

# An Application-Specific Integrated Circuit for Positron Emission Tomography

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**Abstract**—Improving the performance of positron-emission tomography (PET) systems for small animal imaging requires the use of high-speed detectors, such as a Lutetium Oxyorthosilicate (LSO) crystal coupled to avalanche photodiodes (APDs). We have developed an application-specific integrated circuit (ASIC) for reading out the multiple channels of an LSO-APD detector module for use in a small animal PET system.

In this work, we characterize the performance of the ASIC, referred to as the AE172 chip. The AE172 can accommodate both positive and negative input signals, with a programmable conversion gain that ranges from 2.8 mV/fC to 21 mV/fC. The ASIC channels exhibit a linear response and an equivalent noise charge (ENC) of  $\sim 2000$  electrons, RMS. The timing jitter depends on the amplitude of the input signal; and is less than 1 ns for test signals greater than 100,000 electrons.

Connecting the ASIC to a linear APD detector reduces the relative readout noise to 26 electrons referenced to the input of the APD, which is operated at a gain of  $\sim 200$ . An LSO-APD-ASIC detector achieves an energy resolution of 13% for the 511 keV annihilation photons from a  $^{22}\text{Na}$  source, and a coincident timing resolution of  $\sim 13$  ns.

## I. INTRODUCTION

POSITRON Emission Tomography provides images that probe the function of organs by detecting coincident events emitted from radioactively labeled molecular probes. The image quality of a PET instrument depends on the timing performance of the detectors, as well as the ability to determine the 3-dimensional location of an event in the detector using the depth-of-interaction (DOI), especially in small animal PET systems. The use of large arrays of small detectors, such as LSO coupled to an APD, improves the spatial resolution while minimizing the overall detector size for small animal PET systems.

APDs have lower gain than photomultiplier tubes and thus produce smaller pulses. Therefore, the APD signals require amplification and conditioning before digitization by an analog-to-digital converter. Since the system will require many hundreds or even thousands of detectors, an application-

specific integrated circuit (ASIC) is needed to provide a compact platform for processing the many signals with individual charge-sensitive preamplifiers (CSPs), and pulse shapers for each detector element. In addition, the ASIC must provide a fast trigger signal for timing the coincident events.

In concert with other efforts to develop an ASIC for LSO-APD-based PET detectors [1-9], we are developing an ASIC as part of a small animal PET system. Some of the unique features of our ASIC include the ability to process signals of either positive or negative polarity, an on-chip, “winner-take-all” multiplexer, and an input for processing the coincident trigger from other detectors. In this presentation, we describe the ASIC and present the preliminary characterization of its performance.

## II. PROPOSED SMALL ANIMAL PET SYSTEM

Fig. 1 shows an illustration of the proposed small animal PET system, which consists of the following components: segmented LSO scintillation crystals, avalanche photodiode detectors, the ASIC, the data acquisition unit, and the personal computer.

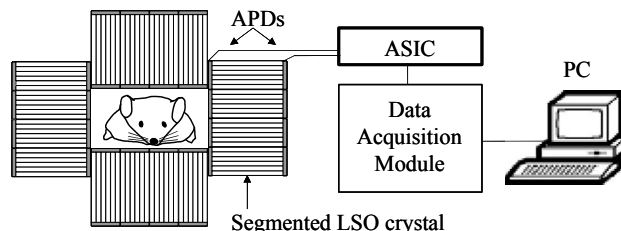


Fig. 1. Illustration of the proposed small animal PET system. The detector modules, comprised of segmented LSO scintillation crystals coupled to APDs, surround the subject of interest. The ASIC reads the signals from the APDs and generates a coincident timing pulse. The data acquisition module digitizes the signals from the ASIC.

In the proposed system, 4 detector modules surround the subject animal, e.g., a mouse. Each detector module consists of a segmented LSO scintillation crystal coupled to a detector at each end. The ratio of the signals from the APD detectors at each end determines the interaction depth of the event in the LSO crystal. The ASIC amplifies the signals from the APD detectors, and provides a fast trigger pulse for coincident processing by the data acquisition module. The ASIC also holds the peak of the signal from APDs for subsequent digitization by the data acquisition module.

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### III. ASIC CHIP

The ASIC chip provides 16-input channels for connecting to the APD detectors. Fig. 2 shows a photograph of the ASIC chip, which is designated as the AE172 chip.

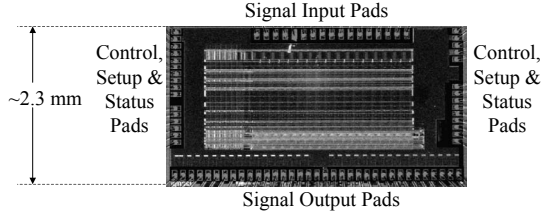


Fig. 2. Photograph of the AE 172 ASIC for the LSO-APD detector module. The chip is 4.1 mm by 2.3 mm. Signal from the detector modules enters the chip through the 16 pads at the top of the photograph. The pads on the side of the chip accept signals for programming various operating conditions of the ASIC. The 32 pads at the bottom of the chip carry the analog output signals from the detector, which consists of a slow, peak-held signal and a fast trigger signal for each channel.

The following stages perform the signal conditioning on the ASIC chip: a charge sensitive preamplifier at the input, a slow pulse shaper, a fast pulse shaper, a fast comparator for generating the coincident trigger pulse, a peak hold circuit, and an on chip multiplexer. Fig. 3 shows the functional components of the chip.

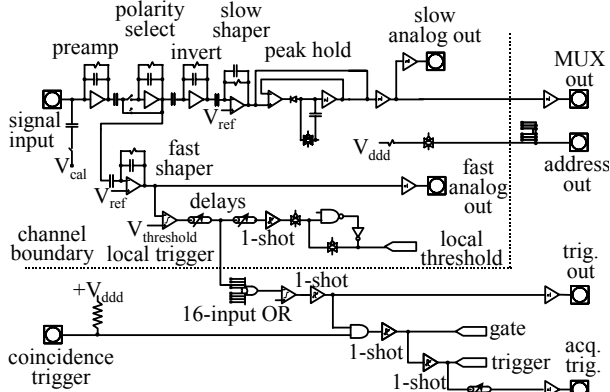


Fig. 3. Block diagram of the circuit components contained on the ASIC chip. The chip is designed to process coincident signals from an APD array in a PET detector module. The channel boundary defines the parts of the chip that are replicated for each channel, which generates the 16 signal input pads, 16 slow analog output pads and 16 fast analog output pads. The slow analog output signals can also be multiplexed when the peak hold is active.

The state of the chip, which includes the preamplifier gain, various thresholds, shaping times, and trimmings, is fully programmable through a 308-bit shift register. Either a parallel port, or the digital signal from a Keithley data acquisition card, provides a conduit for the ASIC program to set-up the operating state of the ASIC chip.

### IV. ASIC CHARACTERIZATION MEASUREMENTS

The initial characterization of the ASIC was performed with electrical pulses, from a pulse generator, injected into the ASIC through a 200 fF capacitor. Fig. 4 shows the conversion gain for the ASIC at the highest and lowest gain settings.

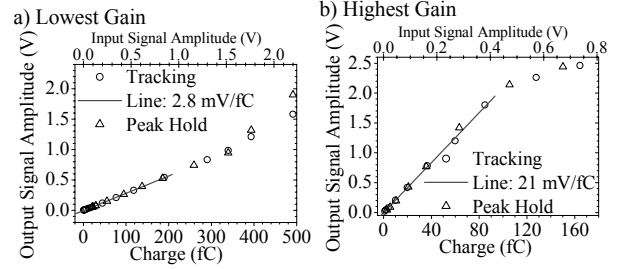


Fig. 4. a) Plot of the output signal as a function of the input signal for the lowest gain setting. The conversion gain, which is recovered from a linear fit of the data, for this gain setting is 2.8 mV/fC. b) Plot of the output signal as a function of the input signal for the highest gain setting. The conversion gain for this gain setting is 21 mV/fC.

Fig. 5 a) shows the measurement of the noise when the ASIC is operated at its maximum gain, with no external connection to the input pad. The signal is coupled to the ASIC input through an on-chip 200-fF capacitor.

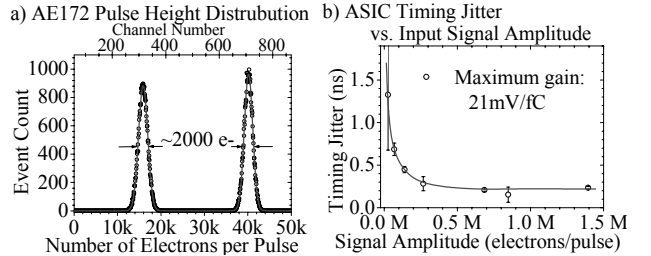


Fig. 5. a) Plot of the output signal as a function of the input signal for the lowest gain setting. The conversion gain, which is recovered from a linear fit of the data, for this gain setting is 2.8 mV/fC. b) Plot of the output signal as a function of the input signal for the highest gain setting. The conversion gain for this gain setting is 21 mV/fC.

From Fig. 5 a), we see that the input noise of the ASIC is  $\sim 2000$  electrons RMS. Fig. 5 b) shows a plot of the timing jitter as a function of the signal amplitude at the input. For the signals anticipated from an LSO-APD detector module for a 511 keV event ( $>0.1$  million electrons), the expected timing jitter introduced by the ASIC is less than 1 ns.

### V. DETECTOR CHARACTERIZATION MEASUREMENTS

The initial characterization of the ASIC-APD detector unit was performed with a 16-element linear APD array connected to the input of the ASIC readout unit. The size of each element in the APD array is 2 mm  $\times$  4 mm. The ASIC readout unit is connected to a Keithley data acquisition card (DAS 1800 series) in a personal computer. Fig. 6 shows the energy spectra, for the 16-elements in the linear APD array, of 5.9 keV x-rays from  $^{55}\text{Fe}$  measured with the APD-ASIC detector system.

An event in any pixel of the 16-element detector generates a trigger that invokes the peak hold and digitization of the signals on all of the 16 channels. Therefore, the noise peak, near zero, is sampled 16 times more than the iron signal, which produces a relatively large peak. For a 16-element linear array, it would be better to record the signal from the multiplexed output, however, we were interested in testing the

individual channel outputs for use with a position-sensitive APD.

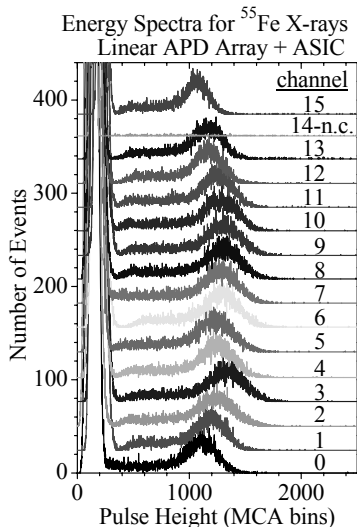


Fig. 6. The energy spectra of 5.9 keV x-rays from an  $^{55}\text{Fe}$  source measured with a 16-element linear APD array connected to the ASIC. The x-rays illuminated the APD detector array in a flood field. Pixel number 14 on the APD array was disconnected from the applied bias.

For the measurement plotted in Fig. 6, the bias applied to the APD array is approximately 1700 V, and the gain of the APD is  $\sim 200$ . When a calibrated charge pulse is applied to the ASIC while connected to the APD detector, we measure a contribution of 26 noise electrons,  $\sigma$ , from the ASIC, referenced to the input signal, on channel 14, which does not contain a contribution from the dark current of the APD detector. On channel 8, which contains the contribution from the dark current of the APD detector, we measure a noise contribution of 130 noise electrons,  $\sigma$ , relative to the input signal. The width,  $\sigma$ , of a pulsed LED signal, which contains contributions from the gain noise and dark noise, is 290 input electrons.

To characterize the performance of the ASIC for PET applications, we assemble an LSO-APD-ASIC detector unit. The LSO crystal measures 3 mm  $\times$  4 mm, by 20 mm in length. We coupled the 3 mm  $\times$  4 mm face of the LSO crystal to an 8 mm  $\times$  8 mm position sensitive APD (PSAPD). We connect the signal from the cathode (top contact) of the PSAPD to a single input channel of the ASIC, and measure the energy spectrum and coincidence timing resolution plotted in Fig. 7, a) and b), respectively.

For the measurement plotted in Fig. 7 a), an external MCA records the analog output from the ASIC because the readout software is in the process of being developed. The measurement shows that the LSO-APD-ASIC detector achieves an energy resolution of 13% for the 511 keV peak from a  $^{22}\text{Na}$  source.

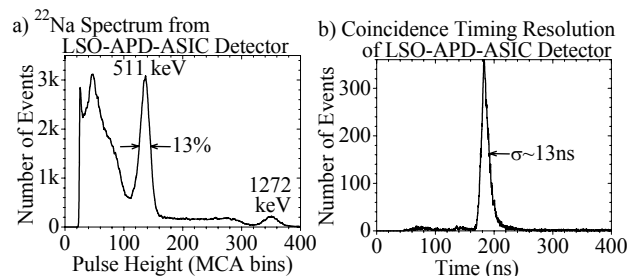


Fig. 7. a) The energy spectrum recorded with the LSO-APD-ASIC detector exposed to a  $^{22}\text{Na}$  source. The size of the LSO crystal is 3 mm  $\times$  4 mm  $\times$  20 mm and it is coupled to an 8 mm  $\times$  8 mm position-sensitive APD. b) The coincidence timing resolution of the LSO-APD-ASIC detector. An LSO crystal coupled to a PMT supplied the start signal for the coincidence timing measurement.

For the coincidence timing measurement, plotted in Fig. 7 b), the signal from the PMT detector is connected to a constant-fraction discriminator, then connected to a time-to-amplitude converter to provide the start pulse. The timing signal from the ASIC is also connected to a constant-fraction discriminator before providing the stop signal for the time-to-amplitude converter. An external MCA records the output from the time-to-amplitude converter. The measurement shows that the LSO-APD-ASIC detector achieves a coincidence timing resolution of  $\sim 13$  ns.

## VI. DISCUSSION AND CONCLUSION

The noise performance, of 2000 e- RMS, for the AE 172 ASIC is comparable to that exhibited by other designs for APD-LSO-based PET systems [3, 6-8, 10]. By coupling the ASIC to an APD detector, which has internal gain, the readout noise from the ASIC is divided by the gain of the detector when referencing the noise relative to the input signal. In this case, the contribution of the ASIC noise becomes negligible relative to the dark and gain noise of the APD, and distribution of light collection from the scintillation crystal. The noise performance of the ASIC is suitable for APD arrays in applications where DOI measurements and the division of the charge by the PSAPD detector reduce the total signal.

The timing jitter introduced by the ASIC is minimal, however, the time walk will limit the coincident timing resolution. The timing walk refers to the dependence of the delay in the fast timing signal on the amplitude of the event pulse. We expect the time walk to be similar to that observed by Visser *et al.* [6].

In this work, we describe the design and performance of an ASIC that conditions the signals from LSO-APD detector modules for a small animal PET system. The noise performance is suitable for APD arrays with 2 mm  $\times$  2 mm pixels, coupled to segmented LSO scintillation crystals. The effect of the timing walk on the coincident timing resolution needs further investigation to determine whether a constant-fraction discriminator should be added to the ASIC design.

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