

A Dual-Ended Readout Detector Using a Meantime Method for SiPM TOF-DOI PET

Han Gyu Kang, Guen Bae Ko, June Tak Rhee, Kyeong Min Kim, Jae Sung Lee, and Seong Jong Hong

Abstract—We have investigated a dual-ended readout detector based on two silicon photo-multipliers (SiPMs) using a 30 mm long cerium-doped lutetium-yttrium oxyorthosilicate ($\text{Lu}_{0.5}\text{Y}_{1.4}\text{Si}_{0.5}$: Ce, LYSO) crystal to study the feasibility of a time-of-flight (TOF) and depth-of-interaction (DOI) positron emission tomography (PET). To improve the timing resolution in the dual-ended readout detector, a novel meantime measurement was employed. The meantime was obtained by averaging two signal arrival times at two SiPMs, each of which was attached to both ends of the LYSO crystal. The meantime method minimizes the arrival time difference along the crystal. Both timing and DOI resolutions using the meantime method were better than those of a single-ended readout detector.

Index Terms—Depth of interaction (DOI), dual-ended readout, meantime method, positron emission tomography (PET), silicon photomultiplier (SiPM), time-of-flight (TOF).

I. INTRODUCTION

A TOF scanner has several advantages over a conventional non TOF-PET scanner, such as a higher signal-to-noise ratio (SNR) in reconstructed images and reduced absorbed doses for patients [1], [2], [3].

A DOI PET also improves the spatial resolution in PET systems of which the ring diameter must be small (e.g. breast and brain dedicated PETs) [4], [5]. The length of a scintillating crystal has a tradeoff relationship between sensitivity and time resolution [6]. A long scintillating crystal improves the sensitivity, but it deteriorates the time walk effect which results in an adverse effect on the time resolution. In addition, the photon

arrival time difference along the crystal is large, which in turn also deteriorates the time resolution [7]. The long scintillating crystal increases the parallax error in both radial and axial directions of the PET scanner. The parallax error can be corrected by using DOI information, which is the estimated position of an annihilation photon interacting with the scintillating crystal. One of the TOF-DOI PET applications is a breast dedicated PET scanner which needs space for biopsy. In this case, a partial ring PET can be beneficial [4]. The TOF-DOI-PET is useful for the partial ring PET system since the lack of annihilation events can be compensated with TOF information. Even though the dual-ended readout detector employing a short length of scintillation crystal with a dimension of $1.5 \times 1.5 \times 10 \text{ mm}^3$ can provide an 1 mm DOI resolution and 350 ps single detector time resolution [8], its short length of crystal is not practical for the application of breast dedicated PET detector which requires a high sensitivity for annihilation photon detection.

In this study, cerium-doped lutetium-yttrium oxyorthosilicate ($\text{Lu}_{0.5}\text{Y}_{1.4}\text{Si}_{0.5}$: Ce, LYSO) scintillation crystals were used with SiPMs [9]. The effect of scintillation crystal length on the time resolution and the photon arrival time was investigated using a single-ended SiPM detector. To improve the timing and DOI resolution and to minimize the arrival time difference along the long LYSO crystal, we employed the meantime method of the dual-ended detector using two SiPMs, each of which was attached to both ends of the LYSO crystal.

II. MATERIAL AND METHOD

A. Validation of a Time to Digital Converter (TDC) bit

Arrival differences between START and channel inputs were measured with a CAEN V775N TDC module with a full scale range of 140 ns and a 12 bit resolution. To validate the TDC bit value of the TDC module, a cable delay method was used. A Tektronix AFG 3101 pulse generator produced a signal, which was subsequently split into two signals. The two signals were then fed into a Kaizu Works KN241 leading edge discriminator (LED) discriminator. One output signal from the LED discriminator was inserted into a KN470 (Kaizu Works) coincidence logic and the other output signal into the channel input of the TDC.

The length of the cable into the channel was varied from 0 ps to 8,150 ps by adding a multiple of 27.2 cm (1,358 ps) long LEMO cables. Since the SiPM gain is highly sensitive to ambient temperature, all of the SiPMs including photomultiplier (PMT) detectors were operated under the constant temperature of 20°C using a temperature-controlled chamber.

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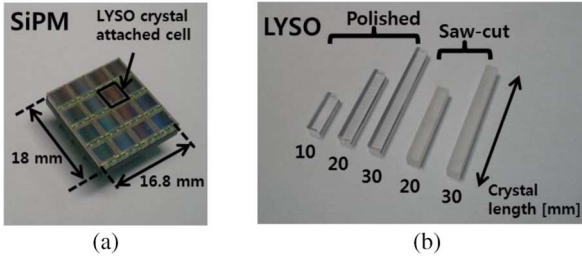


Fig. 1. Photographs of (a) SiPM and (b) various LYSO crystals used in this study.

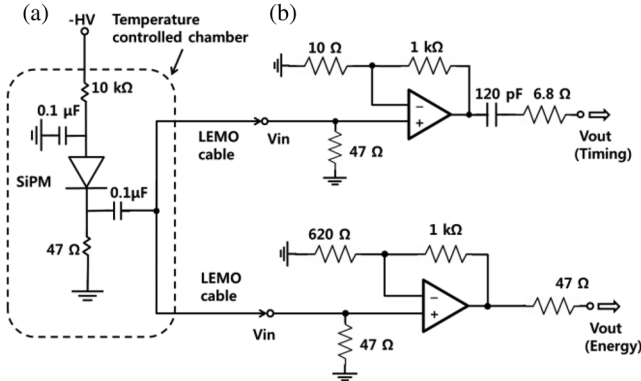


Fig. 2. Simplified circuit: (a) SiPM biasing, (b) amplifiers to measure the timing and energy of the SiPM signal.

B. SiPM and Crystal

The cross section of the LYSO crystal was $2.9 \times 2.9 \text{ mm}^2$ to make it fit into the SiPM sensitive cell area of $3.0 \times 3.0 \text{ mm}^2$ to optimize the light collection efficiency, which is one of the most important factors for accurate timing and energy measurement [10]. The LYSO crystal was coupled to a Hamamatsu S11064-050P SiPM comprised with 3,600 mini cells of $50 \times 50 \mu\text{m}^2$, as shown in Fig. 1(a) and (b).

Although various crystal surface treatments such as saw-cut and chemical-etching methods significantly improve the DOI resolution, these methods also decrease the light collection efficiency deteriorating a timing resolution [7], [11], [12], [13]. To obtain best timing resolution and optimal DOI resolution, an unpolished LYSO crystal with a Teflon reflector was used [14], [15]. In this paper, saw-cut and polished LYSO crystals in Fig. 1 were studied with a Teflon reflector.

C. Front Readout Electronics

Fig. 2 shows a simplified front-end circuit in which a signal was amplified with an AD8000 operational amplifier from Analog Devices. The scintillation pulse from SiPM was divided into high-gain (for timing information) and low-gain (for energy information) amplifiers to obtain fast timing response and good energy linearity. Both amplifiers were composed of a non-inverting manner with 50Ω input impedance, and the amplification gains of high-gain and low-gain amplifiers were set to 101 and 2.7, respectively. To obtain a fast signal rise time ($\sim 4 \text{ ns}$) and falling time ($\sim 6 \text{ ns}$) for timing signal, a 120 pF clipping capacitance was employed at the output of the high-gain amplifier [16], [17].

D. SiPM Breakdown Voltage and Temperature Dependency

To evaluate the basic characteristics of the SiPM such as breakdown voltage and temperature dependency, a SiPM-LYSO detector assembled by coupling the SiPM with a $2.9 \times 2.9 \times 10 \text{ mm}^3$ LYSO crystal was tested under various bias voltages and temperatures. First, the photo-peak values from the SiPM-LYSO detector were plotted with a 0.1 V step as a function of bias voltage, and then a second order polynomial curve was fitted to the photo-peak values as a function of bias voltage. The breakdown voltage of the SiPM was determined by the y-intercept of the fitting curve where the x-axis and y-axis are the photo-peak value and the bias voltage, respectively [18].

To investigate the SiPM gain dependency on ambient temperature, the photo-peak values of the SiPM-LYSO detector were measured with a 0.5°C step from 15°C to 25°C . The SiPM-LYSO detector was irradiated by a ^{22}Na point source and the photo-peak values were plotted against ambient temperatures.

E. Saturation Effect of SiPM

Since SiPM has a finite number of micro mini cells, the SiPM output signal amplitude is not linearly proportional to the number of scintillation lights incident to the SiPM photo sensor. The deviation from the linearity is referred to as saturation effect [19]. The saturation effect of the SiPM was investigated for the single-ended and dual-ended readout detector. The 1.7 V SiPM over-voltage was the optimal bias for the time resolution. The photo-peak values in QDC bit were measured using Co-57 (122 keV), Ba-133 (356 keV), Na-22 (511 keV), Cs-137 (662 keV) isotope sources for the 10 mm, 20 mm, 30 mm long polished Teflon wrapped LYSO crystal with the front irradiation as shown in Fig. 3. The photo-peak values obtained with various photon energies were fitted using Eq. (1) to check the saturation effect of the SiPM [20], [21],

$$y = a(1 - e^{-bx}) \quad (1)$$

where y is a SiPM output amplitude in QDC bit, x is a gamma photon energy, a and b are constants to be determined. Otherwise specified, all the QDC values were not corrected for saturation effects in this paper.

F. Timing Properties of a Reference Detector

A reference detector was assembled with a SiPM coupled with a $2.9 \times 2.9 \times 10 \text{ mm}^3$ LYSO crystal. To evaluate the detector timing resolution of the reference detector, two SiPM-LYSO reference detectors and one fast Hamamatsu R11102 PMT coupled with a $4.4 \times 4.4 \times 10 \text{ mm}^3$ LYSO crystal were used. A high voltage of -1300 V was applied for the fast PMTs, and the bias voltage of about 1.7 V above the breakdown voltage of the SiPMs was applied to the SiPMs. The threshold of the KN241 LED module was set to a 3% level of the pulse amplitude corresponding to the 511 keV photopeak. The 3% LED threshold level showed the best time resolution compared to the 1.5% and 4.5% threshold levels. To find out the exact LED threshold of the 3% level of the pulse amplitude, the amplitudes of the annihilation photo peak events were measured with a Tektronix

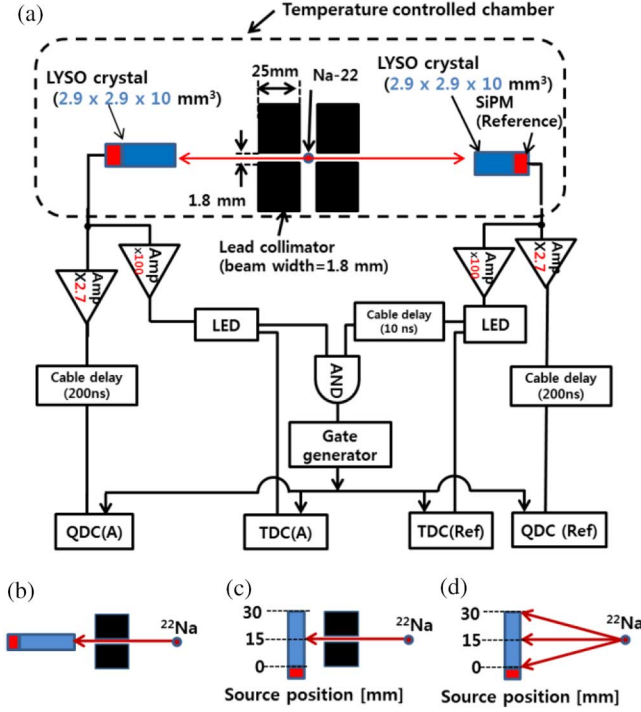


Fig. 3. Experimental setup for the single-ended readout detector: (a) data flow diagram for the measurements of the energy and detector timing resolution with the SiPM/LYSO single-ended readout, (b) front irradiation, (c) side irradiation along the crystal, and (d) side-flood irradiation for the measurement of time-walk effect on the time resolution.

350 MHz oscilloscope. An energy window of $\pm 20\%$ with respect to the 511 keV photo-peak was also applied for timing resolution measurements.

Detector timing resolutions of the reference detectors were obtained by solving the following linear Eq. (2):

$$\begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} T_{PMT}^2 \\ T_{SiPM(RA)}^2 \\ T_{SiPM(RB)}^2 \end{pmatrix} = \begin{pmatrix} T_{PMT-SiPM(RA)}^2 \\ T_{PMT-SiPM(RB)}^2 \\ T_{SiPM(RA)-SiPM(RB)}^2 \end{pmatrix} \quad (2)$$

where T_{PMT} , $T_{SiPM(RA)}$ and $T_{SiPM(RB)}$ are the full-width at half maximum (FWHM) values of the Hamamatsu PMT detector, the reference SiPM(RA) and SiPM(RB) detectors, respectively. $T_{PMT-SiPM(RA)}$, $T_{PMT-SiPM(RB)}$ and $T_{SiPM(RA)-SiPM(RB)}$ are the measured FWHMs with the Hamamatsu PMT and the reference SiPM(RA) detector, with the Hamamatsu PMT and the reference SiPM(RA) detector, and with the reference SiPM(RA) and SiPM(RB) detectors, respectively [22]. Otherwise specified, all the time resolutions in this paper were individual detector timing resolutions obtained by quadratically subtracting the time resolution of reference SiPM detectors.

G. Single-Ended Readout Detector for Timing Measurement

Several single-ended readout detectors were assembled and tested to measure coincident timing resolutions and photo-peak values along the LYSO crystals as shown in Fig. 3(a). The

SiPMs were optically coupled to the LYSO crystals with various lengths (10 mm, 20 mm, and 30 mm) using Saint-Gobain BC-630 silicone optical grease with an index of refraction of 1.465 and all crystal surfaces were wrapped with the Teflon reflector except the surface area coupled to the SiPM. To evaluate the dependency of crystal length on the detector timing resolution as precisely as possible, only the LYSO crystals were replaced from $2.9 \times 2.9 \times 10 \text{ mm}^3$ to $2.9 \times 2.9 \times 30 \text{ mm}^3$ while the other experimental setup conditions such as the SiPM bias and LED threshold level remained intact.

A ^{22}Na point source was collimated by two 25 mm thick lead blocks which were placed to produce an 1.8 mm wide slit. The two lead blocks with the 1.8 mm slit allowed the annihilation photon to be interacted at a desired position along the LYSO crystal, but they prevented the interaction of stray gamma photons with the LYSO crystal. With the $2.9 \times 2.9 \times 30 \text{ mm}^3$ LYSO crystal coupled with the SiPM, energy and timing resolutions were measured along the crystal with a 3 mm step from 3 mm to 27 mm. The LYSO crystals were also irradiated on the front and the side along the entire length of the crystal without collimation to estimate the effect of the parallax error on the detector timing resolution as shown in Fig. 3(b), (c), and (d). Because the time resolution is strongly dependent on the bias voltage of the SiPM, time resolutions were measured with various SiPM bias voltages.

H. Dual-Ended Readout Detector for Timing and DOI Resolution Measurement

The dual-ended readout detector consists of the saw-cut $2.9 \times 2.9 \times 30 \text{ mm}^3$ LYSO crystal wrapped with the Teflon tape and two SiPMs, each of which was coupled to both ends of the crystal. Even though the time resolution could be improved by using the DOI information [23], [24], we used the meantime obtained by averaging two TDC values obtained from two SiPMs to compensate the time walk effect and the photon arrival time shift occurred within the scintillation crystal. Averaging the earlier timing from a large pulse at one end and the lagged timing from a small pulse at the other end would compensate the time walk effect.

All coincidence timing resolutions of the SiPM were measured against the reference SiPM detectors. Fig. 4 shows a block diagram for timing and energy measurements. The SiPM output signal was split into two signals. One signal for timing measurement was fed to a custom-made PCB board containing a pulse shaping amplifier to obtain a fast rising signal, which is crucial for accurate timing resolution measurement [17]. The output signals from the pulse shaping amplifier was fed to the KN241 LED module to pick up the timing, and the V775N TDC module was used for timing measurement [16]. The other split signal for energy and DOI measurements was fed to an amplifier with a gain of 2.7 and then digitized by a CAEN V965 QDC module with a least significant bit (LSB) of 200 fC and a full scale range of 800 pC.

To compare the meantime method with a sum signal method, a sum signal was generated by adding two SiPM signals attached at the end of the LYSO crystal. The output signals amplified by the pulse shaping amplifiers in Fig. 2(b) are tied together

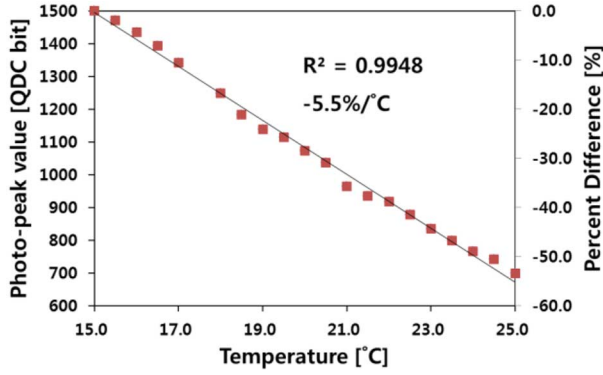


Fig. 8. Photo-peak values of the reference SiPM(RA) detector as a function of ambient temperature.

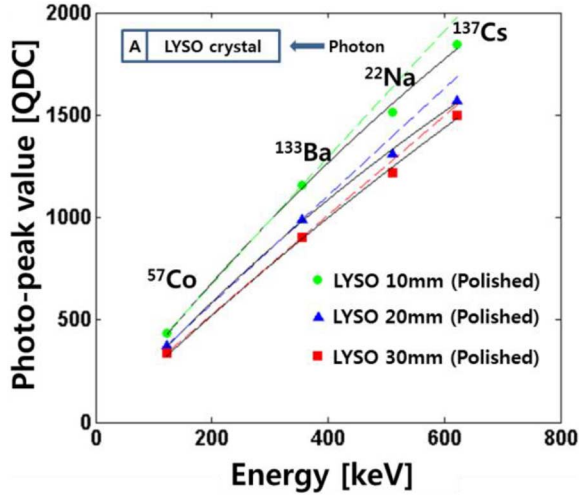


Fig. 9. Photo-peak values of the single-ended readout detector as a function of gamma photon energy. The black solid lines represent the fitting curve for the photo-peak values using the Eq. (1). The solid green, blue red lines are the extrapolation of linear fitting of the ^{57}Co (122 keV) and ^{133}Ba 356 keV.

the photo-peak value were decreased by 82 QDC values and 5.5% respectively.

C. Linearity of SiPM

Fig. 9 shows the saturation effects of the single-ended readout detector. The saturation caused the photo-peak values to be lower by 7.4%, 6.1%, and 4.9% for the 10 mm, 20 mm and 30 mm long polished Teflon wrapped LYSO crystals, respectively. Energy resolutions uncorrected (corrected) for saturation were 12.3% (15.6%), 14.3% (17.5%), and 15.3% (18.9%) for the 10 mm, 20 mm, and 30 mm long LYSO crystals, respectively. However, the dual-ended readout with the front irradiation resulted in almost no saturation as shown in Fig. 10. The saturation reduced the photo-peak value by only 1.8% for the polished 30 mm long Teflon wrapped LYSO crystal. Energy resolutions before and after saturation correction were 10.3% and 12.3%, respectively. No saturation effect was observed for the 30 mm long saw-cut LYSO crystal.

D. Timing Resolutions of the Reference Detectors

The measured FWHMs of $T_{\text{PMT-SiPM(RA)}}$, $T_{\text{PMT-SiPM(RB)}}$ and $T_{\text{SiPM(RA)-SiPM(RB)}}$ were 361 ps,

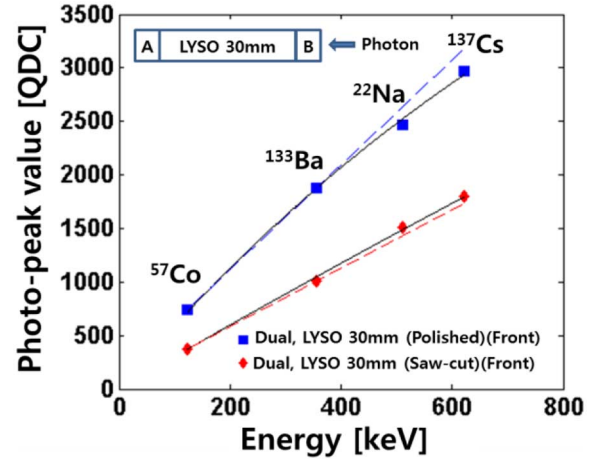


Fig. 10. Photo-peak values of the dual-ended readout detector as a function of gamma photon energy. The solid lines represent the fitting curve of photo-peak values using the Eq. (1) with front irradiation. The dashed blue and red lines are the extrapolation of linear fitting of the ^{57}Co (122 keV) and ^{133}Ba 356 keV.

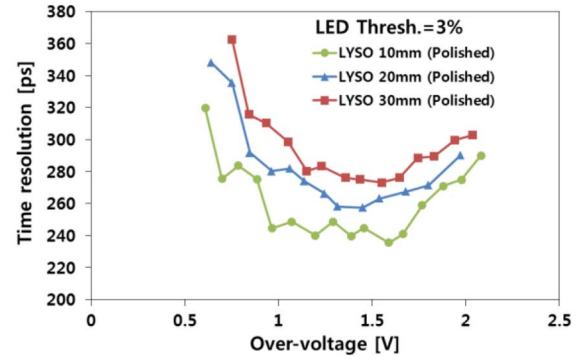


Fig. 11. A comparison of individual detector timing resolutions between the 10 mm and 30 mm LYSO crystals as a function of bias voltage.

387 ps and 337 ps for the Hamamatsu PMT and the reference SiPM(RA), with the Hamamatsu PMT and the reference SiPM(RA), and with the reference SiPM(RA) and SiPM(RB) detectors, respectively. The individual detector timing resolutions of the PMT, SiPM(RA), and SiPM(RB) were estimated to be 288 ps, 210 ps, and 256 ps, respectively.

E. Characteristics of the Single-Ended Readout Detector

Fig. 11 shows the individual detector timing resolutions of the 10 mm, 20 mm, and 30 mm long LYSO crystals as a function of bias voltage for the single-ended readout detector. Even though the crystal length was varied, the optimal SiPM bias for time resolution was roughly the same (an over-voltage of around 1.7 V). As the crystal length increases from 10 mm to 30 mm, the individual detector timing resolution was degraded as the total number of collected scintillation light was decreased and the light travel pathway was increased.

Energy resolutions without saturation corrections were 10.3%, 11.5% and 12.6% for the 10 mm, 20 mm and 30 mm LYSO crystal respectively, as shown in QDC distributions in Fig. 12. The relative photo-peak value differences of the 20 mm and 30 mm LYSO crystal with respect to the photo-peak value

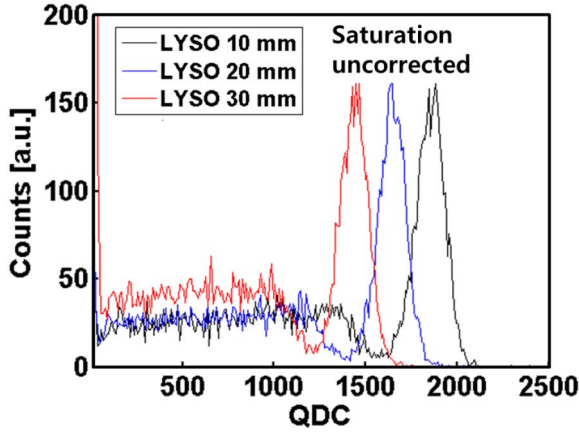


Fig. 12. Energy spectra with different length of LYSO crystals.

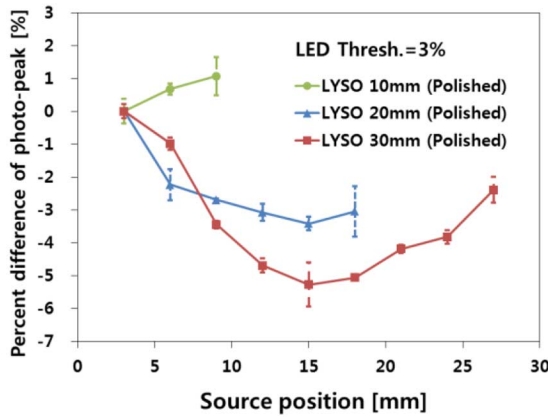


Fig. 13. Percent difference of photo-peak value as a function of source position.

of the LYSO 10 mm crystal were 88.5% and 77.2% respectively. Fig. 13 shows the percent difference of photo-peak value as a function of source position with the 10 mm, 20 mm, and 30 mm long polished SiPM-LYSO detectors. The maximum differences of the photo-peak values were 1.1%, 3.4%, and 5.3% for the 10 mm, 20 mm and 30 mm long LYSO crystal respectively. In case of the 30 mm long LYSO crystal, the lowest photo-peak value was observed at the source position of 15 mm and as the source position moved far away from the SiPM photo-sensor, the photo-peak value was increased again, since the scintillation lights can be reflected by the Teflon tape attached at the entrance surface of crystal.

Fig. 14 shows individual detector timing resolutions as a function of source position with the 10 mm, 20 mm, and 30 mm long polished SiPM-LYSO detector. Individual detector timing resolutions for the side and front irradiations are also given in Fig. 14. When a ^{22}Na point source was irradiated at the side of the crystal, individual detector timing resolution was deteriorated significantly compared to the front irradiation. In particular, as the length of LYSO crystal increased from 10 mm to 20 mm, and to 30 mm, this effect has been worsened since the photon arrival time difference intensified. The individual detector timing resolutions with the side, side-flood and front irradiation were 276 ± 13 ps, 297 ± 20 ps and 280 ± 8 ps for 10 mm long polished crystal and 277 ± 6 ps, 319 ± 11 ps and

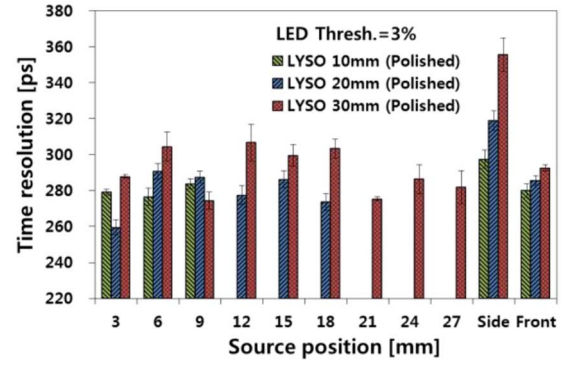


Fig. 14. Individual detector timing resolutions as a function of source position with the 10 mm, 20 mm, and 30 mm long polished LYSO-SiPM detector.

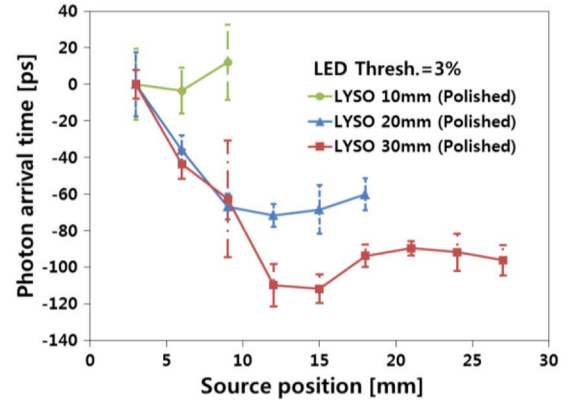


Fig. 15. Photon arrival times as a function of source position with the 10 mm, 20 mm, and 30 mm long polished LYSO-SiPM detector.

285 ± 4 ps for 20 mm long polished crystal and 286 ± 10 ps, 356 ± 8 ps and 293 ± 2 ps for 30 mm long polished crystal respectively.

Even though the individual detector timing resolutions in Fig. 14 did not depend on the source positions strongly for the 10 mm, 20 mm, and 30 mm long LYSO crystal, the difference in the photon arrival time was significant as the length of crystal was increased, as shown in Fig. 15. The maximum differences in photon arrival time were 12.0 ± 20.4 ps, 71.6 ± 13.3 ps, and 111.7 ± 7.8 ps for the 10 mm, 20 mm, and 30 mm long LYSO crystal, respectively.

F. Characteristics of the dual-ended readout detector

The scintillation photon arrival time to the SiPMs as a function of source position is shown in Fig. 16. The arrival times significantly varied from 750 ps at 3 mm to -900 ps at 27 mm for the SiPM(A) detector, and from -750 ps at 3 mm to 700 ps at 27 mm for the SiPM(B) detector. When the meantime method was used, the mean times were varied from 39 ps to -69 ps, with an average of 7.8 ± 33.2 ps as the source position were varied from 3 mm to 27 mm.

Fig. 17 and 18 show the individual detector timing resolutions as a function of SiPM over-voltage using the saw-cut and the polished $2.9 \times 2.9 \times 30$ mm³ LYSO crystal. The polished crystal resulted in significantly better timing resolutions than the saw-cut crystal. The best timing resolution was 287 ps for the

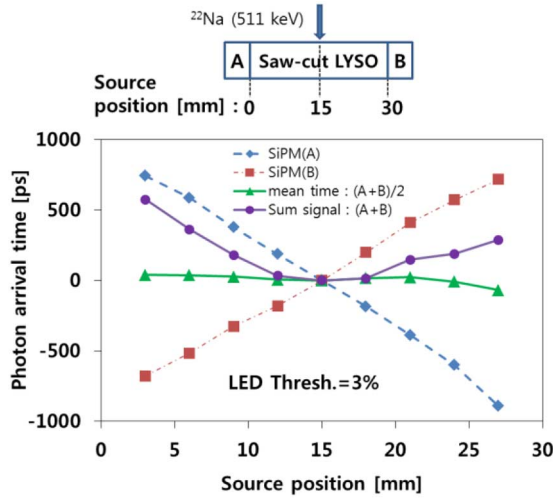


Fig. 16. TDC mean time values as a function of source position with the SiPM/LYSO/SiPM dual ended readout detector using the $2.9 \times 2.9 \times 30 \text{ mm}^3$ LYSO crystal.

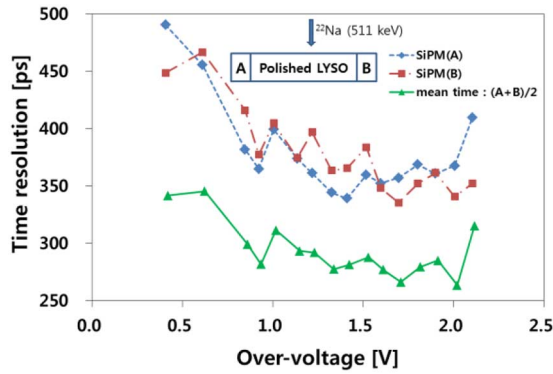


Fig. 17. Individual detector timing resolutions with the dual-ended readout detector with a polished $2.9 \times 2.9 \times 30 \text{ mm}^3$ LYSO crystal.

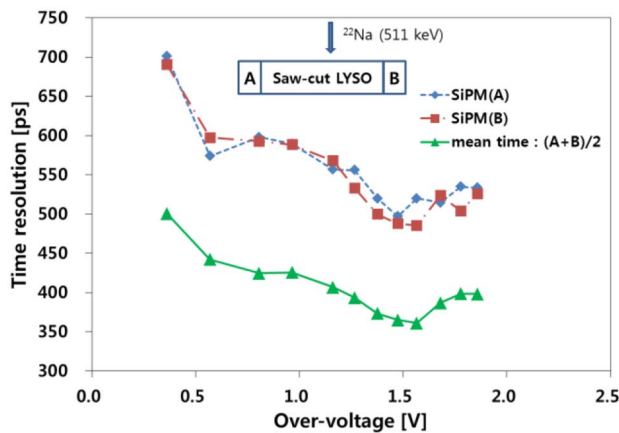


Fig. 18. Time resolution with the dual ended readout detector with a saw-cut $2.9 \times 2.9 \times 30 \text{ mm}^3$ LYSO crystal.

polished crystal and 435 ps for the saw-cut crystals both at the 1.7 V over-voltage.

The meantime resolutions are compared in Fig. 19, as a function of source position for the two different crystal surface treatments. Regardless of the struck positions along the crystal, the

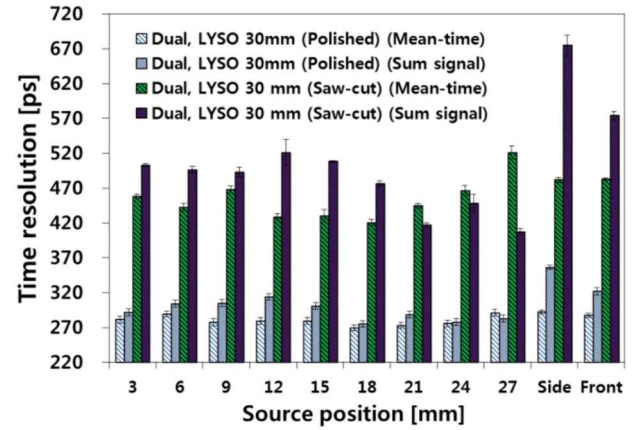


Fig. 19. Comparison of the time resolutions between sum signal and mean-time with different crystal surfaces treatments.

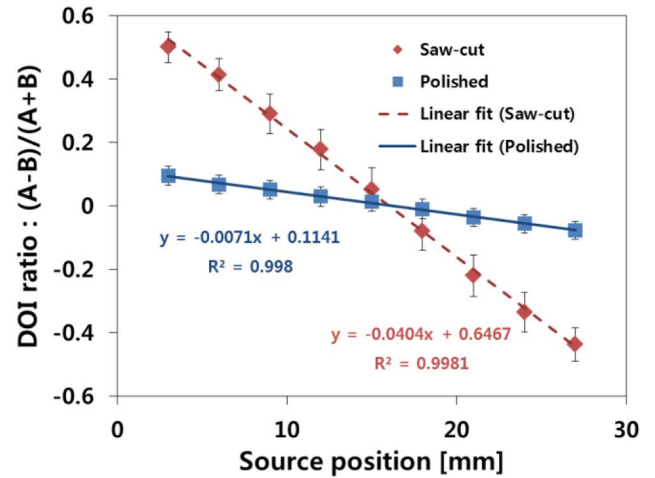


Fig. 20. DOI ratios with the dual-ended readout detector, and error bars indicate FWHMs.

meantime resolutions were stable for the polished crystal, but varied from 365 ps at 15 mm to 523 ps at 27 mm for the saw-cut crystal. The best time resolutions using the sum signal with the side, side-flood and front irradiations were 275 ps, 339 ps and 322 ps for the polished LYSO crystal, and 407 ps, 675 ps and 574 ps for the saw-cut LYSO crystal, respectively. The best meantime resolutions using the 30 mm long LYSO crystal with the side, side-flood and front irradiations were 270 ps, 287 ps and 266 ps for the polished LYSO crystal, and 465 ps, 482 ps and 435 ps for the saw-cut LYSO crystal, respectively.

The DOI resolutions were obtained by the Gaussian fitting of the DOI ratios [11]. Fig. 20 shows DOI ratios obtained with the saw-cut and polished LYSO crystal. The signal asymmetry between two SiPMs attached to the saw-cut crystal was increased significantly compared to the polished LYSO crystal. Fig. 21 shows the DOI ratio histogram as a function of DOI with the dual-ended readout detector using the saw-cut $2.9 \times 2.9 \times 30 \text{ mm}^3$ LYSO crystal. As shown in Fig. 22, the average DOI resolution was $2.88 \pm 0.28 \text{ mm}$ crystal and $8.24 \pm 0.34 \text{ mm}$ for the polished LYSO crystal.

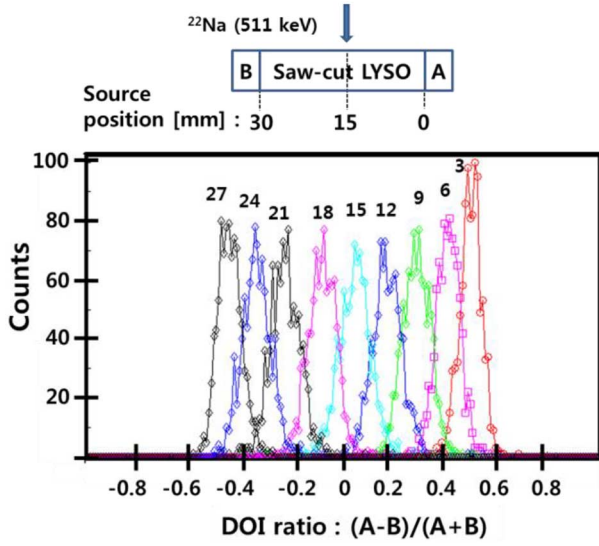


Fig. 21. DOI ratio histogram as a function of source position with the dual-ended readout detector using $2.9 \times 2.9 \times 30 \text{ mm}^3$ LYSO crystal.

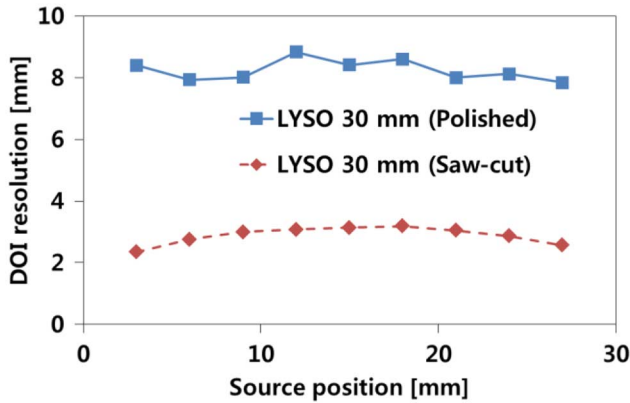


Fig. 22. DOI resolutions as a function of source position with the dual-ended readout detector using $2.9 \times 2.9 \times 30 \text{ mm}^3$ LYSO crystal with different crystal surface treatments.

IV. DISCUSSION

The best individual detector timing resolution in the single-ended readout detector did not depend strongly on the length of the polished LYSO crystal, resulting in 238 ps, 265 ps and 275 ps for the 10 mm, 20 mm, and 30 mm long crystal with a cross section of $2.9 \times 2.9 \text{ mm}^2$, respectively as shown in Table I.

The meantime timing resolutions of the dual readout were 266 ps for the 30 mm long polished crystal and 435 ps for the 30 mm long saw-cut crystal respectively. With the meantime method, the average photon arrival time shift along the 30 mm long LYSO crystal was $7.8 \pm 33.2 \text{ ps}$, which agrees to the expected null value, as shown in Fig. 16. The arrival time difference of $\sim 100 \text{ ps}$ for the 30 mm long SiPM-LYSO single-ended detector is not a significant factor for a $\sim 300 \text{ ps}$ ToF PET. However, the dependency of the signal arrival time on the struck position along the crystal can be an important factor especially for a high sensitive ToF PET with a below 200 ps timing resolution.

The differences in the photon arrival time to the single readout SiPM with the 30 mm long LYSO crystal shown in

TABLE I
SUMMARY OF THE ENERGY, INDIVIDUAL TIME, COINCIDENCE TIME AND DOI RESOLUTIONS OBTAINED IN THIS STUDY WITH THE FRONT IRRADIATION. TIME RESOLUTIONS WITH SUM SIGNALS ARE SHOWN INSIDE PARENTHESES. THE COINCIDENCE TIMING RESOLUTIONS WERE OBTAINED BY MULTIPLYING $\sqrt{2}$ TO THE INDIVIDUAL TIMING RESOLUTIONS

	Single ended			Dual-ended	
Crystal length [mm]	10 (Polished)	20 (Polished)	30 (Polished)	30 (Polished)	30 (Saw-cut)
Energy resolution [%]	10.3	11.5	12.6	11.5	13.8
Energy resolution [%] (Saturation corrected)	14.7	15.7	16.4	12.5	13.8
Individual time resolution [ps]	238	265	275	266 (322)	435 (574)
Coincidence timing resolution [ps]	337	375	389	376 (455)	615 (812)
DOI resolution [mm]	N.A.	N.A.	N.A.	8.24 ± 0.34	2.88 ± 0.28

Fig. 13 were about 111.7 ps between 3 mm and 15 mm, and about 96.2 ps between 3 mm and 27 mm, respectively. The photon arrival time along the LYSO crystal did not show a simple linear relationship between the photon arrival time and the source position. Since the theoretical light propagation speed inside the LYSO crystal with a refractive index of 1.82 is about a 6.07 ps/mm, the arrival time differences are expected to be 72.8 ps between 3 mm and 15 mm, and 145.6 ps between 3 mm and 27 mm, respectively. Complex photon propagation inside the crystal and reflection on the boundary seem to have important factors in the photon arrival time defying the simple linear relationship, which was obtained using the phase velocity. However, the group velocity instead of the phase velocity would be better to properly take into account the reflections in the crystal boundary.

We have investigated the coincidence timing resolution and DOI resolution of the SiPM based dual-end readout detector which employed the $2.9 \times 2.9 \times 30 \text{ mm}^3$ LYSO crystal. Even though the saw-cut LYSO crystal resulted in a significantly improved DOI resolution ($2.88 \pm 0.28 \text{ mm}$) compared to the polished LYSO crystal ($8.24 \pm 0.34 \text{ mm}$), the timing resolution (435 ps) was degraded by about 100 ps compared to the polished LYSO crystal (266 ps) due to probably more irregular reflections on the crystal surface causing more diffuse reflection and more variations on the photon arrival time.

In this paper, we studied the timing resolutions of the 30 mm long scintillation crystal with the mean timing method because the relative efficiencies obtained with GATEv6.2 are 76% and 89% for the 20-25 mm long crystals. It would be interesting to study the timing resolutions of the 20 mm and 25 mm long crystal with the mean timing method.

The dual-ended readout detector has several advantages over the single-ended readout detector such as the DOI information, the improvement of timing resolution, and the negligible

dependency of the arrival time along the crystal. A lately available monolithic MPPC array in SMD package (Hamamatsu S11828-3344M) could be used to build TOF-DOI PETs with the dual-ended readout detector. One of the main problems in terms of signal complexity caused by employing one-to-one coupling between the scintillation crystal and SiPM can be resolved using a novel signal multiplexing method. The number of SiPM signal channels to be processed can be reduced from $M \times N$ SiPM array into $M + N$ using the multiplexing single encoding method which uses row and column signals from the SiPM array [18]. In the same manner, Geiger-mode-avalanche-photodiodes (G-APD) which has cross-strip sensor elements can provide $M + N$ number of channels intrinsically [26]. Since a partial ring PET with a small diameter can be beneficial for the breast dedicated PET which often needs space for biopsy, it could be an ideal application for TOF-DOI PETs with the dual-ended readout detector [4].

V. CONCLUSION

In conclusion, the proposed dual-end readout detector using SiPM with the meantime method can improve both the DOI resolution and the timing resolution significantly. The optimal crystal surface roughness and treatment for TOF-DOI PET and optical coupling alignment between LYSO crystal array and SiPM will be studied in the future work.

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