Gphotons/s TCSPC with XOR Digital Silicon Photomultipliers

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Single Photon Avalanche Diode (SPAD) arrays are widely used in many scientific applications for Time Correlated Single Photon Counting (TCSPC) thanks to the high timing resolution and single photon precision \cite{1,2}. However, at high photon rates, such systems suffer from photon pile-up effect \cite{3}. In our recent work \cite{4}, we have demonstrated a high throughput (14 Gsamples/s) Time-to-Digital Converter (TDC), improving the conversion rate by a factor over 18 compared to state-of-the-art TDC architectures \cite{5}, and rendering converter pile-up insignificant at typical laser repetition rate and intensity. The pile-up problem now moves to the detector array and photon combining network which need to be optimised to obtain an overall TCSPC sensor throughput in the Gphotons/s range.

In this paper we analyse the novel XOR digital Silicon Photomultiplier (dSiPM) architecture as alternative to standard OR dSiPMs \cite{6}. Moreover, we propose a general criterion for the Region of Interest (RoI), i.e. the number of enabled SPAD pixels, to match the performance of XOR combining network thus avoiding detector saturation and non-linearity.

As presented in \cite{4}, the first example of XOR dSiPM, shown in Fig. 1, consists of a $32 \times 32$ array where each pixel contains a buffer, an output Toggle Flip-Flop and an SRAM for controllable RoI. A time-balanced XOR tree digitally combines pixel outputs onto a single channel. At every photon detection, the pixel output toggles its own state and generates either a rising or falling edge on the final single channel through the XOR tree, as shown in Fig. 2. Replacing the monostable circuit of OR dSiPMs with toggles in the novel XOR dSiPM allows easier in-pixel routing (no bias needed for the toggle) and higher count rates thanks to the exploitation of both rising and falling edges of the single channel. We demonstrate how an optimal RoI can be theoretically predicted from the SPAD dead time and the maximum electrical signal frequency of the single-channel. This is confirmed by experimental results showing $\sim 1$ Gphotons/s performance in optimised XOR dSiPMs, see Fig. 3.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig1.png}
\caption{Picture of the XOR dSiPM chip}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig2.png}
\caption{Toggle + XOR Tree in XOR dSiPMs}
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\begin{figure}[h]
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\includegraphics[width=0.8\textwidth]{fig3.png}
\caption{Measured Gphotons/s XOR dSiPM performance}
\end{figure}

REFERENCES:
\begin{itemize}
\item [{\cite{1}}] C. Niclass, et al., “A 100-m Range 10-Frame/s $340 \times 96$-Pixel Time-of-Flight Depth Sensor in 0.18$\mu$m CMOS,” IEEE JSSC, 48, 559-572 (Feb. 2013).
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\item [{\cite{6}}] Y. Haemisch, T. Frach, et al., “Fully Digital Arrays of Silicon Photomultipliers (dSiPM) - a Scalable Alternative to Vacuum Photomultiplier Tubes (PMT),” Physics Procedia, 37, 1546-1560 (2012)
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