Optical delay encoding for fast timing and detector signal multiplexing in PET

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Purpose: The large number of detector channels in modern positron emission tomography (PET) scanners poses a challenge in terms of readout electronics complexity. Multiplexing schemes are typically implemented to reduce the number of physical readout channels, but often result in performance degradation. Novel methods of multiplexing in PET must be developed to avoid this data degradation. The preservation of fast timing information is especially important for time-of-flight PET.

Methods: A new multiplexing scheme based on encoding detector interaction events with a series of extremely fast overlapping optical pulses with precise delays is demonstrated in this work. Encoding events in this way potentially allows many detector channels to be simultaneously encoded onto a single optical fiber that is then read out by a single digitizer. A two channel silicon photomultiplier-based prototype utilizing this optical delay encoding technique along with dual threshold time-over-threshold is demonstrated.

Results: The optical encoding and multiplexing prototype achieves a coincidence time resolution of 160 ps full width at half maximum (FWHM) and an energy resolution of 13.1% FWHM at 511 keV with $3 \times 3 \times 5$ mm³ LYSO crystals. All interaction information for both detectors, including timing, energy, and channel identification, is encoded onto a single optical fiber with little degradation.

Conclusions: Optical delay encoding and multiplexing technology could lead to time-of-flight PET scanners with fewer readout channels and simplified data acquisition systems. © 2015 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4923176>]

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1. INTRODUCTION

As the new generation of positron emission tomography (PET) systems employs semiconductor photodetector arrays with small pixels, it is important to evolve novel methods of multiplexing to control the number of readout and processing channels, interconnects, and the amount of circuitry, without substantial information degradation. Typical electronic schemes such as resistive or capacitive multiplexing can compromise timing, energy, and spatial resolution, and may still require complex data acquisition systems.^{1–4} This is not ideal for the development of new high resolution or time-of-flight (ToF) PET scanners.

In the typical data acquisition architecture for a PET system, the many data acquisition channels must have continuously running electronics to register interactions from annihilation photons. Shifting the readout architecture to a more serial event processing design could reduce the number of channels that must be processed in parallel to detect coincidence events. This work explores this alternative way to process data. If every event is encoded with a unique series

of extremely fast pulses, many channels could in principle be multiplexed into a single system output so that one digitizer at the end of the chain reads out all event information, with little to no degradation. An existing pulse train based method that encodes event information in pulse width has been successfully used in PET to multiplex over 100 detector channels onto a single output.⁵ Disadvantages of this existing method include long dead time and poor time resolution.

State of the art optical techniques have combined data encoding schemes with new multiplexing technology to enable extremely high data rates over optical fibers.⁶ The continuing advancement of optical communications technologies introduces additional ways to encode an increasing number of channels at a high data rate onto a single output fiber. As an alternative to single mode fibers, few mode fibers (FMFs) have been developed to allow both mode division multiplexing (MDM) and polarization division multiplexing (PDM), resulting in data rates in the hundreds of Gb/s.⁷ Optical fibers with multiple cores, known as multicore fiber (MCF) allow space division multiplexing (SDM) schemes

that, when combined with FMF, reach over 1 Pb/s in a single combined fiber line.^{8,9} These data rates are far beyond the requirements of a modern clinical PET scanner, yet they are achieved over single optical fiber lines. Although complex equipment with multiple readouts, coupled with digital modulation schemes such as quadrature phase shift keying (QPSK) are currently required to reach these high throughput rates, these technologies demonstrate the great potential data multiplexing gains that optics could bring to PET data processing.

Compressing PET readouts using optical encoding and multiplexing techniques will allow simplification of the data acquisition system and could reduce overall scanner size, while still enabling excellent performance. Optical elements are insensitive to electromagnetic interference and can transmit fast signals over long distances with little degradation.¹⁰ High speed (>50 Gb/s) optical elements such as laser diodes, modulators, photodiodes, and fiber couplers are readily available as off-the-shelf components, as they are frequently used in state of the art high speed telecommunications systems. These components are fast enough to process the millions of events per second that could occur on the single fiber output of a fully optically multiplexed PET scanner.

Encoding PET detector outputs into optical signals has been demonstrated previously. For example, digital optical communication over fiber was used to avoid electrical data connections in an MRI-compatible preclinical PET scanner.^{11,12} While this technique has the advantage of avoiding the mutual interference that can accompany electrical cables, digitally compresses event data onto a single fiber, and achieves excellent timing resolution, it also requires digital processing electronics housed within the detector modules. These components can draw high power, generate considerable heat, and require more stringent shielding design for operation in an MRI. Optically encoding analog PET signals using fewer electronic components in the front end can mitigate these issues. This work investigates a new method of analog encoding and multiplexing in PET that preserves high performance, while potentially simplifying back end readout architecture.

This method has been implemented with a combination of custom circuitry and optical components. In the optically encoded 2:1 multiplexed coincidence prototype demonstrated here, all of the relevant information in a detector interaction (channel position, timing, energy) is encoded in a series of precisely timed, extremely fast optical pulses. Preliminary measurements with this early optical encoding prototype demonstrated that the method does not fundamentally degrade the timing resolution of silicon photomultipliers (SiPMs),^{13,14} and only one readout channel is required. The high performance readout channel and the low jitter of the optical components allow fast timing to be achieved after signal decoding. This technology shows promise for large-scale optical multiplexing with very few or even one system readout channel required, as well as fast, low jitter timing performance required for ToF PET imaging. Thus, this work would be of interest for research and industrial developers of advanced PET systems.

2. METHODS

2.A. Experimental setup

Proof of concept of the proposed optical delay encoding and multiplexing technique for PET was performed with a custom coincidence fixture using two single pixel $3 \times 3 \text{ mm}^2$ Hamamatsu SiPMs (S10931-050P) coupled to Minicircuits preamplifiers (ZX60-4016E-S+). Experiments were repeated with LYSO crystals of two sizes: $3 \times 3 \times 5 \text{ mm}^3$ and the clinically relevant $3 \times 3 \times 20 \text{ mm}^3$, wrapped in Teflon tape and coupled to the SiPMs with optical grease. Optical waveforms were read out with a JDSU 1550 nm 10 Gb/s XFP ROSA PIN/TIA photodiode and preamplifier receiver, then digitized using an Agilent Infiniium DSO90254A 2.5 GHz 20 Gs/s digital sampling oscilloscope. Coincidence data were collected with a ^{22}Na point source. For calculating coincidence time resolution, an energy window of 2 full width at half maximum (FWHM) width centered on the photopeak mean was used.

2.B. Pulse encoding

Converting raw analog SiPM signals into a form appropriate for optical multiplexing entails multiple steps. Encoding of the timing and energy of SiPM pulses was implemented with a custom dual threshold time-over-threshold (ToT) circuit.¹⁵ The low threshold acts as a timing trigger, while the high threshold acts as a minimum energy gate. The dual threshold approach allows energy to be encoded as pulse width, while preserving fast timing information on the rising edge of the ToT pulse. Due to the nonlinear relationship between energy deposited in the detector and the width of the corresponding output pulse from the encoding stage, raw energy data must be corrected to generate accurate energy spectra. Energy correction for dual threshold ToT was applied using a previously described method,¹⁵ based on fitting raw data to the known photopeak locations of multiple isotopes.

The dual threshold ToT output is then encoded into essentially a bipolar return-to-zero signal. The dual threshold ToT circuit has complementary outputs of opposite polarity. A propagation delay of 60 ps relative to the positive output was introduced on the negative output with a short length of coaxial cable. The two outputs were added together using a resistive combiner (Minicircuits ZX10R-14+). The resistive combiner uses precise resistor values to match 50 Ω impedance between three ports, to split or couple power at high frequencies, without signal reflection or distortion. This results in fast (100 ps FWHM) positive and negative pulses at the respective rising and falling edges of the circuit's output signal (Fig. 1 bottom). The time between this pair of positive and negative pulses then corresponds to the original ToT pulse width, and encodes the energy of the event. Any events that cross the low threshold but fail to reach the high threshold set on the dual threshold ToT board will have a ToT value of 16 ns, and are discarded.¹⁵

These electronic voltage pulses are converted to optical pulses on single-mode optical fiber using integrated 10 Gb/s distributed feedback (DFB) lasers and electroabsorption (EA) modulator packages (EML) with power and thermal

Fig. 1. Optically encoded coincidence setup schematic. Connections to the left of “EML Laser/Modulator” are coaxial cable, connections to the right are optical fiber. Δt_n is the characteristic identifying delay in the pulse train for channel n and ToT_n is the corresponding time-over-threshold used for extracting event energy information. Electronic pulses from SiPMs are encoded with dual threshold ToT, converted to fast bipolar pulse trains, then converted to optical signals where channel ID is encoded with delays. Two optical pulse trains in a coincidence event overlap when the channels are coupled together, and all information is decoded after digitization.

regulation. Each of the two detector channels in this prototype modulates a dedicated EML. The laser sources are biased so that their output amplitude swings positive and negative around a baseline “zero” value, creating the two optical pulse polarities used for encoding. There are two lasers, one for each detector channel, operating at slightly different wavelengths near 1550 nm to prevent noise from destructive optical interference effects between the two channels. Detector channel ID is encoded by splitting each of these optical channels into two arms, introducing a relative delay between the arms that is unique to each channel, then recombining the arms back into a single fiber (Fig. 1). Input pulses to this optical encoding stage are essentially added to a delayed copy of themselves in order to produce an encoded pulse train. In this prototype, the two detector channels were encoded with identifying delays of 450 and 900 ps, achieved with fiber lengths of 9 and 18 cm, respectively. Fiber polarization controllers were placed on each arm of the split signals to prevent fluctuating signal levels as a result of random phase variations in the laser output, caused by thermal variations and mechanical vibrations. Polarization controllers take advantage of the birefringence effects in strained optical fiber to change the polarization state of light in the fiber. The polarization controllers on each arm were adjusted until amplitude fluctuations in the output signal were minimized. The two separate detector channel fibers were then combined with a fiber coupler, forming the single optical output channel for data acquisition from both detectors.

The final result of a scintillation pulse propagating through the full encoding stage for a single detector channel is a digitized optical pulse train of two fast positive pulses followed by two fast negative pulses, encoding the arrival time, energy, and detector channel of the interaction (Fig. 1 top). A given channel ID is encoded by a characteristic delay time between the two positive pulses. A coincidence event appears as two such pulse trains overlapping (Fig. 1 right and Fig. 2). Since the source was centered between the two detectors in this prototype, an additional delay (7.5 ns) was introduced between the two detector channels to prevent overlap of the initial positive pulses in a coincidence event. This delay was subtracted from the event timestamps during pulse processing.

2.C. Pulse decoding algorithm

Optical waveforms were digitized on the oscilloscope, then streamed over ethernet into a buffer on a data acquisition PC. Custom data processing code was implemented in C++, allowing fast decoding of waveform data as it is acquired. Figure 3 depicts the data acquisition and decoding algorithm. As waveform data is read into the buffer, the number of times the signal crosses the scope’s trigger level with a positive slope is counted. If the crossings number fewer than four (the number of positive pulses encoding a coincidence event), the waveform is discarded, thus filtering out single event triggers before more computationally intensive decoding takes place, and effectively increasing acquisition speed. Decoding channel ID, timing, and energy from fast pulse train waveforms in a coincidence event starts with finding the local extrema in the waveform. Only maxima and minima with amplitudes above a set fraction of the maximum signal amplitude are kept, compensating for baseline noise. These extrema correspond to the fast positive and negative pulses encoding event information. Fast pulse timestamps are stored as the time of the signal maximum (positive pulses) or minimum (negative

Fig. 2. Digitized optical waveform of an actual coincidence event from the optical delay encoding and multiplexing prototype. Pulse trains from the detector channels overlap when optically combined. Unique characteristic delays for distinguishing the two detector channels (the delay between pulse pairs) are 900 and 450 ps, encoded with fast 100 ps FWHM pulses. The entire coincidence pulse train is approximately 60 ns long, minimizing potential pileup in the case of high event rates.

FIG. 3. Simplified flow chart of pulse sorting and decoding algorithm for coincidence events. Several checks are performed on the digitized waveform data before coincidence events are accepted. The algorithm is implemented in C++ and runs on a PC using data streamed from a fast oscilloscope.

pulses), since this occurs at a fixed time relative to the SiPM signal crossing the low threshold of the dual threshold ToT circuit, preserving the fast timing information. The difference in positive peak timestamps is calculated sequentially for all peaks to determine which peak pairs correspond to a channel identifying delay value (450 and 900 ps in this prototype). This process is repeated for the negative peaks. If there are both positive and negative peak pairs corresponding to the same detector channel present, it is counted as an event identified on that channel. The event time is the timestamp of the first positive peak, and the ToT, which corresponds to event energy, is calculated as the difference in timestamps of the first positive and first negative peaks. If an event is identified on both detector channels, and both events have a ToT value above the minimum energy threshold, a coincidence event is recorded. The difference in the timestamps of the two events is written to disk along with the ToT values for both events, and the scope is set ready to trigger on the next event.

The algorithm shown in Fig. 3 could be modified to also process other types of events, such as triple coincidences with annihilation photons and a prompt gamma ray. This pulse encoding scheme is extremely flexible, since the information for every interaction is fully recoverable. Once the location, timing, and energy of each event have been decoded, any arbitrary coincidence logic can be executed.

3. RESULTS

3.A. Time resolution

Coincidence timing data were collected with $3 \times 3 \times 5$ and $3 \times 3 \times 20$ mm³ LYSO crystals. In the case of $3 \times 3 \times 5$ mm³ crystals, a coincidence time resolution of 160 ± 5 ps FWHM was observed (Fig. 4). For $3 \times 3 \times 20$ mm³ crystals, the time resolution was 271 ± 4 ps FWHM. Figure 5 shows time resolution as a function of high threshold value, with generally improving time resolution as the high threshold is increased. This is due to improved energy resolution and rejection of false coincidences from low energy events.¹⁵

A similar detector setup ($3 \times 3 \times 5$ mm³ LYSO with Hamamatsu SiPMs) using a standard electronic readout yielded a coincidence timing resolution of 147 ± 3 ps FWHM.¹⁶ In this case, scintillation pulses from the detectors were also digitized directly using the scope, and coincidence timing was determined using a low threshold on the signal leading edge. This result is comparable to the timing resolution of 160 ± 5 ps

FWHM obtained with the new optically encoded and multiplexed prototype. Of note is that this standard readout requires four scope channels for a coincidence measurement (each of the two detector channels is split for separate timing and energy pickoff), while the optically multiplexed readout requires only one scope channel to achieve similar results. This reduced number of readout channels is one of the main motivations for the optical delay encoding and multiplexing concept.

3.B. Energy resolution

In the case of $3 \times 3 \times 5$ mm³ crystals, an energy resolution of $13.1\% \pm 0.7\%$ FWHM at 511 keV was observed after correcting for ToT and LYSO nonlinearity (Fig. 6), and an energy resolution of $16.2\% \pm 0.9\%$ FWHM at 511 keV was achieved for $3 \times 3 \times 20$ mm³ crystals after linearity correction.¹⁵ Figure 7 shows energy resolution for high threshold sweeps from 300 to 700 mV (detector pulse amplitude is approximately 800 mV). Energy resolution improves due to greater signal dynamic range as the high threshold is increased.¹⁵

4. DISCUSSION

4.A. Performance

As previously shown,¹⁵ the coincidence time resolution achieved with electronic-only readout from the dual threshold

FIG. 4. Coincidence time resolution histogram for detector pair with optical encoding and multiplexing, $3 \times 3 \times 5$ mm³ LYSO, with 160 ps FWHM achieved.

FIG. 5. Coincidence time resolution at different dual threshold ToT high threshold values for optically encoded and multiplexed detector pair. Data shown for both $3 \times 3 \times 5$ and $3 \times 3 \times 20$ mm³ LYSO crystals.

ToT boards with no optical encoding was 154 ± 2 ps FWHM for $3 \times 3 \times 5$ mm³ LYSO crystals. The results presented here (160 ± 5 ps FWHM) indicate that the addition of optical delay encoding and multiplexing has very little effect on the time resolution of the prototype. A jitter of 3 ps has been measured on the leading edge of the fast optical encoding pulse when compared to an electronic reference pulse. This jitter is partially accountable for the minor timing degradation observed. A comparison of electronic-only and optically encoded and multiplexed dual threshold ToT readout coincidence time resolution at different high threshold values shows good agreement (Fig. 8).

In the electronic case, time resolution decreases monotonically as high threshold increases, whereas in the optically encoded case, this is not observed at all higher threshold values. This is the result of slight variations in measurement conditions across the various data collection trials, stemming from the relatively lower acquisition rate of the digitizing scope in the optically encoded case. Since data from the opti-

FIG. 6. ²²Na spectrum with optical encoding and multiplexing, $3 \times 3 \times 5$ mm³ LYSO. Top: uncorrected dual threshold ToT energy spectrum (raw data). Bottom: same energy spectrum after linearity correction (Ref. 15); this method achieves 13.1% FWHM energy resolution at 511 keV.

FIG. 7. Linearity corrected (Ref. 15) energy resolution measurements from a dual threshold ToT high threshold sweep from 300 to 700 mV, for both $3 \times 3 \times 5$ and $3 \times 3 \times 20$ mm³ LYSO in the optically encoded and multiplexed prototype. Below 300 mV, the low dynamic range of the ToT signal prevents successful energy linearization (Ref. 15).

cally encoded prototype are output on only a single channel, the scope is set to trigger on every waveform with a rising edge that crosses a certain threshold. The waveform is then streamed to the data acquisition PC and analyzed with the pulse sorting algorithm (Fig. 3) to determine if a coincidence has occurred. This method requires that every triggered waveform be processed, including single events and random coincidences. In contrast, the electronic-only readout setup uses two output channels, so the scope trigger logic can be set to ignore single-channel events and any two-channel events with large temporal separation. Events that are not coincidences are then effectively identified and discarded before further computationally intensive waveform analysis is performed, allowing for much faster data acquisition. As a result, performing a threshold sweep with the electronic-only setup takes on the order of hours, while the same set of acquisitions with the optically encoded and multiplexed prototype takes days. Ambient temperature was not regulated over the course of acquisitions, and optical grease coupling scintillators to SiPMs was reapplied between long measurements due to absorption

FIG. 8. Coincidence time resolution vs dual threshold ToT high threshold value for both a fully optically encoded and multiplexed detector pair ($3 \times 3 \times 5$ mm³ LYSO), and the same detector setup using electronic-only readout. Optical time resolution data from Fig. 5. Electronic-only (using dual threshold ToT, but no optical encoding) data from previous study (Ref. 15). The high threshold has been swept from 100 to 700 mV.

by the Teflon tape wrapping the crystals, leading to potential variability in photodetector performance and light collection efficiency across the long acquisition times required for large measurement sets. Indeed, while both the 5 and 20 mm long crystals follow the general trend of decreasing time resolution with increasing high threshold, they show different minor fluctuation patterns at the highest thresholds (≥ 500 mV in Fig. 5). This long acquisition time is due to the relatively slow waveform data digitization, transmission, and processing speed of this prototype scope and PC based data acquisition system, and is not inherent to the optical encoding and multiplexing technique.

There is also a trade-off between time resolution and event rate, as a lower timing threshold improves timing performance but is more likely to trigger the readout on dark counts and noise than a higher threshold. More noise triggers increase overall dead time and could decrease system sensitivity. To increase the true coincidence event rate to a practically useful level would require a dedicated data acquisition system based on a very fast free running ADC or TDC. FPGA-based TDC and ADC systems have been shown to achieve fast timing performance¹⁷ and are capable of a high throughput of millions of events per second.¹⁸ The digital sampling scope used in this prototype is capable only of acquiring on the order of hundreds of events per second, insufficient for a practical PET data acquisition system. Commercially available high performance ADCs, such as the Fujitsu 65 Gs/s CHAIS ADC with 8 bit resolution and 20 GHz bandwidth, can acquire data at high enough rates to continuously sample the waveforms of every event detected during a standard PET scan. Such high performance components are costly and impractical for a traditional system with many readout channels. Optical multiplexing has the potential to compress many detector channels into a single readout; so, the use of relatively few very high performance digitizers may be feasible in such a system.

The degradation in both timing and energy performance observed in the 20 mm long crystals as compared to the 5 mm long crystals is likely due to higher light loss and transit time variance along the greater crystal length.¹⁹ The optically encoded and multiplexed prototype nevertheless achieves fast timing results for both crystal lengths. Energy resolution in this prototype may be slightly degraded by the current implementation of the dual threshold ToT encoding method. The recorded interaction energy is entirely dependent on the falling edge of the detector output pulse¹⁵ and is therefore highly influenced by noise. Since dual threshold ToT uses separate signal paths for timing and energy information, filtering the energy path could reduce falling edge noise, thereby improving energy resolution without affecting timing performance.

4.B. Advanced decoding logic

The coincidence decoding logic implemented in this prototype does not decode events in which the actual pulses themselves overlap and impinge on each other (Fig. 9). Since the point source position was fixed and a delay was added between the detectors, pulse overlap was not possible in this prototype.

FIG. 9. Pulses from both events of a coincidence may overlap when signals are combined, resulting in a single broadened and/or higher amplitude pulse. Correct event information can still be decoded by using both the positive and negative pulses for improved channel identification for overlapping pulses. In this case, both delay lengths *A* and *B* are identified in the positive pulses, from the timestamp difference in the larger overlapped pulse and the smaller normal pulses. Both delays *A* and *B* are again identified in the negative pulses, allowing each to be fully decoded.

In a full system, overlap may occur in the initial pulses of two events due to annihilation occurring precisely halfway between the two detectors, or by random chance with any two photon pulses from separate events. There are several possible ways of addressing this situation, which would likely occur in a larger system with many detector channels and a nonpoint source. The system could be optimized to both reduce the occurrence of pulse overlaps and to successfully decode them. The simplest approach is to discard any events in which the pulses appear to overlap. This allows the decoding algorithm to be relatively fast and simple, but is not ideal since it sacrifices some system sensitivity. The decrease in sensitivity would depend on several factors, such as the event rate, the system geometry, the number of multiplexed channels, and the pulse width used for encoding. Optimizing delays in each detector channel before they are combined into the main output fiber can minimize the likelihood of overlap, eliminating any sensitivity loss. This is similar to the delay employed between detectors in the two channel prototype, but on a larger scale. For example, a delay of approximately 5 ns between channels on opposite sides of a whole body PET scanner would ensure that coincidences along this line of response will not produce pulse trains with overlapping initial pulses, regardless of the annihilation position (including at the field of view center). Since these delays are known for each channel and do not change, they can be subtracted from the timestamp during processing, or compensated for with a convex optimization method.²⁰ Delay optimization will not prevent pulse overlap in all cases, however, so more advanced logic must be implemented to successfully decode and avoid the need to discard these events.

Overlapping pulses will add in intensity, likely resulting in a broadened pulse with up to twice the amplitude of a single pulse (Fig. 9). Pulse width and height do not vary appreciably under normal conditions, so a major change in either of these characteristics in the output waveform could indicate overlapping. Based on the timestamps of any pulses before and after the overlap and the known possible channel identifying delays, the decoding algorithm could determine which pulses should be grouped together, thereby recovering all information from the original event pulse trains. For example, the positive and negative pulses contain the same channel identifying

information, so either set of pulses can be used for this purpose in the event that one set is compromised by pulse overlap.

The redundancy inherent to encoding with both positive and negative pulses (see Fig. 9) can also aid in decoding pulse trains in cases of degeneracy from multiple possible identifying delay values. Encoding detector channel identity with delays between two pulses gives three possible combinations of pulse pairings (Fig. 10 left). In a system with few channels, the characteristic channel delays can be spaced far enough apart that it is unlikely that more than one of the possible pulse pair combinations will result in acceptable delay values for both events. In a system with many channels, however, the characteristic delays will need to be more closely spaced (limited by data acquisition system jitter and sampling rate), leading to uncertainty as every pulse pair combination corresponds to possible characteristic delays. This degeneracy can be resolved by also determining the possible pair combinations encoded by the negative pulses, similarly to the proposed method of recovering pulse information in the event of overlap (Fig. 9). Due to the imperfect energy resolution of the encoding scheme, it is unlikely that two 511 keV events in coincidence will have precisely the same ToT value at the same time. Therefore, only one of the three possible combinations of negative pulse pairs (Fig. 10 right) will match with the possible positive pulse pairs, indicating the true detector channel identities.

The issue of delay value degeneracy could be avoided by encoding detector channel identity using three pulses rather than two (Fig. 11). Encoding with three pulses would require an extra delay stage with a precise delay, increasing the amount of hardware required for encoding. Increased splitting of the input signal would also reduce the signal-to-noise ratio (SNR) of the output signal.

FIG. 10. Degeneracy in possible pulse pair combinations in readout waveform. This can be resolved through comparison of possible combinations of both the positive and negative pulses, provided the two events do not have precisely the same ToT value. In the case shown here, slightly different ToT values cause the negative pulse pattern to differ from the positive pulse pattern. Delay values *C* and *D* are found in both the positive and negative pulse combinations, indicating that these delays correspond to the correct detector channels for this coincidence.

FIG. 11. Coincidence pulse train if each channel were encoded with a series of three pulses rather than two. Encoding in this way removes the potential degeneracy of the two pulse case, as there is only one combination of identifying delays for which there are two groups of three evenly spaced pulses, even in the case of an overlap in which both detector events have the exact same ToT value (the case shown here). Delay values *A* and *B* are both each found twice within the possible positive and negative pulse pair combinations, so they must correspond to the correct detector channels. Interaction timestamps and energy values can then be extracted.

4.C. Multiplexing potential

4.C.1. Optical multiplexing methods

Different wavelengths of lasers were used in this prototype to prevent signal degradation from interference effects when the two detector channels were combined onto a single output fiber. The lasers used in this prototype are available as part of a 16 channel wavelength-division multiplexing (WDM) system. In WDM, separate channels are encoded on different wavelengths that are all transmitted on a single fiber. The different wavelengths are separated at the receiving end and read out individually. This approach has previously been proposed for multiplexing high speed signals for nuclear physics instrumentation.²¹ The optical pulse encoding method demonstrated here is designed to function with a direct readout of overlapping pulse trains, as opposed to a WDM system in which the overlapping data must be separated by wavelength before being read out. Dense WDM systems capable of simultaneously encoding 160 channels at terabit data rates have been developed.²² The front end optical multiplexing hardware of such a system could be used to encode many PET detector channels on a single fiber, and it would not be necessary to separate the individual channels before readout, saving cost and complexity in the back end. Encoding with different wavelengths and the use of polarization controllers may be unnecessary in a system carefully designed to avoid interference effects. This may be achieved through precise control of optical phase and path length, as well as temperature and vibration stabilization. Liquid or air cooling systems commonly used in PET scanners would work well for overall thermal regulation in the system, and the laser sources could each have small thermoelectric coolers (TECs) to manage temperature, as the ones used in the prototype did. Other previously mentioned advanced optical multiplexing methods, including MDM, PDM, and SDM, introduce yet more ways of increasing data capacity.⁷⁻⁹

4.C.2. Photonic devices

Multiplexing fiber couplers are widely available, as they are frequently used in optical networking and telecommunication. Several high-capacity fiber couplers cascaded together can be used to reduce many individual output channels to one

single fiber. For example, four 4×1 fiber couplers cascaded into another 4×1 coupler will give a 16:1 multiplexing ratio. Microscopic photonic power couplers and nanophotonic delay devices could be combined such that much of the delay encoding and multiplexing aspect of this technology is achieved on compact photonic integrated circuits.^{23,24} This would have the advantage of miniaturizing the delay encoding hardware into extremely compact integrated devices that reduce system size and light loss from connections between many discrete components. Delays can also be controlled extremely precisely with advanced integrated photonics technologies, opening the possibility of encoding more detector channels with smaller differences between identifying delays. High speed WDM can also be implemented using photonic chip devices.²⁵ The potential compactness of an integrated optical encoding system coupled with the insensitivity of optics to electromagnetic interference suggests that this technology may also be useful for PET data acquisition in combined PET/MRI systems. In such a system, the PET detectors, as well as all of the optical encoding and multiplexing hardware, could be placed within the MRI bore with appropriate shielding. The encoded signals could then be transmitted out of the MRI room on optical fiber and read out by a data acquisition system installed in another room to avoid interference.

4.C.3. Channel identification

Incorrect channel identification becomes a concern as the number of multiplexed channels increases. As long as the channel identifying delay differences are well within the resolution of the digitizer, there is very little likelihood of incorrect assignment. For delay difference values near the timing jitter of the readout, the probability of correct or incorrect assignment is directly related to the readout timing resolution. For this reason, it is advisable to implement only delay differences that are well within the readout's performance specifications. Channel identification jitter (between the positive pulses) in the current prototype is <1 ps, since it is based on a physical fiber delay over a very short distance, which will not change unless there is significant vibration or other external effects on the fiber, and the scope used for readout is extremely accurate. These effects therefore would not contribute to channel assignment error in a system with more channels unless the differences in delays used are <1 ps.

The number of channels that can be encoded onto a single fiber also depends in part on the baseline noise in each of the channels. Noise sources such as laser relative intensity noise (RIN) on each optical channel will sum together with optical multiplexing, effectively raising the noise floor of the signal on the combined optical channel. Only one or two signal pulses occur together at a given time, but the summed baseline noise of every channel is always present. More channels multiplexed onto a single output leads to higher noise floor and reduced SNR, degrading the ability to precisely identify signal pulses, and preventing effective pulse decoding. The SNR of pulses in the combined optical channel should ideally be as high as possible, making it vital to both maximize pulse amplitude and minimize the noise contribution from each channel when

a high multiplexing ratio is used. Cross talk in the usual sense of coupling between electronic traces should not be an issue with an optical implementation due to the lack of electrical parasitics in optical fiber. Each of the lasers used in this prototype has a maximum optical power of approximately 1.5 mW. Even if several laser channels in a scaled-up system are pulsing at the same time, the light intensity will be insufficient to cause any appreciable nonlinear phase or polarization effects, as the nonlinear refractive index of fused silica fiber is small, at approximately 3×10^{-16} cm²/W.²⁶

4.C.4. Nested multiplexing

Although the optical encoding and multiplexing method has been demonstrated here with 1:1 coupling of detector element and encoding channel, it could also be applied on top of other multiplexing methods. Schemes such as Anger logic or cross strip multiplexing are often used to reduce the number of readout channels in position sensitive or highly pixelated detector arrays.^{1,27,32} The pulses output from these analog multiplexing methods could be further multiplexed onto a single fiber using optical pulse train encoding. For example, dozens or hundreds of pixels in a detector array could be electrically connected using Anger logic, resulting in four outputs. This might be the extent of the multiplexing in a typical PET system. However, each of those four Anger logic outputs could be optically encoded and multiplexed onto the same fiber, along with the outputs from other detector arrays. Applying the pulse train decoding algorithm to these encoded signals would result in recovery of the channel ID, timing, and width of the pulses from the first layer of multiplexing, to be further decoded with the corresponding Anger logic. Data encoding schemes that already use pulse width could be further multiplexed using fast optical pulses.^{5,28} In these schemes, pulse widths are used to encode position or energy information. Although they can be multiplexed onto a single signal line, the pulses cannot overlap, limiting event rate. Converting these "slow" electronic pulse trains to fast optical pulse trains that can overlap would allow a higher multiplexing ratio and event rate. As the fast optical pulse encoding method could completely recover the original multiplexed signals in a nested scheme, there is no need for the scintillation crystals and photodetectors to be 1:1 coupled. Any existing light sharing method could be used, including monolithic crystals, and arrays with more crystals than detector pixels. Another approach to multiplexing uses spatially varying sensitivity encoding.²⁹ This is accomplished through custom photodetector devices, the electronic outputs of which could be further multiplexed using fast optical pulse encoding. Optical encoding and multiplexing in the form demonstrated in this work is not, however, applicable to photodetector devices that use on-chip readout electronics to digitize interaction information.^{30,31}

4.C.5. Acquisition rate

The digitizing scope used to acquire data for this prototype samples waveforms at 50 ps intervals, and the combined

optical stage and scope shows a maximum timing jitter of approximately 20 ps. With these performance parameters, unique identifying channel delays could theoretically be implemented in 50 ps increments, corresponding to about 1 cm of fiber delay added to successive channels. Assuming a pulse width of 100 ps and a maximum identifying delay value of 50.05 ns in the system, a total of 1000 channels can be uniquely encoded on a single fiber output. Pulse train durations are at most approximately 100 ns, and the encoding pulses are fast enough to allow decoding of overlapped events. This upper limit will vary in practice according to encoding pulse width, ADC sampling rate and jitter, optical SNR, light loss, and optical interference effects, but serves to illustrate the large multiplexing ratio that may be possible with this technology.

High single event rates or a scanner with many thousands of detector channels without additional multiplexing may require different hardware configurations to avoid significant pileup and data acquisition system saturation. For example, a clinical scanner with 30 000 individually read out detector elements would require 30 high performance optical readout channels, each supporting a single event rate of approximately 10 Mcps given the above pulse width and delay values. If a total single event rate higher than 300 Mcps is required for high sensitivity or high activity imaging, there are several options. The fast encoding pulse width could be decreased, potentially allowing more successfully decodable pulse train overlap. A modified ToT circuit could give shorter pulse trains to reduce the likelihood of overlap. Additional high performance optical readout and digitizer channels could be added, proportionally increasing the maximum event rate. These digitizer channels could output event data packets, to be transmitted and processed in a modular daisy chain data acquisition configuration.¹⁸ In practice, 1:1 coupling would likely not be used in a system of this size, reducing the number of optical channels and readouts required.

5. CONCLUSION

Optical encoding and multiplexing of PET detector signals has been shown to be feasible for fast timing in PET. A custom dual threshold ToT circuit coupled to commercially available optical components has achieved fast timing performance with both 5 mm and clinically relevant 20 mm length LYSO scintillation crystals coupled to SiPMs. Timing, energy, and position information for multiple detector channels can be simultaneously transmitted on a single fiber without sacrificing performance, and decoded by a single high performance digitizer channel. This technology has the potential to greatly simplify the data acquisition requirements for ToF capable PET systems with many detector elements, without degrading performance.

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