Development of Multi-Channel Fast SiPM Readout Electronics for Clinical TOF PET Detector

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***Abstract*–Silicon photomultipliers (SiPM) are rapidly adapted in simultaneous time of flight (TOF) PET and MRI imaging system in recent years due to its fast timing response and immunity to magnetic field. The aim of this work is to develop multi-channel fast SiPM readout electronics for clinical TOF PET detector. The detector module is assembled by directly coupling a 12x12 LYSO crystal block to an 8x8 Sensl FB30035 SiPM array. We are developing two approaches of compact readout electronics to handle the large number of SiPM output channels. One is a low noise and high bandwidth, 128-channel ASIC to readout the 64 fast outputs and 64 standard outputs of the 8x8 SiPM array. The other approach is a conventional electronics based multiplexing readout scheme using discrete components. A charge division resistor network reduced 64 channels of standard output to four energy signals, and multiplexing and summing circuits reduced 64 channels of fast output to one timing signal, making the detector block highly compact and scalable. The ASIC design has been finished and it's ready for tape-out. Preliminary performance of the detector module readout by conventional electronics was evaluated. 12×12 LYSO crystals were well resolved and identified in the flood image and the average energy resolution was 15.6% ±1.3%. For single crystal pair, 240ps coincidence resolving timing (CRT) was achieved. It was dropped down to 500ps for detector block to single crystal configuration, due to the combination effects of: 1) degradation of fast signal rising edge by output capacitance addition of SiPMs and 2)large white electronic noise and ultrahigh dark count rate. The readout design will be further optimized by increasing the signal bandwidth and reducing noise to get better timing performance at a cost of increasing circuit complexity to a reasonable level. The performance of ASIC readout will be evaluated and good timing performance is expected due to the individual pixel timing pick-off.**

I. Introduction

In our previous work, we evaluated the performance of a sub-millimeter resolution PET block detector based on 4x4 fast SiPM array [1]. Very good timing and energy resolution were achieved with a dual readout of both fast and standard outputs from this new SiPM. Recently we proposed a larger detector module using 8x8 SiPM array for clinical TOF PET. The large number of readout channels becomes a big challenge, and two approaches are under investigation in this study. The first approach is to develop an 128-channel ASIC chip to readout the 64 fast outputs and 64 standard outputs of the 8x8 SiPM array. Its advantage is the low noise and high bandwidth to achieve good timing performance and low system complexity, at the cost of relatively long period of development. The second approach is to develop a multiplexing scheme of conventional readout circuit using discrete electronic components. This compact readout scheme is intended to satisfy required timing performance and keep the electronics cost low at the same time.

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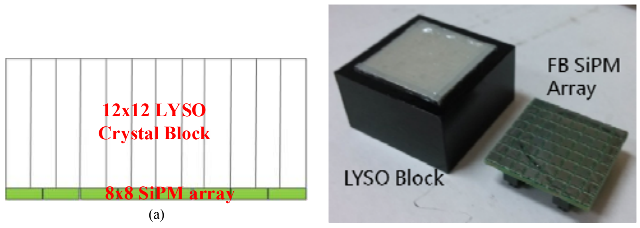
II. Material and Methods

A. Detector Module Setup

A 12x12 array of 2.7x2.7x20 mm^3 LYSO crystals were directly coupled to a 8x8 SiPM array through silicone optical grease illustrated in Fig.1 (a). The SiPM array were was fabricated by tiling 64 individual elements of MicroFB-30035-SMT (SensL, Ireland) which has 4774 of 35 um x 35 um microcells.



(a) (b)

Fig.1. (a) Side view of detector module (b) Photographic image of LYSO block and FB SiPM array.

B. Readout Scheme

Fig.2 shows the block diagram of the detector and data readout system architecture. 64 channels of standard output are multiplexed to generate signal E for energy information and X, Y for position decoding. 64 channels of fast output are multiplexed to generate signal T for timing information. Signal T is processed by a 25ps RMS TDC implemented inside the FPGA [2]. After coincidence detection, data are transferred to the PC via Giga-byte Ethernet.

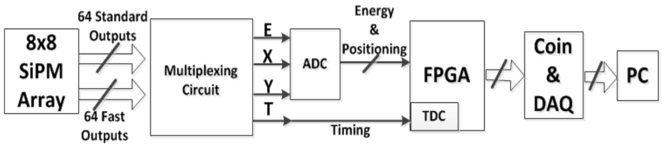


Fig.2. Block diagram of readout architecture.

We are developing both conventional electronics based and ASIC based multiplexing circuit to reduce the 128 channels of one block to four outputs for energy, position and timing discrimination.

Fig.3 shows the conventional electronics based multiplexing scheme. A charge division resistive network is used to multiplex the 64 standard outputs to four position encoding signals(A,B,C and D).And then they are amplified and processed by anger logic circuit to generate E,X and Y signals. As shown in fig.4 (a), the resistor network is modified to match the large capacitance of SiPM from the regular Discretized Positioning Circuit (DPC) utilized in PSPMT readout [3]. Electric circuit simulation was performed and Fig.4 (b) shows the position map of the 64 SiPM cell positions which were successfully separated. The weight of the edge cells are increased to compensate the insufficient light sharing for resolving edge crystals better.

64 fast outputs are divided into 4 groups by connecting every 16 pixels together and each multiplexed output is readout with a 2GHz bandwidth RF amplifier. This multiplexing method will degrade the timing performance because the rising slope of each fast signal will become slow due to the output capacitance of the other channels. Then the 4 pre-amplified fast signals are summed together and fed into a high pass filter to extract high frequency signal components. The output is processed by a comparator to generate timing signal T. Discrete components are used so the circuit design become much easier and faster.

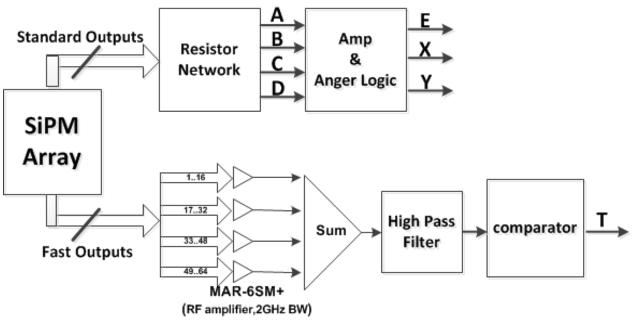


Fig.3. Conventional electronics based multiplexing scheme

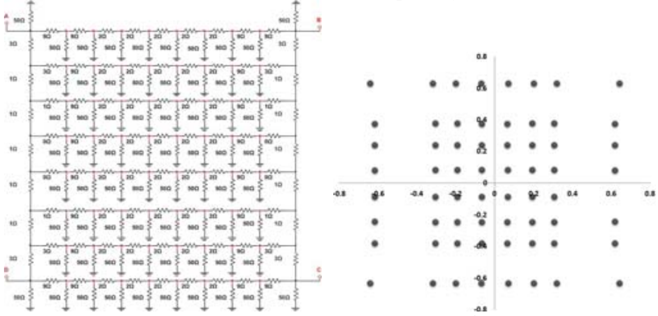

(a) (b)

Fig.4. (a) Schematic of resistor network (b) Position map of 64 channels

The 128-channel ASIC based multiplexed scheme is shown in Fig.5. The 64 standard outputs are processed by the embedded anger logic inside the ASIC to generate signal E, X and Y. The 64 fast outputs are individually fed into comparators followed by a logic or gate to generate the T signal. Much better timing performance is expected because the effect of dark counts is much smaller than conventional electronics based scheme in which 64 fast channels are summed together.

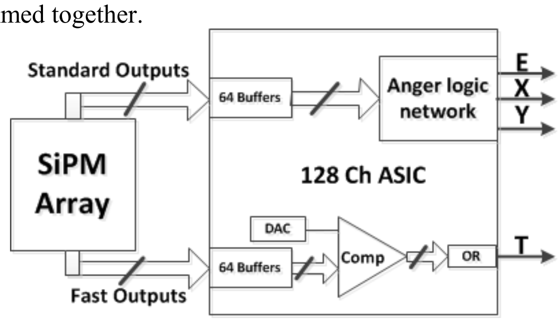
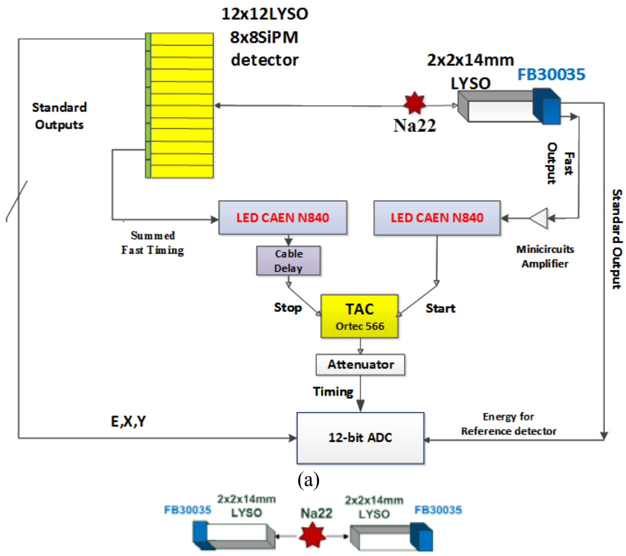


Fig.4. ASIC based multiplexing scheme

C. *Performance Evaluation of Conventional Electronics Based Multiplexing Scheme*

Fig.5 (a) illustrates the experiment setup for the performance evaluation of the detector module readout by conventional electronics based multiplexing scheme. The detector was measured against a single LYSO crystal of 2x2x14mm^3 coupled to a FB30035 SiPM pixel. The fast output of block and single pixel were fed into a leading edge discriminator (LED) CAEN N840 for timing pickup. The outputs of LED were sent to ORTEC 566 time-to-amplitude converter (TAC). The signal E, X, Y of block and standard output of single pixel and attenuated TAC output were digitized by a DAQ system with 12 bits ADCs. The coincidence timing resolution of the reference single pixel was measured using the similar setup described above.



(a)

(b)

Fig.5. (a) Coincidence measurement setup for detector module (b) Single pixel timing resolution measurement

III. Results

A. *Flood Image and Energy Resolution of Crystal Block*

3 million coincidence events were acquired with SiPMs working at 4V over bias voltage (OV). The 2D position histograms of crystal block are shown in Fig.6 (a). All 12x12 crystals are well separated and identified. Fig.6 (b) depicts the

energy resolution at 511 keV across all the 144 crystals after flood image segmentation. Mean, standard deviation, minimum (best) and maximum (worst) energy resolution values were 15.6%, ± 1.3%, 13.9% and 22.8% respectively.

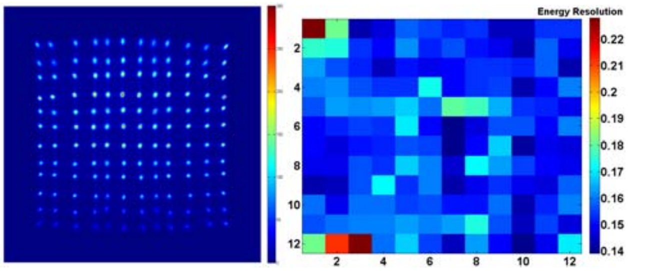


Fig.6. (a) Flood histogram of the crystal block. (b)Energy resolution across all crystals of the block

B. *Timing Resolution for Single Pixel*

Coincidence resolving timing (CRT) for a pair of single SiPM pixels was evaluated. Fig.7 shows the CRT as a function of the LED threshold expressed in photoelectron number for different SiPM over voltages. The single photo amplitude was measured with the oscilloscope by triggering on the dark count level of the SiPMs. Coincidence events were taken into account with energy of 450keV to 650 keV. With higher bias voltage, the timing performance benefits from increased slope of the rising edge, but suffers from the higher dark count rate. At 5V OV， 240ps CRT can be achieved.

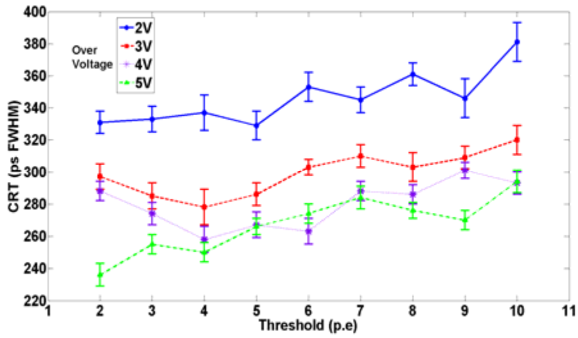
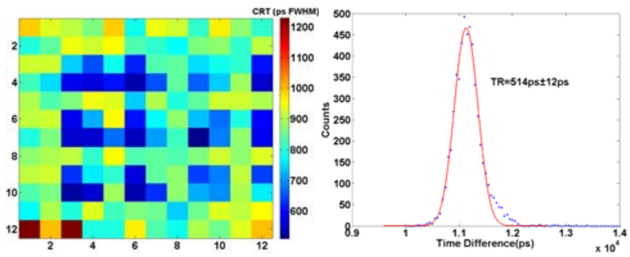


Fig.7. CRT as a function of the LED threshold for different bias voltages.

C. *Timing Resolution of Detector Module*

Fig. 8 (a) depicts the coincidence timing resolution across the 12 x 12 crystals in the block against the reference single pixel. In this initial evaluation, the best CRT was 514ps, as shown in fig.8 (b).



(a) (b)

Fig.8. (a) CRT across the 12 x 12 crystal block; (b) Best timing spectrum

IV. Discussion and Conclusions

The difference between crystal-to-crystal CRT and crystal-to-block CRT is mainly caused by the slope of signal rising edge and noise. By connecting multiple cells together, the slope and amplitude of fast output are largely decreased as shown in fig.9, leading to the degradation of timing performance. The noise gain of amplifier for block readout is much larger than that for single pixel. As shown in fig.10, the white noise of block output is much larger. Summing together of all the pixels for block results in the 64 times of dark noise. There is a large fluctuation on baseline due to the ultrahigh dark count rate. The white electronic noise and dark counts will severely affect the accuracy of timing pick-off.

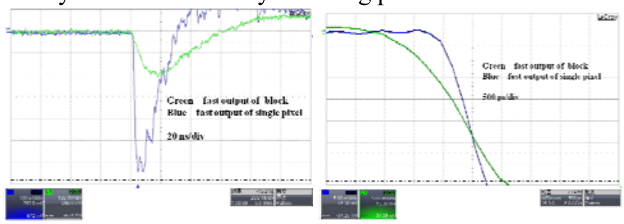


Fig.9. Typical waveform(left) and initial rising edge(right) of fast output of block and single pixel.

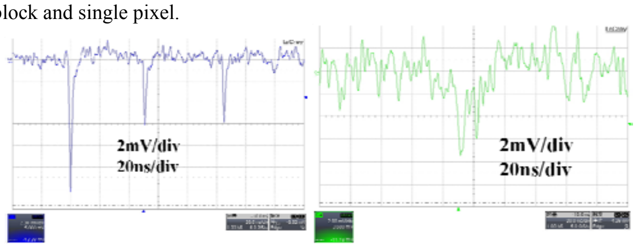


Fig.10.White electronic noise and dark counts on fast output of single pixel (left) and block (right).

In order to keep the fast rising edge of the signal, the fast output should be buffered and amplified in earlier stage. And amplifier with high bandwidth and low noise is necessary to increase the signal noise ratio (SNR) for better timing performance. The fast outputs should be multiplexed to several groups for timing pick-off individually to reduce the effect of dark noise.

In this study, we are developing compact readout circuit for multi-channel fast SiPMs for clinical TOF PET detector. Preliminary test of conventional electronics based multiplexing scheme shows good crystal identification capability and energy resolution but bad timing resolution. The readout design are being optimized to make a tradeoff between timing performance and circuit compactness. Improved timing performance of ASIC based readout scheme is expected, and the evaluation studies are underway.

References

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[2] W. Pan, et al, "A 20-ps Time-to-Digital Converter (TDC) Implemented in Field-Programmable Gate Array (FPGA) with Automatic Temperature Correction", IEEE Trans. Nucl. Sci.,V61,No.3, June 2014

[3] S.Siegel, et al, "Simple Charge Division Readouts for Imaging Scintillator Arrays using a Multi-Channel PMT", IEEE Trans. Nucl. Sci., vol. 43, p. 1634, 1996.