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Development of a multiplexed readout with high position resolution for positron emission tomography

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ABSTRACT

Detector signals for positron emission tomography (PET) are commonly multiplexed to reduce the number of digital processing channels so that the system can remain cost effective while also maintaining imaging performance. In this work, a multiplexed readout combining Anger position estimation algorithm and position decoder circuit (PDC) was developed to reduce the number of readout channels by a factor of 24, 96-to-4. The data acquisition module consisted of a TDC (50 ps resolution), 4-channel ADCs (12 bit, 105 MHz sampling rate), 2 GB SDRAM and USB3.0. The performance of the multiplexed readout was assessed with a high-resolution PET detector block composed of 2×3 detector modules, each consisting of an 8×8 array of 1.52×1.52×6 mm^3 LYSO, a 4×4 array of 3×3 mm^2 silicon photomultiplier (SiPM) and 13.4×13.4 mm^2 light guide with 0.7 mm thickness. The acquired flood histogram showed that all 384 crystals could be resolved. The average energy resolution at 511 keV was 13.7 ± 1.6% full-width-at-half-maximum (FWHM) and the peak-to-valley ratios of the flood histogram on the horizontal and vertical lines were 18.8 ± 0.8 and 22.8 ± 1.3, respectively. The coincidence resolving time of a pair of detector blocks was 6.2 ns FWHM. The reconstructed phantom image showed that rods down to a diameter of 1.6 mm could be resolved. The results of this study indicate that the multiplexed readout would be useful in developing a PET with a spatial resolution less than the pixel size of the photosensor, such as a SiPM array.

1. Introduction

Advances in positron emission tomography (PET) to obtain higher resolution and sensitivity require the use of a large number of small detectors, which leads to an increase in both complexity and cost when developing a PET system [1,2]. Therefore, it is important to develop a multiplexing circuit, that can effectively reduce the number of digital processing channels to achieve a simple and cost effective design while maintaining imaging performance.

A resistive charge division circuit uses a simple resistor network to multiplex detector signals, and it has been extensively used because it effectively reduces the number of channels of a detector to four analog signals containing energy and position information [3–7]. However, it has a limitation in its non-linear position estimation at the corners of the detector due to the presence of noise and inadequate light spread. Furthermore, the high capacitance of the silicon photomultiplier (SiPM) channels leads to a degradation in the timing performance of the detector.

A position decoder circuit (PDC) has also been used to multiplex detector signals, and it is implemented with one-to-one coupling between the scintillator pixel and the pixelated photosensor channel, such as a SiPM [8–11]. The PDC has the capacity to output the digital address and the analog pulse of the channel with the signal from many detector outputs. However, the PDC only allows one-to-one crystal-sensor coupling, which limits the spatial resolution to less than the photosensor channel size.

In this study, we have developed a multiplexed readout with high position resolution for PET combining Anger position estimation algorithm and PDC. The goal was to develop the multiplexed readout with a high multiplexing ratio while maintaining the accuracy of the position estimation over the entire field of view (FOV) and to evaluate the performance of the multiplexed readout by measuring the flood histogram, peak-to-valley ratio, energy resolution, timing resolution and hot-rod phantom image.

2. Materials and methods

2.1. Configuration of the PET detector

A PET detector block was composed of 2×3 detector modules, each

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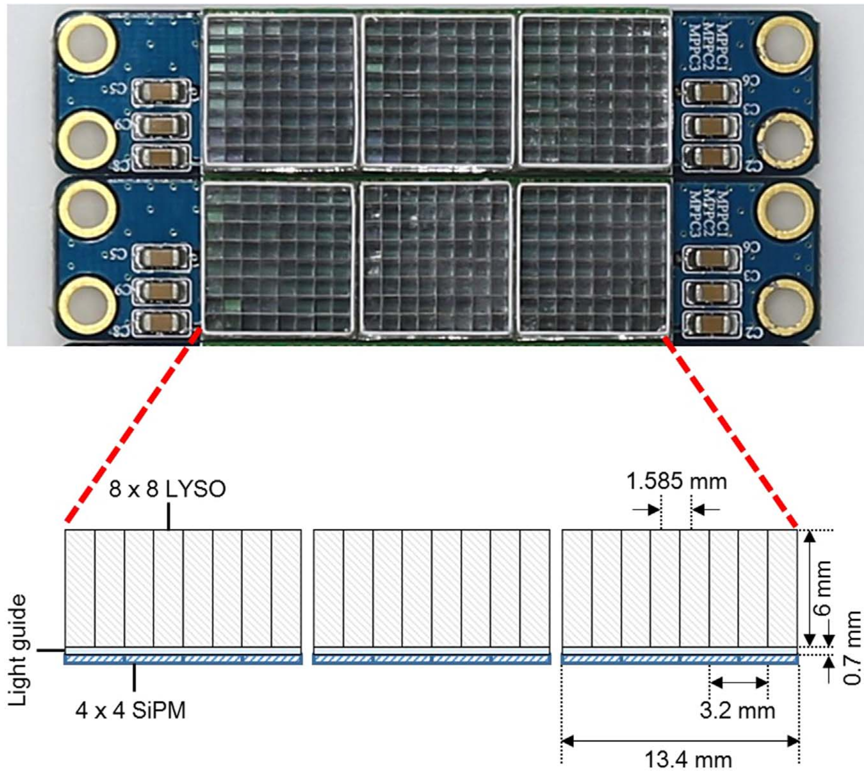

Fig. 1. A detector block composed of 6 SiPMs and 6 arrays of LYSO on a custom-made PCB (top) and its side view (bottom).

of which consisted of an 8×8 array of 1.52×1.52×6 mm^3 Lutetium Yttrium Orthosilicate (LYSO, Crystal Photonics, Inc., USA) and a 4×4 array of 3×3 mm^2 SiPM (S11828–3344 M, Hamamatsu, Japan), as shown in Fig. 1. Each crystal was optically separated using an enhanced spectral reflector film (ESR, 3 M, USA) with a 65 µm thickness. A light guide with 0.7 mm thickness was placed between the LYSO array and the SiPM optically coupled with silicone adhesive (3145 RTV, Dow Corning, USA). The 2×2 LYSO array was matched to one channel of the SiPM. The 3 SiPM arrays were mounted to a custom-made printed circuit board (PCB) that included 3 flexible flat cable connectors to transmit 48 analog signals of 3 SiPMs and to supply the operating voltage.

2.2. Principle of multiplexed readout for PET

A multiplexed readout was developed by combining the position decoder circuit (PDC) [9] and Anger position estimation algorithm (Anger) [4] to reduce the number of readout channels by a factor of 24, 96-to-4. The method of identifying the fastest signal used in PDC was applied to distinguish the coarse position of a gamma interaction among the entire groups in the detector block. Then, Anger was used to calculate the fine position inside a group using 4 SiPM channels. In this study, the multiplexed readout consisted of 24 detector boards mounted on a main board and DAQ module.

The 96 channels of 6 SiPMs were grouped into the 24 groups of the detector boards as G_1, G_2, ..., G_{24}, according to the scheme shown in Fig. 2. The four signals of each SiPM group A_i, B_i, C_i and D_i, i=1, 2, ..., 24, were fed into the first preamplifiers, which had 80 MHz bandwidth and < 4 mW power consumption per channel, of each detector board and the amplified signals were then split into two signals, as shown in Figs. 3 and 4. One signal was fed into the summing amplifier, a high-speed operational amplifier (op-amp) with 1.5 GHz bandwidth and 4100 V/µs of slew rate, and subsequently to the comparator for the time and coarse position information. A summing amplifier and a comparator with a high-speed and wide bandwidth were used to reduce the timing jitter to obtain accurate time information. The other signal was fed into the second preamplifier and was utilized to estimate the energy and the fine position information.

A field programmable gate array (FPGA) mounted on the main board was used to identify the group in which the gamma ray has interacted among the 24 groups (Fig. 4) [8]. From the output signals of the comparators of the 24 detector boards, the FPGA identified the group with the fastest signal. Then, the FPGA generated the address for the coarse location by identifying the group number of the detector block and transmitted the enabling signal to turn on the analog switch of the identified detector board to pass the selected analog pulses to data acquisition module (DAQ), as shown in Fig. 3.

2.3. Data acquisition module (DAQ)

The signals detected by the FPGA on the main board were transmitted to a custom-made DAQ consisting of a TDC, 4-channel ADCs, 2 GB SDRAM and USB3.0, as shown in Fig. 3. A 200 MS/s flash ADC was used to implement the TDC with an intrinsic timing resolution of 50 ps. A 4-channel 12-bit 105 MHz ADC was employed to obtain the energy and fine position information. The timing signal and 4-channel analog signals were digitized by TDC and 4-channel ADCs. The time mark and each maximum value of the digitized 4-channel analog pulses were processed during the prescribed processing time ranging from 10 ns to 2 µs. The DAQ was operated according to the corresponding parameters controlled by host PC, including the offset calibration, input delay, processing time and acquisition mode.

The energy was estimated by summing all of the digitized ADC peak values and the X, Y fine position were calculated as follows [4]:

$$X = \frac{B + D}{A + B + C + D}$$

$$Y = \frac{A + B}{A + B + C + D}$$

where A, B, C, and D are the digitized 4-channel ADC's peak values of analog signals with a group selected by FPGA.