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Development of a Prototype Detector Using APD-Arrays Coupled With Pixelized Ce:GAGG Scintillator for High Resolution Radiation Imaging

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***Abstract*—A novel digital PET scanner based on Time over Threshold method is developed. The positron emission tomography (PET) is composed of 144channel Ce:$Gd_3Al_2Ga_3O_{12}$ (GAGG)-Avaranche photodiode (APD) detector arrays individually coupled with custom designed Time over Threshold (ToT) application-specific integrated circuit (ASIC) to realize the high count rate and good spatial resolution. Such an imaging system provides a simple front-end circuit and flexible digital signal processing like multiplexing such as a pulse train method. The measured energy resolution of the detector system was 6.7% for the 511 keV peak, and 4.25 ns time resolution was measured with a single detector module. The measured spatial resolution for a point source was 1.37 mm FWHM for our initial data with a columnar ^{22}Na source.**

***Index Terms*—Avalanche photodiode (APD), positron emission tomography (PET), scintillator.**

I. Introduction

SCINTILLTORS coupled with Si based photodiode have been widely used in many applications, such as high energy physics, astrophysics, and medical imaging. Recently, demands for a gamma camera detecting gamma-rays from ^{131}I, ^{134}Cs, ^{137}Cs, etc., have been increasing after the accidents in the Fukushima Daiichi nuclear power plant. In these applications, scintillators require such properties as good energy resolution, high stopping power, high light yield, and fast decay. In addition, positron emission tomography (PET) is a very effective tool to analyze the distribution of target molecules and plays an important role in small-animal molecular imaging. The precise imaging of radio-labeled tracers is necessary for biological research to reveal the function of a biological system. Therefore, many PET scanners have been designed and developed for animal PET systems and the theoretical limit of spatial resolution may be within reference [1]–[12]. Also, some PET scanners are developed using the individual readout method to achieve both high count rate capability and better spatial resolution. However, the individual readout system introduces complex and power-consuming front-end signal processing hardware, such as analog-to-digital converters (ADCs) for the energy measurement and time-to-digital converters (TDC) for the timing measurement [13]. Recently, digital signal processing using a Field Programmable Gate Array (FPGA) has become a very powerful technology.

Thus, matching between the emission wavelength of scintillators and sensitive wavelengths of Avaranche photodiode (APD) is also very important. Recently, $\mathrm{Ce{:}Gd_3Al_2Ga_3O_{12}}$ (Ce:GAGG) has attracted attention because of its interesting properties, such as Ce^{3+} 5d-4f emission peaking at 520 nm, high density (6.63 g/cm^3), high light output (around 48,000 photon/MeV), fast decay time (88 ns), very low level of natural radioactivity, and good energy resolution of 4.8%@662 keV [14]–[18]. In this paper, we demonstrate the performance of a prototype detector using a 12×12 channel APD-array coupling with Ce:GAGG array. Three 48-channel front-end application-specific integrated circuit (ASIC) boards are inserted into the APD-array and motherboard with the FPGA digital processing circuit. The assembled detector modules with 144-channel gamma-ray detector were developed. Performance of the detector and position mapping results using coincidence mode were examined.

II. Detectors and Electronics

A. Scintillatior Arrays and APD-arrays

A 50 mm diameter boule of Ce1%:GAGG was grown by the Czochralski (Cz) method and $2 \times 2 \times 5$ mm^3 size sample

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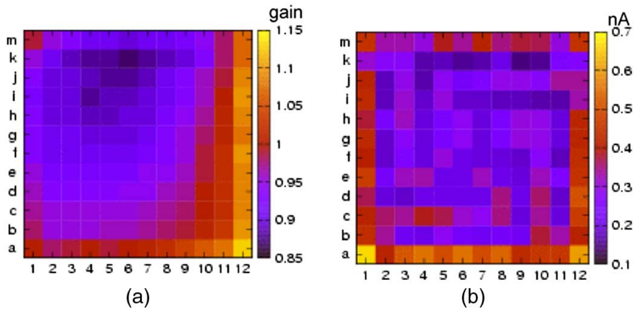

Fig. 1. (a) Gain uniformity and (b) dark current distributions of the APDarray, operated at a gain of 100.

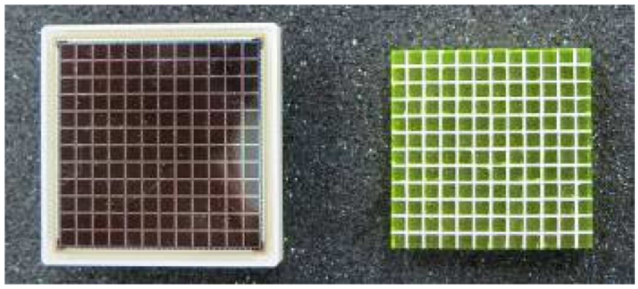

Fig. 2. Pictures of a 12×12 APD array (left) and 12×12 Ce:GAGG matrix (right).

pieces were cut and polished in Furukawa Co. Ltd. The sample showed 50,000 photon/MeV and energy resolution of 5.6% at 662 keV by the $2 \times 2 \times 5$ mm^3 size sample using a APD S8664-55 (Hamamatsu). The APD-array described here was designed with the technology of S8664 APD series (reverse-type). The APD-array has a 12×12 pixel structure with an active area of 2.05×2.05 mm^2 per pixel and a 0.25 mm gap between the pixels. The APD-array allows stable operation at a gain around 100, with extremely low dark noise (less than 1.81 nA/pixel) for each pixel, even at room temperature ($+18^\circ\mathrm{C}$). An avalanche gain of 100 is achieved with bias voltage of 388 V. Gain uniformity and dark current distribution of the APD-array operated at a gain of 100 are shown in Fig. 1. Note the excellent uniformity of avalanche gain (left) with low leakage current distributions (right). Gain fluctuation was characterized by direct irradiation on each APD pixels using $^{55}\mathrm{Fe}$ x-ray source and the gain fluctuation is only $\pm 8\%$ over the APD device.

Finally, a prototype gamma-ray camera consisting of the APD-array optically coupled with a Ce:GAGG matrix was fabricated. Fig. 2 shows pictures of the 12×12 Ce:GAGG matrix and APD array, where each pixel is $2 \times 2 \times 5$ mm^3 in size and divided with a reflective $\mathrm{BaSO_4}$ layer of 0.25 mm thickness. The performance of the Ce:GAGG matrix was tested by taking the energy spectrum of a $^{137}\mathrm{Cs}$ source. The APD signals were fed into a preamplifier (Clear Pulse 581 K) and a shaping amplifier (ORTEC 570; shaping time 2 μs), and finally digitized with a multichannel analyzer (Amptek MCA8000A). We operated the APD-arrays under bias voltages of 330 V. All the data were taken at $+18^\circ\mathrm{C}$. Fig. 3 shows an example of an energy spectrum obtained with a single pixel in the APD-Ce:GAGG matrix for the $^{137}\mathrm{Cs}$ source. The energy resolution of the 662 keV gamma-rays is 5.9% (FWHM). The variation of energy resolution and signal amplitude (due to inhomogeneities of APD gain and Ce:GAGG light yield) was only $\pm 1.6\%$ and 33%, respectively (Fig. 3).

B. Readout Electronics

Readout electronics consist of three custom-designed Time over Threshold (ToT) based ASICs, and all outputs from the ASIC are connected to a Cyclone II FPGA, which enables flexible digital signal processing and multiplexing. The analog and digital circuits are integrated in this chip and a window-type multi-level threshold discriminator was implemented using a digital encoder. The ToT pulse is generated when the signal is between the lower level discriminator (LLD) and upper level discriminator (ULD). The digital circuit generates two pulses with widths after the first ToT trigger pulse (see Fig. 5). The readout chip includes 48-channel ToT function to produce both the timing information and the energy information in a binary readout channel, and each channel consists of a charge-sensitive preamplifier and a leading-edge-type discriminator. The individual threshold of the chip is controlled by 12-bit off-chip threshold-controlling DACs [19]. The DACs, an AC coupling RC network, and the ASICs are mounted on a 3×6 cm^2 front-end board (see Fig. 6). The range of the threshold adjustment equals 0.8 mV. The gain of a charge-sensitive preamplifier is designed to be 5 V/pC and the measured noise level was $\sim$1,200 electrons FWHM. The noise level was satisfactory for both timing and energy resolutions. The typical duration of ToT digital output is from 100 to 400 ns, which matches with the simulation results. The threshold variation in the designed ASIC was within 160 mV and can be adjusted with 12-bit DACs.

C. Detector Module

Fig. 7 shows the energy resolution for 511 keV gamma-rays from a Na^{22} source measured using ToT digital output. The pulse duration of ToT is measured using a Cyclone III based FPGA with a 250 MHz clock. It shows clear 511 keV and 1.28 MeV photo-peaks, and an energy resolution of 6.7% (FWHM) @ 511 keV that is good enough for gamma-camera, SPECT and PET detector.

Fig. 8 shows a readout system for our gamma-ray detector system. All 144 channels of a GAGG-APD detector are individually connected to the channels of a ToT ASIC. In the ToT ASIC, a charge-sensitive preamplifier converts a charge signal to a voltage signal, and the ToT circuit with a discriminator converts it into a digital pulse with some duration. All the ToT outputs are connected to an Altera Cyclone II FPGA. The FPGA integrates the ToT outputs and multiplexes them to send to the Data Acquisition System (DAQ). The FPGA board also communicates with the threshold-controlling DACs.

Fig. 9 shows the coincidence time resolution for 511 keV annihilation gamma rays from $^{22}\mathrm{Na}$ source using two opposing detector modules. The measured time resolution is 6 ns FWHM for coincidence without energy window. The time resolution for one detector module is calculated to be 4.2 ns. Time resolution is measured with a HRMTime TCSPC module (from SensL Co.). This result is well within the operating specification of our

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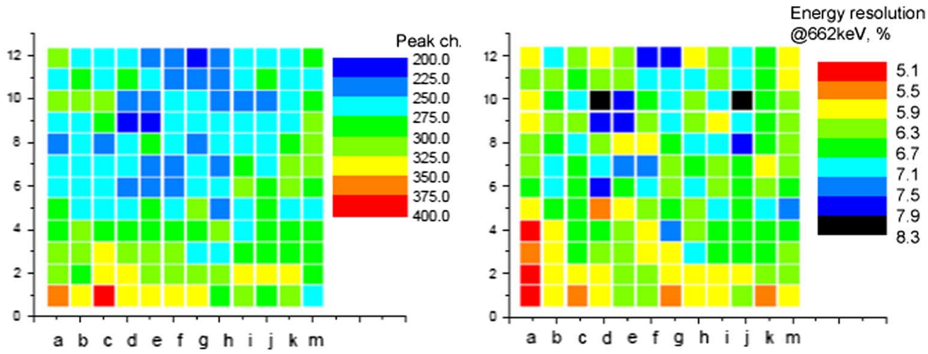

Fig. 3. The variation of energy resolution and signal amplitude in the APD-Ce:GAGG matrix for the ^{137}Cs source.

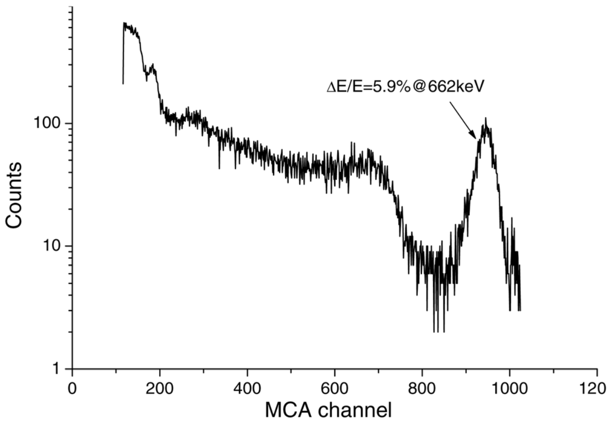

Fig. 4. Example of an energy spectrum obtained with a single pixel in the APD-Ce:GAGG matrix for the ^{137}Cs source.

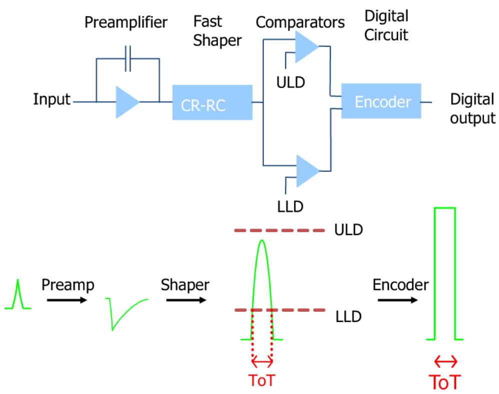

Fig. 5. Schematic drawing of ToT based signal processing method.

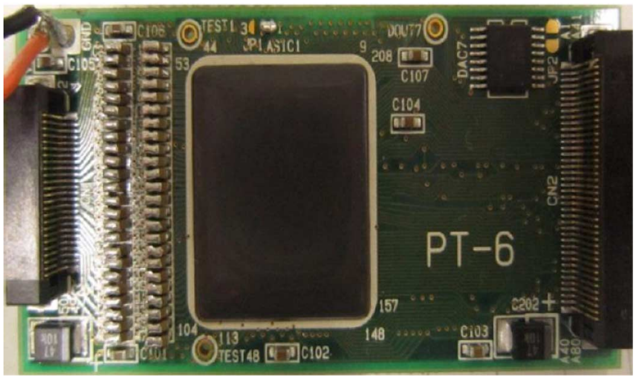

Fig. 6. Front-end ASIC board for the gamma detector.

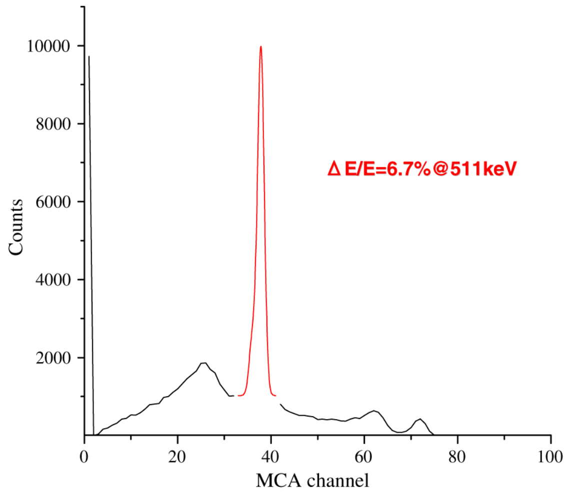

Fig. 7. Energy resolution for 511 keV gamma rays from Na^{22} source measured with ToT output by Altera Cyclone III FPGA.

animal system $\sim$ 20 ns timing window. The threshold of each channel can be optimized with 12-bit off-chip DACs controlled by an FPGA board.

D. Image Reconstruction

The dual-headed PET system is built with two gamma-ray detector modules to form a detector ring (Fig. 10) and the detector modules are covered and fixed with an aluminum-based solid frame. A simple X and Y wired OR logic is used to reduce the number of transmission lines from 144 to 24, which are then read out by a DAQ. Five percent of the pixels are not working because of damage to the channel of the front-end ASIC or APD pixels. The energy spectra of all the channels are shown in Fig. 11.

The detector ring size is designed to be 72.5 mm (crystal to crystal). The FOV has a diameter of 25 mm by axial direction of 25 mm. We have measured a point source of ^{22}Na and successfully reconstructed an image with ML-EM reconstruction

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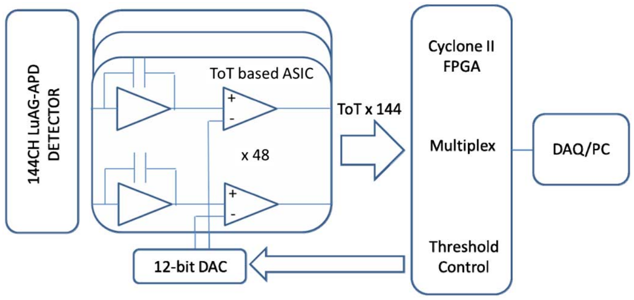

Fig. 8. Overall layout of the readout system for the imaging system module. The 144-channel LuAG-APD detector is individually connected to the ToT based ASIC. The FPGA handles and multiplexes the digitized data and controls off-chip 12-bit DACs.

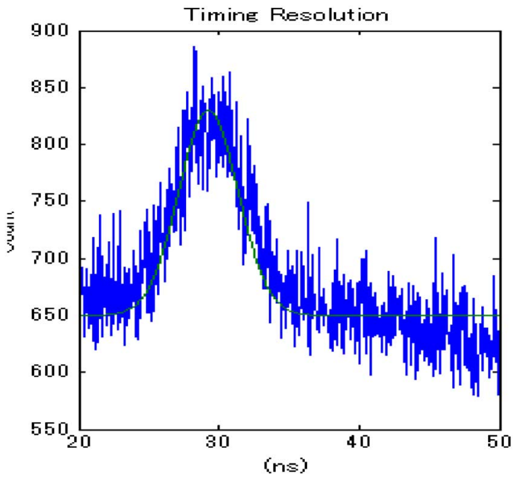

Fig. 9. Time resolution for 511 keV annihilation gamma-rays measured with two coincidence modules.

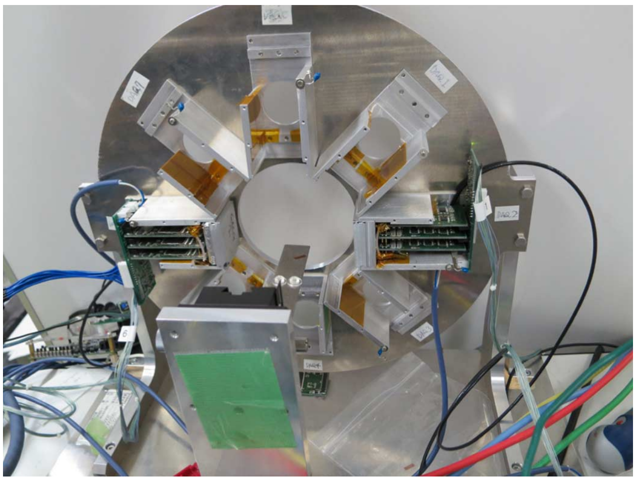

Fig. 10. The PET system with two detector modules.

algorithm. Fig. 12 shows the image of the reconstructed point source. The measured spatial resolution is 1.37 mm FWHM.

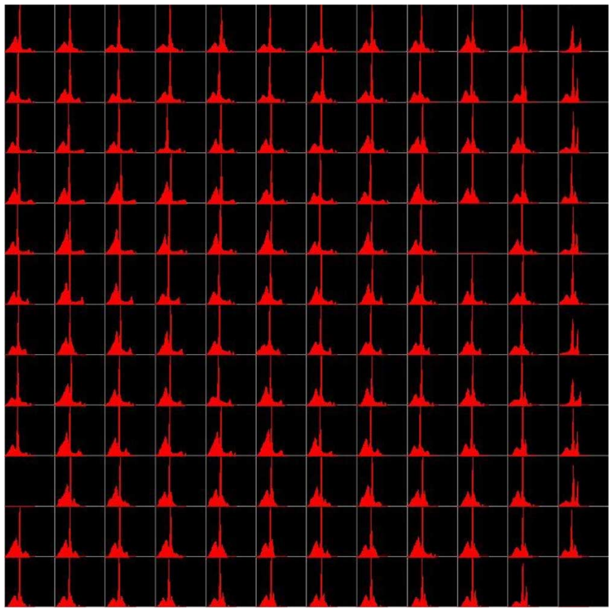

Fig. 11. Measured energy spectra of 144 channels in one detector module.

Fig. 12. Reconstructed image of a point source of $^{22}\mathrm{Na}$.

III. Conclusion

A novel digital PET scanner based on the Time over Threshold (ToT) method has been developed. The PET is composed of 144-channel GAGG-APD detector arrays and individually coupled custom-designed ToT ASICs to realize high count rate and good spatial resolution. Such an imaging system provides a simple front-end circuit and flexible digital signal processing like multiplexing such as a pulse train method. The measured energy resolution of the detector system was 6.7% for the 511 keV peak, and 4.25 ns time resolution was measured with a single detector module. The measured spatial resolution for a point source was 1.37 mm FWHM for our initial data with a columnar $^{22}\mathrm{Na}$ source. We think our imaging system with fully custom ASICs will be a useful tools for molecular imaging with high flexibility. These results suggest that the detector using APD and Ce:GAGG arrays are promising devices not only for PET but also SPECT and gamma-camera applications. In addition, demands for ^{137}Cs hot-spot imaging using a gamma-camera has increased in Japan after the accidents in the Fukushima Daiichi nuclear power plant, and we intend to test our detector for such a purpose as well.

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