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Abstract. Maintaining excellent timing resolution in the generation of silicon photomultiplier (SiPM)-based time-of-flight positron emission tomography (TOF-PET) systems requires a large number of high-speed, high-bandwidth electronic channels and components. To minimize the cost and complexity of a system's back-end architecture and data acquisition, many analog signals are often multiplexed to fewer channels using techniques that encode timing, energy, and position information. With progress in the development SiPMs having lower dark noise, after pulsing, and cross talk along with higher photodetection efficiency, a coincidence timing resolution (CTR) well below 200 ps FWHM is now easily achievable in single pixel, bench-top setups using 20-mm length, lutetium-based inorganic scintillators. However, multiplexing the output of many SiPMs to a single channel will significantly degrade CTR without appropriate signal processing. We test the performance of a PET detector readout concept that multiplexes 16 SiPMs to two channels. One channel provides timing information with fast comparators, and the second channel encodes both position and energy information in a time-over-threshold-based pulse sequence. This multiplexing readout concept was constructed with discrete components to process signals from a 4×4 array of SensL MicroFC-30035 SiPMs coupled to $2.9 \times 2.9 \times 20$ mm³ Lu_{1.8}Gd_{0.2}SiO₅ (LGSO):Ce (0.025 mol. %) scintillators. This readout method yielded a calibrated, global energy resolution of 15.3% FWHM at 511 keV with a CTR of 198 ± 2 ps FWHM between the 16-pixel multiplexed detector array and a $2.9 \times 2.9 \times 20$ mm³ LGSO-SiPM reference detector. In summary, results indicate this multiplexing scheme is a scalable readout technique that provides excellent coincidence timing performance. © 2017 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JMI.4.1.011012]

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1 Introduction

Precise measurement of the difference in arrival times of annihilation photons at the detector ring of a positron emission tomography (PET) system facilitates event localization along the line-of-response (LOR) between two detection elements. Incorporating this information into the image reconstruction process produces significant gains in image signal-to-noise ratio (SNR), relative to image reconstruction with no 511-keV photon time-of-flight (TOF) information. Moreover, as system coincidence timing resolution (CTR) improves, the ability to better localize the origin of annihilation events along LORs further increases image SNR. The relationship between system CTR and image SNR improvement, relative to a scanner with no TOF capability, can be estimated according to $\sqrt{[(2 * D)/(c * \Delta t)]}$, where D is the subject diameter, c is the speed of light, and Δt is the system CTR.¹ The improvements TOF-PET techniques have benefits, such as decreased patient radiation dose, shorter scan time, improved lesion detectability,^{2,3} increased accuracy and precision of lesion uptake measurements,^{4,5} and less sensitivity to errors in data correction techniques^{6,7} (normalization, scatter, and attenuation corrections). These realizations have

spawned considerable efforts to investigate to what extent CTR can be improved and to develop fast detector designs for TOF-PET.

With advancements in silicon photomultipliers (SiPMs) with higher PDE and lower noise, as well as signal processing techniques to optimize timing performance,^{8–12} sub-200 ps FWHM CTR is easily achievable with single pixel, bench top experiments.^{13–15} However, a whole body PET system will have tens-of-thousands of scintillator pixels. Providing each one of these pixels with its own dedicated readout channel presents a complex and potentially cost prohibitive engineering challenge. Here, we consider an alternate more “scalable” detector readout strategy that multiplexes many SiPMs to a single timing channel while minimizing factors degrading CTR.

2 Materials and Experimental Methods

2.1 Considerations for Fast Timing with Multiplexed Silicon Photomultiplier Arrays

Engineering multiplexing schemes that can tie a large number of channels to a single readout while preserving timing resolution is a challenging problem. To minimize degradation of timing

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Fig. 1 A next-generation PET detector module and readout concept is depicted. In this design, subunits consisting of 4×4 arrays of sensors are multiplexed to two channels, one for timing and another that encodes energy and position of interaction.

resolution when moving from single pixel SiPMs to multiplexed arrays: (1) scintillation crystals with an optimized reflector configuration should be 1:1 coupled to SiPMs with matching active area, (2) each channel would ideally have its own dedicated preamplifier to minimize capacitive shaping effects from the interconnection of multiple SiPMs in a multiplexing scheme,¹⁵ (3) preamplifiers should be low noise and high gain, (4) timing channels should include a high-pass filter or pole-zero compensation^{10,11} to minimize the effect of baseline fluctuation on timing performance, and (5) effects of multiplexing schemes used for crystal identification and energy information on timing signals should be minimized. When all of these points are addressed in a multiplexing scheme, the remaining factors that influence timing resolution are mostly uncorrelated dark noise, after pulsing, and cross talk from combining many pixels into a single readout channel. The method used to record signals

and perform time pickoff is also an important factor. In this work, we first investigate the amount of SiPM timing channels that can be combined while maintaining a timing resolution less than 200 ps FWHM. Then, a prototype detector module readout scheme was tested that multiplexed a 4×4 array of SiPMs to two channels (one for timing and one for position and energy).

2.2 Multiplexed Detector Readout Concept

The multiplexed PET detector module readout concept presented in this work is illustrated in Fig. 1. A detector module is depicted with a typical area ($\sim 5 \times 5$ cm²) for a whole body PET block detector, comprising 16 submodules of 4×4 SiPM arrays of 3×3 mm² sensors, 1:1 coupled to $3 \times 3 \times 20$ mm³ scintillators. A multiplexing readout is implemented for each submodule that reduces the channel number by a ratio of 16:2. One of these two channels contains timing information encoded into a digital signal, the other contains both position and energy information in a digital pulse sequence. With this readout, 256 SiPMs would read out by 16 timing channels and 16 energy and position channels. Utilizing a separate energy and position signal for each submodule would facilitate operation at high event rates, as well as the possibility to accurately position events that Compton scatter¹⁶ between submodules (since scatter events are much more probable than single interaction photoelectric events).

2.3 Effects on Timing with Increasing Multiplexing Ratio

To investigate the number of timing channels that could be combined before time pickoff while maintaining a CTR less than 200 ps FWHM, two test boards were designed and fabricated to combine a selectable number of SiPMs into a single channel. The board was designed with the schematic shown in Fig. 2(a). Eight channels from a 4×4 array of SensL MicroFC-30035 SiPMs were passed to Minicircuits MAR-6 preamplifiers. These SiPMs were used, since they have a “fast output” terminal

Fig. 2 In (a), a schematic of the electronic readout is shown for measuring CTR versus the number of timing channels multiplexed to a single output. The experimental setup using boards employing the readout design detailed in (a) for measuring CTR of $\text{Lu}_{1.8}\text{Gd}_{0.2}\text{SiO}_5$ (LGSO):Ce (0.025 mol. %) crystals coupled to SensL MicroFC-30035 SiPM arrays is shown in (b).

that provides a low capacitance path from the Geiger-mode cells that comprise the sensor. This provides a built-in high-pass filter for timing channels. They are also low noise sensors, with dark noise <100 kHz/mm², after pulsing 0.2%, and cross talk 7% at 2.5 V over breakdown.¹⁷ This is potentially beneficial in a multiplexing design that combines the noise from many sensors into a single readout channel. Up to eight timing channels could be combined on these test boards. Therefore, the timing performance of multiplexing ratios up to 8:1 could be tested. A common energy signal was used for energy and coincidence processing, which came from shorting the anodes of the SiPMs together, before the 50 Ω resistor connected to ground.

The experimental setup used to measure CTR versus multiplexing ratio [using boards with schematic shown in Fig. 2(a)] is shown in Fig. 2(b). A $2.9 \times 2.9 \times 20$ mm³ LGSO:Ce (0.025 mol. %)¹⁸ crystal was optically coupled to one of the SiPMs in the array. The crystals were wrapped in enhanced specular reflector (ESR), and Teflon tape was used to cover the top of the crystals. ESR around the sides of the crystals was held in place by tightly wrapping it in Teflon tape. The common energy signals from the SiPM arrays were used for energy gating and coincidence processing. The timing channels were digitized at 20 GSamples/s by an Agilent 2 GHz DSO90254A oscilloscope. Digitized waveforms were processed

with simple leading discrimination (to mimic comparators later used in the final readout design). CTR was measured for multiplexing ratios of 1:1 (single sensor of the array, no multiplexing), 2:1, 4:1, and 8:1 by increasing the number of sensors connected to a common output. With the addition of each channel into this combined timing output, the dark pulses, after pulsing, and cross talk from additional SiPMs were incorporated into the output channel.

2.4 Crystal Array and Multiplexed Silicon Photomultiplier Array Readout

Measurements described in Sec. 2.3 guided the design of a prototype readout to multiplex a 16-channel array of SiPMs to two channels, such as that described in Sec. 2.2. The 16-channel SiPM array was coupled to 16 $2.9 \times 2.9 \times 20$ mm³ LGSO:Ce (0.025 mol. %) crystals epoxied into a 4×4 array [Figs. 3(a) and 3(b)], such that the exit faces of the crystals one-to-one (1:1) matched the sensitive areas of the SiPMs in the array Fig. 3(c). A detail of the dimensions of the glass spaces used to space the scintillation crystals is shown in Fig. 3(b), and the dimensions of the SiPM array that match the assembled array [corner of Fig. 3(b)] are shown in Fig. 3(c). In this assembly, 3M ESR

Fig. 3 The crystal array dimensions used in measurements with the multiplexed detector readout are shown in (a). In (b), a magnified view of the intercrystal dimensions of the array is shown. The dimensions of the SiPM array, in which the crystal array is designed to match, are shown in (c).

Fig. 4 Schematic showing the multiplexing detector readout concept. In a first layer of multiplexing, 16 timing channels are reduced to 4 outputs and 16 energy and position channels are reduced to 4 outputs. In separate, second layers of multiplexing for timing, energy, and position, the total number of outputs from the 16 SiPM array is reduced to 2.

reflector¹⁹ is epoxied with Dymax OP-20 optical adhesive²⁰ to both the glass spacer and the scintillator crystals.

A schematic of the readout concept is shown in Fig. 4. The basic concept was to split the readout into separate segments that multiplex timing, position, and energy information independently. For the energy and position multiplexing, the anodes of the SiPMs were connected to a resistive mesh with a four-corner Anger readout. This first layer of multiplexing reduces the channel number from 16 to 4. In a second layer of multiplexing, each corner of the Anger readout was amplified by a factor of 10 and then passed to a comparator, which encoded energy information into a digital pulse via time-over-threshold (ToT). Three of the digital pulses were given an increasing delay in 500 ns increments using active delay chips (Maxim DS110LE-500) and then connected to a common output, creating a serialized pulse sequence that encoded both energy (total width of all pulses) and position information (width of each pulse in Anger calculation) into a single channel.

Timing information was taken from the fast output of the SiPMs. The fast channel from each SiPM was connected to a Minicircuits MAR-6 preamplifier²¹ (represented as an inverting amplifier in Fig. 4), and the signals from four preamplifiers were connected to a common output. This first layer of timing channel multiplexing reduced 16 channels to 4. In a second layer of multiplexing, each of the four timing channels was passed to fast comparators (Analog Devices ADCMP572) to perform leading edge time pickoff on the timing signals. Once the 511-keV time of interaction information is encoded into the leading edge of the digital pulse from the comparators, the signals from many comparators are combined into a single output. This second

level of multiplexing reduces the number of timing channels to one.

The major assumption behind the methodology of our approach for multiplexing of timing information is that the two-layer scheme outlined in Fig. 4 can provide improved timing performance, compared to the most simplistic and straightforward readout strategy of simply shorting the outputs of all channels together. As mentioned in Sec. 2.1, appropriate signal processing^{10,11} can minimize the effects of dark noise causing baseline fluctuations that degrade timing performance. However, when many channels are combined into a single output, the inability of these techniques to perfectly compensate for the significant increase in noise influences the precision of the timing estimate.²² If instead, only a few channels are combined to a single comparator (4:1 in the schematic shown in Fig. 4) and then comparator outputs are combined into a single output, a more accurate time pickoff is encoded in the leading edge of the comparator's digital output pulse. As long as there is no degradation of the leading edge of the digital outputs from the first layer of multiplexing, the timing performance achievable with just a few channels shorted together is, in principle, also achievable with many more (in this case 16) channels combined to a single output in the two-layer scheme provided in Fig. 4. In Sec. 2.5, we outline experimental measurements that investigate this methodology by comparing measured CTR for a multiplexed 16 pixel detector array with signals read from: (1) just after the first layer of multiplexing, (2) with the full two-layer multiplexing readout, and (3) when all 16 pixel signals have been shorted together after amplification. If the methodology behind this approach is valid, then the timing

performance should be the same for just a few channels at the first layer of multiplexing shown in Fig. 4 as with 16 channels multiplexed with this two-layer scheme. Also, the performance should be better compared to the most simple case where all 16 timing channels are shorted together, and the noise from 16 channels influences time pickoff by the comparator, as opposed to our two-layer scheme that is only influenced by the noise from four channels.

In the printed circuit board for the multiplexed detector array, a single uniform bias was applied to all the SiPMs in the multiplexed array. Previous iterations of these (and other commercial) SiPMs required the optimum bias to be found for each SiPM due to variations in breakdown voltage from sensor-to-sensor. However, the performance of these SiPMs is now much more uniform. In fact, a large study of 146,590 of SensL SiPMs, showed <100 mV standard deviation in breakdown voltage.²³ Therefore, the difference in optimum bias from sensor-to-sensor is minimal. Moreover, providing each sensor with its own independent bias increases the complexity of the detector bias circuitry and also the detector readout, which is counter to the focus of this work of providing a simplified readout for an array of SiPM-based PET detectors (Fig. 1).

2.5 Measurements with the Multiplexed Detector Array

The ToT values from the energy side of the multiplexed detector array were calibrated by recording energy spectra from ¹³³Ba, ²²Na, and ¹³⁷Cs sources, providing a calibration curve with 356, 511, 662, and 1275 keV energies. The 511-keV energy performance was then taken from the calibrated detector response when irradiated by annihilation photons from a ⁶⁸Ge source, where 100,000 events were recorded. The 511-keV photopeak was fit with the sum of a linear and normal distribution. Global energy resolution was taken from the FWHM and mean of the normal distribution in the fit. A flood map of the position response of the multiplexed output was also taken from the measurement with irradiation from the ⁶⁸Ge source.

The timing performance of the detector array with multiplexed readout was measured with the experimental setup shown in Fig. 5. The single channels from the second layer of multiplexing were passed to the DSO90254A oscilloscope. The fast and standard (energy) channels from a single SensL

Fig. 5 Experimental setup for the timing performance of the SiPM array with multiplexed readout. “MX” on the readout schematic for the multiplexed detector array stands for “multiplexing.”

MicroFC-30035 SiPM were also connected to the oscilloscope. Coincidence processing was performed with the oscilloscope software between the single pixel and the multiplexed array, and pulses were digitized at 20 GSamples/s. Simple leading edge time pickoff was performed on the timing signal from the single pixel reference detector, and the rising edge of the comparator outputs provided the time of interaction information from the multiplexed readout. Comparator thresholds were taken at the optimal threshold from the 4:1 multiplexing measurements described in Sec. 2.3. Forty thousand coincidence events were recorded, providing 16,134 energy qualified coincidence events from a full-width-at-tenth-maximum window of the 511-keV photopeak. CTR was measured on a per-pixel basis with a normal distribution fit, and the mean of this normal distribution was used to calibrate out any time-walk between pixels due to differences in trace length on the readout board. With this calibration, all timestamps were combined into a global measurement of CTR.

As mentioned in Sec. 2.4, CTR measurements were also performed to validate the methodology behind the two-layer multiplexing approach outlined in Fig. 4. Another measurement was performed with the output from one comparator in the first layer of multiplexing (see Fig. 4) used as the timing signal from the detector array. This tests the achievable CTR from four channels shorted together, sharing a single comparator. The results of this measurement can be compared with those from the entire detector array in the two-layer multiplexing scheme to validate the assumptions behind our multiplexing scheme, outlined in Sec. 2.4. CTR measurements were also performed with the outputs of all 16 channels shorted together after the preamplifier stage and processed with a single comparator. This additional measurement facilitates a direct comparison between our approach and simply shorting all channels together.

3 Results

3.1 Coincidence Timing Resolution Versus Multiplexing Ratio

The measured CTR with a bias voltage sweep, for a single SiPM in the array, is shown Fig. 6(a). The best CTR was 160 ± 3 ps FWHM at a bias of 32 V. This measurement provided both the optimum SiPM bias for measurements with higher multiplexing ratios, as well as a reference timing performance to be compared to for experiments with the multiplexed SiPM array (Fig. 4). The measured CTR with increasing multiplexing ratio is shown in Fig. 6(b). The values range from 160 ± 3 ps with no multiplexing to 190 ± 3 ps with eight timing channels multiplexed to a single output. From these measurements, it was chosen to use a maximum of 4:1 multiplexing ratio on the timing channels before time pickoff in the first layer of multiplexing readout, in order to provide a margin below 200 ps FWHM coincidence timing.

3.2 Position Response and Energy Resolution

An example output pulse from the second layer of energy and position multiplexing is shown in Fig. 7(a). Each digital pulse in the pulse sequence is labeled with its corresponding corner of readout from the resistive mesh, facilitating an Anger logic calculation of the position of interaction. The resultant flood map of 511 keV photopeak events is shown in Fig. 7(b). Each pixel can be clearly distinguished. The calibration curve for

Fig. 6 A voltage sweep of CTR for single SensL MicroFC-30035 SiPMs coupled to 20 mm length LGSO:Ce (0.025 mol. %) crystals in coincidence is shown in (a). In (b), CTR is shown with the noise from additional channels multiplexed to a single output in ratios of 1-to-1 to 1-to-8.

converting ToT values (in ns) to energy (in keV) is shown in Fig. 8(a). Energy calibration was performed on the global ToT spectrum for all crystals. Figure 8(a) represents the calibration curve for the global ToT-based energy spectrum, where the energy bars reported are taken from the sigma of the fit to the characteristic photopeak. The energy of each event was taken from the total sum of all the pulses in the digital pulse sequence [Fig. 7(a)], since the total charge created from each event was split four ways into an Anger logic output in the first layer of the multiplexing readout. The global energy resolution from the multiplexed detector is shown in Fig. 7(b), for 100,000 events. The measured energy resolution was 15.3% at 511 keV, taken from the FWHM and mean of the normal distribution of the fit.

To minimize the influence of each channel of the energy multiplexing scheme on each other, they were combined to a single output using a power splitter combiner (Minicircuits AD4PS-1). This component has a bandwidth from 1 to 500 MHz, and therefore, influences signal shape that results from the shaping of the DC component of the signal seen in Fig. 7(a). This yields the slanted slopes of the digital pulse sequence. The prototype circuit for the second layer of energy multiplexing, as assembled, also exhibited some minor baseline instability. However, these two characteristics should not affect the width of the digital pulses, and we achieve a global energy resolution of 15.3%

Fig. 7 An example of the serialized pulse sequence from the energy multiplexing of the detector array is shown in (a). In (b), the flood map for the detector is shown.

Fig. 8 The calibration curve to convert ToT values from the energy multiplexing of the detector array into keV is shown in (a). In (b), the global energy spectrum for 100,000 events from 511-keV photon source is shown.

at 511 keV. The apparent barrel distortion of the flood map is due to the inherent nonlinearity of the relationship between the charge in each pulse and the resultant width of each pulse. This nonlinear relationship is well known and is a function of the threshold applied. This was verified during the development

Fig. 9 Global CTR for the multiplexed detector array.

of the second layer of multiplexing readout by digitizing the raw waveforms from the four-corner Anger logic output. Using the amplitude of the digitized waveforms from each corner in the Anger formula, the flood map is reconstructed with no distortions.

3.3 Timing Performance with the Multiplexed Detector Readout

The measured CTR between the reference detector and the multiplexed detector array, shown in Fig. 9, was 198 ± 2 ps FWHM. This is the global CTR for the multiplexed detector readout. As mentioned in Sec. 2.5, in addition to measuring the achievable CTR with the multiplexing design, additional measurements were performed to validate the methodology behind the two-layer multiplexing scheme. The measured CTR for one comparator output from the first layer of the two-layer multiplexing scheme was found to be 198 ± 3 ps FWHM, the same achievable timing performance with all 16 channels multiplexed using the scheme outlined in Fig. 4. This measurement validates the assumption that many channels can be multiplexed in the second layer of the multiplexing scheme without degrading timing performance. The achievable CTR was also measured when all 16 channels were shorted together after amplification and processed with a single comparator. The resulting CTR was 227 ± 11 ps FWHM. These measurements validated our assertions that (1) the achievable timing performance with 4:1 multiplexing ratio in the first layer of multiplexing can be maintained with a 16-channel readout in the second layer by first encoding time of interaction in the leading edge time pickoff scheme with a comparator before combining all channels and (2) this timing performance is better than the simple case where all 16 channels share one leading edge discriminator, where the noise from 16 channels influence time of interaction estimation, rather than just four, like in the schematic presented in Fig. 4.

4 Discussion

The global CTR for 511 keV photoelectric events between the reference detector and multiplexed detector array was 198 ± 2 ps FWHM. Accounting for the contribution from the $2.9 \times 2.9 \times 20$ mm³ LGSO:Ce reference detector, the CTR between two identical, multiplexed detector arrays is estimated to be 229 ± 5 ps FWHM

$CTR_{\text{two modules}}$

$$= \sqrt{CTR_{\text{module versus reference}}^2 - \left(\frac{CTR_{\text{two reference}}}{\sqrt{2}} \right)^2} \cdot \sqrt{2}. \quad (1)$$

In selecting a design for the multiplexing readout using the measurements in Sec. 2.3, a multiplexing ratio of 4:1 was chosen for the first layer of timing multiplexing. However, the CTR measured between the multiplexed array and reference detector (Fig. 9) was higher than that measured with the experimental setup described in Sec. 2.3 [the single pixels, with multiple sensors multiplexed to a single channel, Fig. 6(b)]. While the measurements described in Sec. 2.3 were performed to guide the design of the multiplexing readout, these two scenarios are not identical. The CTR versus degree of multiplexing measurements depicted in Fig. 2(b) do not account for the additional indirect optical cross talk generated during the avalanche process of the Geiger-mode cells of the SiPM being incorporated into each timing channel due to crystals being coupled to all sensors, as in the case of the experimental setup in Fig. 5. It has been shown that indirect optical cross talk significantly increases dark count rate, even for a single sensor.²⁴ In the multiplexed array, four channels are combined to a single output. Therefore, the effects of this indirect cross talk on dark count rate are increased threefold relative to the 4:1 case in Fig. 6(b). The single pixels used with the experimental setup in Fig. 2(b) also have better optical isolation than the pixels bonded into an array in Fig. 4. We have measured the same crystal array used in the experiment outlined in Fig. 4 to have 11% lower light output than the single pixels with a photomultiplier tube. In the crystal array, pixels are bonded to ESR reflector with an optical epoxy, as opposed to an air gap between the crystal and reflector, as in the single pixel experiments [Fig. 2(b)]. This effective light loss is even worse when coupled to the SiPM array. To 1:1 match the crystal cross section to the sensitive area of the SiPMs, glass spacers are bonded between scintillator pixels [Figs. 3(a) and 3(b)]. Light leaking from the scintillator to the glass spacer can potentially fall on the relatively large dead space (1.2 mm) between the active area of the SiPMs in the array. Additionally, scintillation light cross talk between scintillator pixels not within the same 4:1 grouping in the first layer of the multiplexing scheme is lost and does not contribute to the leading edge time pickoff estimate for time of interaction. We believe these effects are the main reasons for the discrepancy between the CTR for 4:1 multiplexing in Fig. 6(b), and the CTR measured in Fig. 9.

The positions of pixels in the flood map shown in Fig. 6(b) were clearly distinguishable, and the global energy resolution was measured to be 15.3% at 511 keV. This energy performance could be further optimized in future work. To distinguish each pixel using Anger readout from the first energy and position multiplexing layer (the resistive mesh), comparator outputs had to be set at a relatively low threshold (50 mV). It is well known that ToT measurement of energy resolution is increasingly nonlinear as the threshold used is lowered toward the baseline of a pulse.²⁵ The energy performance could potentially be improved with a dual-threshold ToT readout, where the low threshold sets the start time, and a higher threshold is used for stop time where the ToT measurement is less susceptible to nonlinear effects of pulse width versus energy.

The 500-ns delay incorporated between each digital pulse of the multiplexed energy and position readout was a conservative design choice to make sure that none of the digital pulses overlapped. The largest ToT value from any of the four pulses from the energy side of the multiplexing scheme was about 400 ns, which would reduce the overall achievable pulse sequence duration to 1.6 μ s. However, in this proof-of-concept work, we used the pulses directly from the resistor matrix in the energy

multiplexing channel. It would be relatively simple to further reduce each pulse in the four-pulse sequence ToT duration to a few hundred nanoseconds with C-R shaping of the pulses from the four-corner Anger output in the first layer of the energy multiplexing scheme. This would facilitate a total pulse duration of about 800 ns. But optimizing the duration of the serialized pulse sequence for the energy side of the multiplexed output is beyond the scope of this work, which focused on measurements of degrees of multiplexing versus CTR. We also note that this “dead time” would only be for a 4×4 crystal section of a complete PET detector block, comprising ~ 16 of these 4×4 of arrays of crystals. (Fig. 1). Therefore, this dead time is only for a very small portion of a full detector block or module and would see an average count rate of one-sixteenth that of a 5×5 cm² traditional PET block detector with Anger readout.

The multiplexed SiPM readout was implemented onto separate boards as it was developed, with discrete components for proof-of-concept measurements. However, this readout design could be simply integrated into a practical footprint on readout boards for practical, scaled-up, clinical detector modules. Furthermore, the entirety of the timing multiplexing could be encompassed in analog ASICs, such as the NINO chip,²⁶ using a logical OR operator on or after the chip. The energy and position multiplexing could be reduced to a dense resistor mesh with only four operational amplifiers, low-power comparators, and three active delay chips. Thus, the two-layer position and energy multiplexing could be realized in a simplistic and compact footprint as well.

An updated version of the SiPMs used in this work has recently been released, the SensL J series.²⁷ These sensors have similar dark count rate, after pulsing probability, and cross talk probability as the C series sensor, but the PDE is improved to 50% at the optimum bias voltage (compared to $\sim 40\%$ for the C series) in a tile-able through-silicon-via package. Therefore, implementing these sensors into our proposed readout would provide an estimated 20 ps improvement in CTR, according to the well known proportional relationship between CTR and inverse root of detected scintillation photon statistics $\text{CTR} \propto \sqrt{\tau_d/(n \cdot \text{PDE})}$.^{28–30} As a result, CTR between two multiplexed modules closer to 200 ps may be possible with the presented multiplexing readout technique and these sensors. In this proof-of-concept work, $2.9 \times 2.9 \times 20$ mm³ crystals were used to provide 1:1 coupling with the SiPMs in the sensor array shown in Fig. 3(c). Clinical detector modules typically have 4-mm wide crystal elements. With the proposed multiplexing readout, detectors having 4-mm wide crystals would use a sensor with a corresponding 4×4 mm² active area. We have tested SiPMs of the same type used in this work with an active area up to 6×6 mm² coupled to a matching crystal area and observed ≤ 10 ps degradation in CTR.

5 Conclusions

We have developed a highly multiplexed, SiPM-based TOF-PET detector readout concept. The readout multiplexes 16 SiPMs to one timing channel and one channel that encodes both energy and position (8:1 overall multiplexing ratio). The calibrated, global 511 keV energy resolution was measured to be 15.3% FWHM. The CTR between the multiplexed detector array and a $2.9 \times 2.9 \times 20$ mm³ LGSO:Ce (0.025 mol. %) crystal coupled to a single SiPM of the same type used in the detector array was 198 ± 2 ps FWHM. Unfolding the timing resolution of the reference detector, the CTR between two

identical multiplexed detectors would be 229 ± 5 ps FWHM, a result that should scale to the full module depicted in Fig. 1. Therefore, this highly multiplexed scheme offers reasonable trade off in achievable CTR for improved scalability of PET detector modules comprising 1:1 coupling of crystals to SiPMs to a full system.

Disclosures

No conflicts of interest, financial or otherwise, are declared by the authors.

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