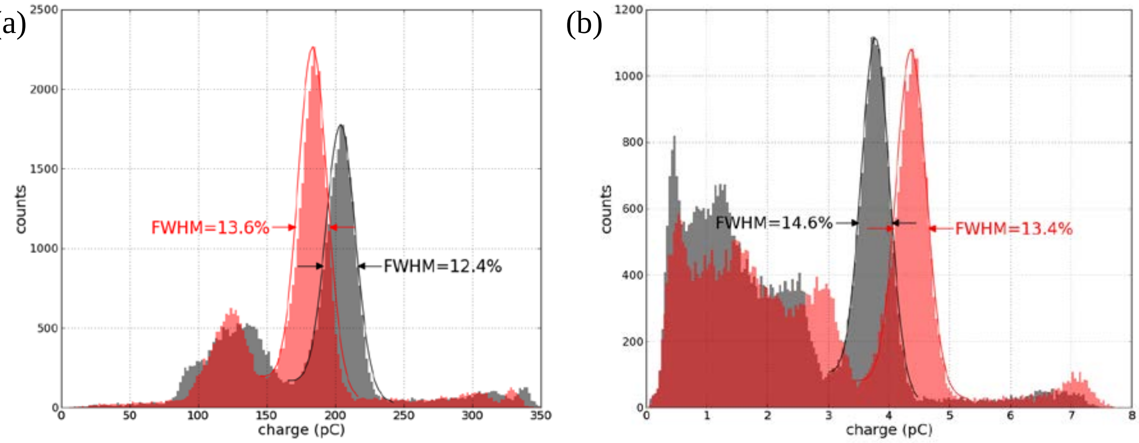

Figure 4: Charge spectra showing the 511keV peak using (a) the standard output and (b) the fast output. Spectra from two detectors is shown, which create the CRT data shown in Figure 3(b).

3.4 Single Photoelectron Peak and Threshold Scan

The fast signal terminal pulses are sufficiently short so that dark pulses can be resolved from the noise pedestal. This is performed during scintillator signal capture. This is demonstrated in Figure 5(a), where amplitude deviation from the median signal in dark (non-scintillating) part of the traces used to construct the CRT results of section 3.2 is shown. Using this information, it is possible to normalize the voltage thresholds in terms of photoelectrons, as in Figure 3(c) and Figure 3(d).

(a) (b)

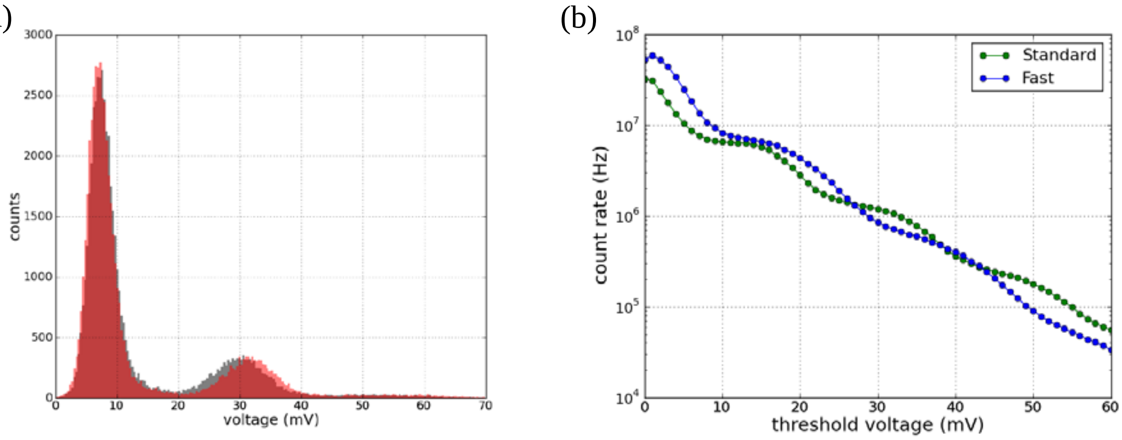

Figure 5: (a) Amplitude spectra in dark, demonstrating that the fast terminal clearly resolves single photoelectron dark events; (b) threshold amplitude scan demonstrating lower crosstalk in fast signal than in standard terminal.

The thresold amplitude scan shown in Figure 5(b) demonstrates reduced cross-talk of the fast terminal compared with in standard mode. This is thought to be due to the fast signal's ability to aggresively discriminate between cross-talk events that occur within a pulse-width (~2ns) so that pile-up may occur. Thus the fast terminal cross-talk is reduced to 8.5% from the standard mode cross-talk of 20%.

3.5 High Frequency Response

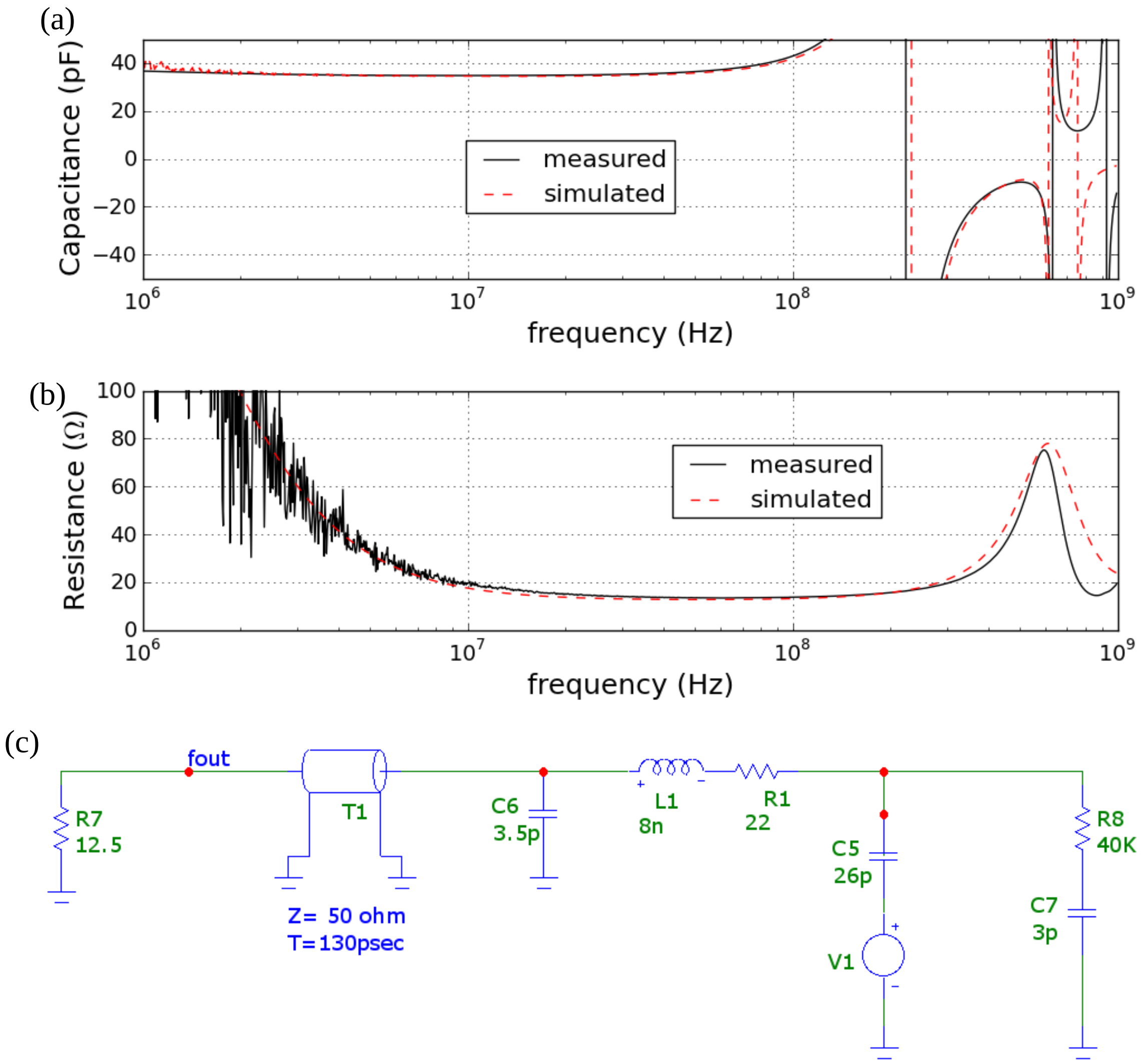

Figure 6(a) Capacitance and (b) Resistance of the fast terminal signal output, as measured with a Vector Network Analyzer. Simulated curves, corresponding to the spice circuit in (c), are shown in red dashes.

Figure 6(a) and (b) shows the Vector Network Analyzer (VNA) output of a fast terminal device. The output capacitance and resistance of the fast terminal is flat over a wide frequency range, becoming distorted at over 3MHz due to resonances due to parasitic capacitances and inductances. Figure 6(c) shows a spice circuit that accurately models the high frequency response of the fast terminal over wide frequency range up to 700MHz.

4. Summary and Conclusions

We have introduces a new fast terminal readout which improves the timing performance of SPMs over a wide range of thresholds. In addition, the fast terminal has low output capacitance which makes it highly compatible with high-frequency signal processing. This is the first demonstration that ability to detect first scintillation photon through improved SPM detector output response signal can lead to significantly improved CRT. Further improvements in photon detection efficiency (PDE) combined with a fast mode detector architecture should provide SPMs which reach the highest levels of performance possible with SPM technology.

References

[1] Emilie Roncalie and Simon R. Cherry, *Application of Silicon Photomultipliers to Positron Emission Tomography*, *Annals of Biomedical Imaging* **39**, 1358-1377 (2011)

[2] R. F. Post and L. I. Schiff, "Statistical limitation on the resolving time of scintillation counter," *Phys. Rev.*, vol. 80, pp. 1113, 1950.

[3] patent WO2011117309, N. Pavlov Silicon Photomultiplier and Readout Method

[4] www.photek.com

[5] D. Breton et al., "High resolution photon timing with MCP-PMTs: a comparison of a commercial constant fraction discriminator (CFD) with the ASIC based waveform digitizers TARGET and Wavecatcher", SLAC-PUB-14048.