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Analog electro-optical readout of SiPMs achieves fast timing required for time-of-flight PET/MR

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Abstract

The design of combined positron emission tomography/magnetic resonance (PET/MR) systems presents a number of challenges to engineers, as it forces the PET system to acquire data in space constrained environment that is sensitive to electro-magnetic interference and contains high static, radio frequency (RF) and gradient fields. In this work we validate fast timing performance of a PET scintillation detector using a potentially very compact, very low power, and MR compatible readout method in which analog silicon photomultipliers (SiPM) signals are transmitted optically away from the MR bore with little or even no additional readout electronics. This analog ‘electro-optical’ method could reduce the entire PET readout in the MR bore to two compact, low power components (SiPMs and lasers). Our experiments show fast timing performance from analog electro-optical readout with and without pre-amplification. With $3\text{mm} \times 3\text{mm} \times 20\text{mm}$ lutetium-yttrium oxyorthosilicate (LYSO) crystals and Excelitas SiPMs the best two-sided fwhm coincident timing resolution achieved was $220 \pm 3\text{ps}$ in electrical mode, $230 \pm 2\text{ps}$ in electro-optical with preamp mode, and $253 \pm 2\text{ps}$ in electro-optical without preamp mode. Timing measurements were also performed with Hamamatsu SiPMs and $3\text{mm} \times 3\text{mm} \times 5\text{mm}$ crystals. In the future the timing degradation seen can be further reduced with lower laser noise or improvements SiPM rise time or gain.

1. Introduction

The aim of this work is to demonstrate time-of-flight (ToF) capable performance from analog electro-optical readout of SiPMs (Olcott et al. 2009). Such a system would allow silicon photomultipliers (SiPM) signals to be transmitted tens of meters before readout with minimal electronics, while preserving their fast timing information. Transmitting SiPM signals tens of meters before readout could be attractive for positron emission tomography/magnetic resonance (PET/MR) systems because it would allow for a PET system with

minimal components inside the MR-bore, and with the PET ring electrically floating with respect to the MR system.

The design of PET/MR systems presents many engineering challenges. MR systems are often space constrained, have large static, radio frequency (RF) and gradient fields, and are sensitive to any interference to these fields. In order to build a PET/MR system the PET system will have to deal with this harsh environment. Ideally the PET system would be compact, have very little ferrous metal to maintain static B field uniformity of the MR system, minimize the amount of electronics inside the MR bore to prevent interference, and shield any electronics that do remain in the bore all while preserving the PET system's timing, energy and position resolution.

Figure 1 shows three approaches to PET/MR systems. The first PET/MR systems used an optical readout where scintillation light was transmitted directly from the MR bore by optical fibers or light guides (Shao et al. 1997). This 'optical' approach had good MR compatibility as it used no electronics or metal components inside the sensitive region of the MR bore. However, light loss and dispersion degraded the PET performance (Wehrl et al. 2009). With the development of solid state detectors like APDs and SiPMs that may be operated within the MR bore, scintillation signals were converted to electrical signals and transmitted out of the MR bore. This 'electrical' approach has achieved good PET performance, and has been used to make a number of PET/MR systems (Hong et al. 2013) (Pichler et al. 2006) (Wehrl et al. 2009). Electrical readout is not without its challenges. Having SiPMs driving long electrical cables can lead to timing degradation (Kim et al. 2011), numerous shielded cables leaving the MR bore can be quite bulky, and electronics inside the MR bore will need to be shielded and perhaps cooled. While these challenges have been successfully dealt with, it begs the question whether there may be another approach to signal transmission for PET/MR.

In the 'electro-optical' readout approach scintillation light is first converted to an electrical signal, then back into an optical signal by a laser for transmission out of the MR bore (Olcott et al. 2009). This type of readout has the advantage of using a fiber-optic which is highly compact, MR compatible, high bandwidth, low amplitude dispersion, and low temporal dispersion. Electro-optical readout systems can leverage optical communication components, which are becoming increasingly low power, compact, and integrated with electronic systems. In addition, it does not require an electrical connection, facilitating the creation of an RF penetrable PET insert (Lee et al. 2013).

Electro-optical readouts can take several forms. Some examples are seen in Figure 2. In digital electro-optical readout the analog PET signals are digitized before optical transmission. This can be done in more traditional ways such as having digitizers like analog to digital converters in the MR bore to send bits over the optical link, or with pulse width modulation, or time-over-threshold type methods where a digital pulse is sent over the optical link. Digital methods have been shown to achieve very fast timing performance (Bieniosek et al. 2013). They also allow for high levels of multiplexing to reduce the number of optical links. They may require a large amount of electronics inside the MR bore though less so with pulse width modulation methods.

To reduce the amount of electronics in the MR bore analog electro-optical readout can be used. In analog electro-optical readout the analog scintillation pulse is sent directly over the optical link with or without amplification. This paper explores the time resolution performance of analog electro-optical readout schemes, and for the first time demonstrates fast timing performance for ToF with analog electro-optical readout.

2. Methods

To test the timing resolution of analog electro-optical readout we first obtained an appropriate laser for signal transmission. For our readout we needed a laser that could be compact, low power, and coupled to fiber optics for medium range transmission. For this we chose a vertical-cavity surface-emitting laser (VCSEL). VCSELs are semiconductor laser diodes commonly used for optical communications that can be made very compactly through semiconductor processes, with very low threshold currents, and at ideal wavelengths for fiber-optic communication. For these experiments we use multi-mode 850nm HFE4192-58X VCSELs (Finisar, Sunnyvale, USA), which is designed for 4.25 Gbps communication. The VCSEL was characterized as seen in Fig 3. A bias current of 1.7 mA was chosen to minimize noise, and power dissipation (2.8 mW) while surpassing the laser threshold current.

After optical transmission the SiPM signal must be converted back into an electrical signal for data acquisition. Two receivers were tested for use in our experiments, a HFD3180-203 GaAs photo-receiver (Finisar, Sunnyvale, USA) and a 1621 silicon photo-diode (New Focus, Santa Clara, USA). The response of each of these photodetectors can be seen in Figure 4. The New Focus receiver has a gain of 0.55A/W, rise time of 1ns, and saturation power of 5mW. The Finisar receiver has a built in trans-impedance amplifier, giving a total gain of 2500 V/W, its rise time is 80 ps, and its saturation power is 60uW. The New Focus receiver shows a response shape similar to the electrical input, but does not have the gain and bandwidth needed for fast timing measurements. The Finisar receiver has a built in trans-impedance amplifier that saturates before the peak of the scintillation pulse, however it does have enough gain and bandwidth for fast timing measurements. As a result the Finisar receiver was used for timing experiments. However, because the Finisar receiver saturates, and the scintillation signal could not be attenuated without sacrificing timing resolution, the energy information was obtained separately. It is important to note that the New Focus results show that energy information can be obtained from electro-optical readout. This has also been shown in previous works (Olcott et al. 2009). With the proper receiver both timing and energy resolution measurements can be made with the same electro-optical setup.

Three readout modes were used (see Fig 5). A purely electrical readout mode was used as a gold standard. Analog electro-optical readout was tested in two modes, one with a Minicircuits ZX60-4016E+ 4GHz preamplifier, and one without. In each electro-optical mode the SiPM signal with or without amplification was sent to a passive 90/10 splitter. 90% of the signal was sent to the VCSEL and transmitted over a 10m long LC/LC multimode 62.5um fiber-optic patch cable for timing information. The other 10% was sent directly to the Agilent 2.5 GHz 20GSa/s DSO90254A oscilloscope for energy information. Event energies were determined by measuring the SiPM pulse waveform maximum

magnitudes. All timing spectra are energy windowed with all events within one fwhm of the 511 keV photo-peak accepted. Timing waveforms were digitized, and timing pickoff was determined by leading edge threshold where thresholds were measured with respect to the signal baseline (Vinke et al. 2009). Two identical detectors and readouts were used to take time resolution measurements in response to Na-22 point sources in each readout mode, with 3mm × 3mm × 5mm lutetium-yttrium oxyorthosilicate (LYSO) crystals and 3mm × 3mm × 20mm LYSO crystals. 3mm × 3mm C30742-33-50-C (Excelitas, Waltham, USA) and S12572-50 (Hamamatsu, Hamamatsu, Japan) SiPMs were used (see Table 1 for SiPM properties). All experiments were performed at room temperature with no thermal regulation.

3. Results

Single SiPM cell dark counts were observed with no crystal on the SiPM. Figure 6 shows the single cell responses for each readout mode with the Excelitas SiPM. A clear single cell pulse can be seen with the electrical and electro-optical with pre-amp readout modes. Without the pre-amp the single cell response is still visible, but the noise of the laser and receiver is quite significant compared to the single cell pulse. The Hamamatsu device had a single cell maximum amplitude 3.75 times smaller than the Excelitas device at the optimal bias voltage for timing performance (see Figure 7). Thus noise was more significant compared to the amplitude of the pulses for the Hamamatsu signals.

The results of the timing experiments are seen in Figures 8 and 9. The timing resolution at optimal leading edge threshold (with one sigma fitting errors) achieved with Excelitas SiPMs and 3mm × 3mm × 5mm crystals was 147ps +/- 1ps in electrical mode, 148ps +/- 2ps in electro-optical with preamp mode, and 182 +/- 2ps in electro-optical without preamp mode. With 3mm × 3mm × 20mm crystals and Excelitas SiPMs the timing achieved at optimal leading edge threshold was 220 +/- 3ps in electrical mode, 230 +/- 2ps in electro-optical with preamp mode, and 253 +/- 2ps in electro-optical without preamp mode. The timing resolution achieved at optimal leading edge threshold with Hamamatsu SiPMs and 3mm × 3mm × 5mm crystals was 145ps +/- 2ps in electrical mode, 155ps +/- 3ps in electro-optical with preamp mode, and 225 +/- 2ps in electro-optical without preamp mode. With 3mm × 3mm × 20mm crystals and Hamamatsu SiPMs the timing achieved at optimal leading edge threshold was 175 +/- 1ps in electrical mode, 191 +/- 2ps in electro-optical with preamp mode, and 260 +/- 3ps in electro-optical without preamp mode.

Finally to confirm our timing measurement methods a timing spectrum was taken with two point sources separated by 46mm. The expected difference in time from a 46mm separation is 306.7ps, given by the speed of light. The observed timing spectrum is seen in Figure 10. Both sources are clearly separated with 302 +/- 2ps difference in mean (error bar is one sigma fitting error). The measured time difference is quite close to the expected difference (306.7ps), with slight deviations due to position and alignment uncertainties.

4. Discussion

The electro-optical readout modes were able to achieve excellent timing performance with some degradation due to the noise of the laser and optical receiver. Pre-amplification largely

mitigated the timing degradation (see Figures 8 and 9). The Excelitas SiPMs showed worse timing performance than the Hamamatsu SiPMs in electrical readout mode due to lower photon detection efficiency, and worse single photon timing resolution (see Table 1). However, the Excelitas SiPMs showed much lower timing degradation compared to the gold standard electrical readout in electro-optical without pre-amp mode. Excelitas SiPMs had a 15% degradation with 20mm length crystals and 24% with 5mm length crystals compared to 49% and 55% with Hamamatsu SiPMs.

The low degradation for pre-amplified and Excelitas electro-optical readouts suggests that signals with higher slope are less effected by the analog electro-optical readout (see Figure 7 for Excelitas vs Hamamatsu slope). The effect on timing resolution of adding an independent noise source (like a laser) was expected to be highly dependent on signal slope. For example, with simple linear ramp, jitter from a fixed noise source in a leading edge discriminator timing system is inversely proportional to slope ($\text{slope} = \Delta V / \Delta T$, therefore for a noise ΔV , the jitter, $\Delta T = \Delta V / \text{slope}$). In the future, degradations in timing resolution in electro-optical without pre-amp mode may be minimized by using a laser or receiver with less noise or by using an SiPM with a higher single cell amplitude and slope to make the slope larger in comparison to the noise.

As technology progresses optical systems are also becoming increasingly compact and low power to meet the demands of modern communications systems. Semiconductor lasers are currently available in very dense packages (12 optical I/Os on a $7.8\text{mm} \times 8.2\text{mm}$ package are available on the AFBR-77D1SZ MicroPod (Avago, San Jose, USA) for example), and VCSEL laser thresholds of $<100\mu\text{A}$ have been demonstrated (Michalzik et al. 2003). Researchers are also developing high bandwidth, low power optical communication networks for integration on silicon CMOS (Matsuo et al. 2011). This suggests that very low power, very compact lasers and fiber-optics are available and could be used to build a whole-body ToF electro-optically coupled PET system.

5. Conclusions

This work shows that fast SiPM timing information for PET can be preserved after analog electro-optical signal transmission. In the future this readout strategy could drastically simplify the design of high performance ToF PET/MR systems by reducing the in-bore electronics to as little two active components (SiPMs and VCSELs). With modern semiconductor fabrication techniques and the increasing integration of optics into electrical systems both of these components could be extremely compact and low power, reducing PET's in-bore footprint, power consumption, and mutual interference with the MR system.

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References

- Bieniosek M, Olcott P, Levin CS. Readout strategy of an electro-optical coupled PET detector for time-of-flight PET/MRI. *Physics in Medicine and Biology*. 2013; 58(No 20):7227. [PubMed: 24061218]
- KJ, Choi Y, Jung JH, K J, Hu W, Lim HK, Huh Y, Kim S, Jung JW, Kim KB. A prototype MR insertable brain PET using tileable GAPD arrays. *Med Phys*. 2013; 40(No 4)
- Kim KB, Choi Y, Kang J, Jung JH, Hu W. A Pulse Restoration Circuit Minimizing Performance Degradation of PET Detector Caused by Using Long Cable. *IEEE*. 2011 NSS/MIC MIC12.M-127.
- Lee BJ, Olcott PD, Hong KJ, Grant AM, Chang CM, Levin CS. Studies of Electromagnetic Interference of PET Detector Insert for Simultaneous PET/MRI. *IEEE*. 2013 NSS/MIC M06-8.
- Michalzik R, Ebeling KJ. *Operating Principles of VCSELs*. Springer Series in Photonics. 2003; 6:53–98.
- Matsuo S, Shinya A, Chen CH, Nozaki K, Sato T, Kawaguchi Y, Taniyama H, Notomi M. 20-Gbit/s directly modulated photonic crystal nanocavity laser with ultra-low power consumption. *Optics Express*. 2011; 19(No 3)
- Olcott P, Peng H, Levin CS. Novel Electro-Optical Coupling Technique for Magnetic Resonance-Compatible Position Emission Tomography Detectors. *Molecular Imaging*. 2009; 8(No 2):74–86. [PubMed: 19397853]
- Pichler BJ, Judenhofer MS, Catana C, Walton JH, Kneilling M, Nutt RE, Siegel SB, Claussen CD, Cherry S. Performance Test of an LSO-APD Detector in a 7-T MRI Scanner for Simultaneous PET/MRI. *J Nucl Med*. 2006; 47:639–647. [PubMed: 16595498]
- Shao Y, Cherry S, Farahani K, Meadors K, Siegel S, Silverman R, Marsden P. Simultaneous PET and MR imaging. *Phys Med Biol*. 1997; 42
- Vinke R, et al. Optimization of digital time pickoff methods for LaBr3-SiPM TOF-PET detectors. *Nuclear Science Symposium Conference Record (NSS/MIC)*, 2009 IEEE. :2962–2968. Oct. 24 2009-Nov. 1 2009.
- Wehrl HF, Judenhofer MS, Wiehr S, Pichler BJ. Pre-clinical PET/MR: technological advances and new perspectives in biomedical research. *Eur J Nucl Med Mol Imaging*. 2009; 36(Suppl 1):S56–S68. [PubMed: 19194703]

Figure 1. Three approaches to PET readout proposed for PET/MR systems. Optical readout directly transmits scintillation photons, electrical readout converts scintillation light to an electrical signal, and electro-optical readout converts scintillation photons to an electrical signal then back to an optical signal for transmission out of the MR bore.

Figure 2. Different electro-optical PET approaches. Digital approaches convert the signal to bits or a digital pulse (where the rising edge contains the timing information and the pulse width contains the energy information) before optical transmission. Analog approaches (the subject of this work) directly send the analog scintillation pulses optically.

Figure 3.

Characterization of the HFE4192-58X VCSEL. Its current rises exponentially with voltage (left). After the laser threshold current is surpassed, it's optical power (middle) and output noise levels (right) rise linearly with current. To optimize SNR a laser bias just above the VCSEL's threshold (1.7mA) was chosen.

Figure 4.

Two optical receiver waveforms in response to 511keV scintillation signals are shown in comparison to the electrical signal (top). The New Focus receiver (bottom left) shows a full scintillation waveform, but does not have the bandwidth or gain necessary to make fast timing measurements. The Finisar receiver (bottom right) has a built in trans-impedance amplifier that saturates before the signal peak, but does enable fast timing measurements.

Figure 5. Simplified schematics for the three data acquisition modes used in our experiments. In electrical mode an amplified SiPM signal was sent directly to a high speed oscilloscope for timing pickoff. In electro-optical modes 10% of the analog SiPM signal (with or without amplification) was sent directly to the oscilloscope to for energy information. The other 90% was sent to the electro-optical link for timing pick-off.

Figure 6. Excelitas single cell waveforms as seen by the three readout modes. The single cell pulse is seen in all the readout modes, but is degraded by noise in electro-optical without pre-amp mode.

Figure 7. Dark current waveforms of Excelitas (left) and Hamamatsu (middle) SiPMs at the optimal bias voltage for timing performance. The discrete levels in the waveforms correspond to discrete numbers of single cell pulses. The difference between one and two single cell pulse peak magnitudes is $\sim 16.5\text{mV}$ for Excelitas SiPMs, and $\sim 4.4\text{mV}$ for Hamamatsu SiPMs. The single cell comparison (right) shows the higher magnitude and slope of the an Excelitas single cell pulses compared to Hamamatsu single cell pulse.

Figure 8. Excelitas fwhm timing resolutions for each readout mode with $3\text{mm} \times 3\text{mm} \times 5\text{mm}$ and $3\text{mm} \times 3\text{mm} \times 20\text{mm}$ LYSO crystals at threshold voltage levels normalized to the amplitude of a single cell pulse for each readout mode. The electro-optical readout degraded timing, but still maintained excellent performance.

Figure 9. Hamamatsu fwhm timing resolutions for each readout mode with $3\text{mm} \times 3\text{mm} \times 5\text{mm}$ and $3\text{mm} \times 3\text{mm} \times 20\text{mm}$ LYSO crystals at threshold voltage levels normalized to the amplitude of a single cell pulse for each readout mode. The electro-optical readout degraded timing, but still maintained excellent performance.

Figure 10.

Timing spectrum of a two source simultaneous acquisition with $3\text{mm} \times 3\text{mm} \times 5\text{mm}$ crystals in electro-optical without pre-amp mode and Excelitas SiPMs. The two sources can be clearly seen in the timing spectrum and are separated by 302 ± 2 ps, quite close to the expected 306.7ps. All error bars are 1 sigma fitting errors.

Table 1

Vendor reported typical timing performance parameters for the SiPMs used at data sheet recommended conditions.

	Property			
	PDE @ 420nm	Gain	Dark Count Rate	Single photon timing resolution
Excelitas C30742-33-50-C	30%	1.5e6	1.0 Mcps	300 ps
Hamamatsu S12572-50	35%	1.25e6	1.35 Mcps	250 ps