Dual-ended Readout PET Detector Module Based on GAPD Having Large-area Microcells

Jihoon Kang, Yong Choi, Key Jo Hong, Wei Hu, Yoonsuk Huh, Hyun Keong Lim, and Byung-Tae Kim

Abstract—A dual-ended readout PET detector module based on Geiger-mode avalanche photodiode (GAPD) with large-area microcells was proposed to obtain high photon detection efficiency (PDE) and to overcome the energy non-linearity problem. Theoretical analysis and experimental measurement were performed for the single- and dual-ended PET detector modules which were consisted of the two types of GAPDs with 50×50 µm² and 100×100 µm² microcell sizes. A Monte Carlo simulation was conducted to predict the number of incident photons impinging on the GAPD entrance surface to estimate the light collection efficiency (LCE) and linearity performance. Also, the depth of interaction (DOI) ratio histogram was obtained. Experimental study was performed to acquire the energy spectra of different γ-rays, and the linearity was evaluated by analyzing the photo-peak channels. The simulation results showed the LCE of dual-ended PET detector modules were improved 9% and 55% comparing to the single-ended one, with 50×50 µm² and 100×100 µm² microcells GAPDs, respectively. Also, it was estimated that the proposed method can provide excellent (3-4 mm) and uniform DOI resolution. In the experimental measurement, the 511 keV photo-peak channels of dual-ended PET detector modules was increased 26% and 71% comparing to the single-ended one, with 50×50 µm² and 100×100 µm² microcells GAPDs, respectively. The coefficient of determination (R²) was improved from 0.86 to 0.93 with 100×100 µm² microcells GAPD. The similar improvement in photo-peak channel and linearity was observed in the simulation results. It demonstrated that the dual-ended PET detector configuration could considerably improve the non-linearity properties of GAPD without modification of microcell size and, hence, such configuration could provide high LCE, as well as DOI capabilities, for high PET detector performance.

Index Terms—Geiger-mode avalanche photodiode, photon detection efficiency, dual-ended readout PET detector module

I. INTRODUCTION

Geiger-mode avalanche photodiode (GAPD) consists of hundreds or thousands of the microcells, and the total number of fired microcells reflects the number of absorbed photons. However, the finite number of microcells induces the significant deviations of linearity when the number of converted photons is larger than the number of microcells. These non-linearity properties may render implementation of GAPD with large-area microcells difficult for high photon flux detection and PET application (Fig. 1 (a)) [1-3]. A common approach is the utilization of GAPD with small-area microcells to solve the linearity problem for the development of LSO based PET detector (Fig. 1(b)) [4-7]. This approach, however, has apparent drawbacks decreasing the photon detection efficiency (PDE) and gain caused by the increase of dead space in the active area of GAPD.

We propose a new approach, dual-ended readout PET detector configuration in which generated photons in the LSO crystal were detected by two GAPDs (Fig. 1(c)). The main advantage of this method is the increase of the number of microcells detecting the photons without modification of microcell size. It is possible to improve the linearity and light collection efficiency (LCE), while PDE and gain of the GAPD were unchanged. Additionally, it could provide the depth information of γ-ray interaction.

Fig. 1. Problem and achievable approach of GAPD non-linearity for PET applications.

The aim of this study is to investigate the advantages of the dual-ended PET detector modules based on GAPDs with large-area microcells, comparing to the single-ended one. Theoretical analysis and experimental measurement were performed to characterize light collection efficiency (LCE), linearity and depth of interaction (DOI) capability of both detector configurations.

II. MATERIALS AND METHODS

The evaluation was performed for four PET detector modules: two single-ended readout PET detector modules...
consisted of the two types of GAPD with 50×50 µm² and 100×100 µm² microcells (Fig. 2 (a),(b)), and two dual-ended readout PET detector modules consisted of the two different microcell size used above (Fig. 2 (c),(d)).

Each of the two types of 3x3 mm² GAPD (Hamamatsu Photonics, Hamamatsu, Japan) was coupled to 3x3x20 mm³ LYSO pixel crystal (Sinocera, Shanghai, China) with optical grease (Saint-Gobain Crystals, Hiram, Oh, USA). The primary specification of GAPDs was listed in Table I [4, 5, 8].

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**Fig. 2. Schematics of four PET detector modules.** Single-ended (top row; (a) and (b)) and dual-ended (bottom row; (c) and (d)) readout configurations were consisted of the two types of GAPD with 50×50 µm² (left column; (a) and (c)) and 100×100 µm² (right column; (b) and (d)) microcells.

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**TABLE I. SPECIFICATIONS OF GAPDS**

<table>
<thead>
<tr>
<th>GAPD microcell sizes</th>
<th>50×50 µm²</th>
<th>100×100 µm²</th>
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</thead>
<tbody>
<tr>
<td>No. microcells</td>
<td>3600</td>
<td>900</td>
</tr>
<tr>
<td>Fill factors (%)</td>
<td>61.5</td>
<td>78.5</td>
</tr>
<tr>
<td>PDE @ 420 nm (%)</td>
<td>&gt; 30</td>
<td>&gt; 45</td>
</tr>
<tr>
<td>Gain</td>
<td>7.5×10⁵</td>
<td>2.4×10⁶</td>
</tr>
<tr>
<td>Dark counts (Mcps)</td>
<td>3</td>
<td>3.5</td>
</tr>
</tbody>
</table>

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**A. Theoretical analysis**

A Monte Carlo simulation using DETECT2000 was conducted to investigate the light distribution after conversion of the γ-ray in LYSO crystal using a light yield of 27 photons/keV. A total of 10000 γ-ray interactions with the different random numbers were generated to obtain sufficient statistical accuracy. The impinging photons on the GAPD entrance surface were simulated and recorded for each interaction event. The number of fired cells calculated by using Eq. (1) [11].

\[
N_{\text{fired microcells}} = N_{\text{total microcells}} \times \left(1 - e^{-\frac{N_\text{photons}}{N_{\text{fired microcells}}}}\right)
\]  

where, \(e, (\text{PDE}) = \text{Quantum efficiency} \times \text{Fill factor} \times \text{Geiger-mode avalanche probability}

1) **Light collection efficiency (LCE):** In order to evaluate whether or not LCE would be improved by the proposed dual-ended PET detector module comparing conventional single-ended PET detector module, the number of fired cells and output electron for 511 keV γ-rays were estimated. The LCE was calculated using Eq. (2).

\[
\text{LCE} = \frac{\text{Number of counted photons}}{\text{Number of entered photons}}
\]

2) **Linearity performance:** The linearity performance was estimated by simulating four different energy γ-rays (Co-57: 122 keV, Na-22: 511 keV and 1275 keV, and Cs-137: 662 keV). The number of fired cells and output electron as a function of γ-ray energy was estimated for each of the four PET detector modules.

3) **DOI capability:** For the two dual-ended PET detector modules, event-by-event data were analyzed for seven different DOI locations, ranging from 1 mm to 19 mm along the LYSO crystal, in 3-mm steps. The DOI ratio was calculated using Eq. (3) [12].

\[
\text{DOI ratio} = \frac{S_2}{S_1 + S_2}
\]

where, \(S_1\) is the detected fired cell number from one end and \(S_2\) is the detected fired cell number from other end.

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**B. Experimental measurements**

The GAPD outputs were fed to custom-made charge sensitive preamplifiers and then to shaping amplifiers for signal shaping and inverting. The amplified signals were digitized and recorded by a commercial DAQ unit (VHS-ADC-V4; Lyrtech Inc, Quebec, Canada). The GAPD with 100×100 µm² and 50×50 µm² microcells were operated at 70.4 and 70.7 V, respectively. The temperature was stabilized at 25°C during the measurements.

1) **Energy spectra for 511 keV γ-rays:** For each of the four PET detector modules, the energy spectra of 511 keV γ-rays were acquired for 5 min. A Na-22 point source (diameter 0.5 mm), with an activity of 5 µCi, was placed 10 mm away from the crystal.

2) **Linearity performance:** Additional energy spectra were acquired using different point sources (Co-57 (~3 µCi) and Cs-137 (~ 7 µCi)) and the linearity performance was assessed by photo-peak channels obtained from Gaussian fit. These experiments were repeatedly performed for four PET detector modules with the same electronic setup described above.
3) DOI capability: The dual-ended PET detector modules were irradiated by a collimated F-18 source at different DOI position. The data acquired from each GAPD were further processed to compute the energy spectra (output1+output2) and DOI ratio (output2/output1+output2) for each incident interaction as a function of the DOI position. The DOI resolution was analyzed from the FWHM for each histogram.

III. RESULTS

A. Theoretical analysis

1) Light collection efficiency (LCE): The numbers of simulated incident photons were 5855 ± 59 and 6395 ± 58, with single-ended and dual-ended PET detector module, respectively. The calculated results were summarized in Table II and III. The numbers of fired microcells of dual-ended PET detector modules were increased 21% and 68% comparing to the single ended one, with 50×50 μm² and 100×100 μm² microcells GAPDs, respectively. Moreover, the LCE of dual-ended PET detector modules were improved 9% and 55% comparing to the single ended one, with 50×50 μm² and 100×100 μm² microcells GAPDs, respectively.

<table>
<thead>
<tr>
<th>Detector types</th>
<th>Single-ended</th>
<th>Dual-ended</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. fired microcells</td>
<td>1390</td>
<td>1684</td>
</tr>
<tr>
<td>No. output electron</td>
<td>1.0×10⁹</td>
<td>1.2×10⁹</td>
</tr>
<tr>
<td>LCE (%)</td>
<td>23.7</td>
<td>26.3</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Detector types</th>
<th>Single-ended</th>
<th>Dual-ended</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. fired microcells</td>
<td>852</td>
<td>1436</td>
</tr>
<tr>
<td>No. output electron</td>
<td>2.0×10⁹</td>
<td>3.4×10⁹</td>
</tr>
<tr>
<td>LCE (%)</td>
<td>14.5</td>
<td>22.5</td>
</tr>
</tbody>
</table>

2) Linearity performance: The linearity of output electron as a function of γ-ray energy considerably improved in the dual-ended PET detector module configuration (Fig. 3). The estimated coefficient of determination (R²) of dual-ended configurations increased from 0.96 to 0.99 and from 0.78 to 0.87 compared to single-ended one, for 50×50 μm² and 100×100 μm² microcells GAPDs, respectively.

3) DOI capability: Fig. 4 shows the profiles generated by the incident γ-rays for two dual-ended PET detector modules at seven different depths. The average DOI resolutions were 3.8 mm and 4.1 mm, with 50×50 μm² and 100×100 μm² microcells GAPDs, respectively.

B. Experimental measurements

1) Energy spectra for 511 keV γ-rays: No considerable improvement of energy resolution was observed in dual-ended configuration compared to single-ended one. However, the photo-peak channels of dual-ended PET detector modules
were increased 26% and 71% comparing to the other, with 50×50 \(\mu m^2\) and 100×100 \(\mu m^2\) microcells GAPDs, respectively (Fig. 5). The increments were similar to those estimated by theoretical analysis shown in Table II and III.

2) \textit{Linearity performance}: The linearity performance was considerably improved (Fig. 6) and it was similar to the results obtained by theoretical analysis (Fig. 3). The \(\text{R}^2\) values were changed from 0.97 to 0.99 and from 0.86 to 0.93, compared to single-ended one, for 50×50 \(\mu m^2\) and 100×100 \(\mu m^2\) microcells GAPDs, respectively.

3) \textit{DOI capability}: Figure 7 shows the depth profiles for two dual-ended PET detector modules at seven different depths. The average DOI resolutions were 3.7 mm and 3.8 mm, with 50×50 \(\mu m^2\) and 100×100 \(\mu m^2\) microcells GAPDs, respectively.

IV. \textbf{DISCUSSION}

Light collection efficiency (LCE), linearity and DOI capability were considerably improved with the dual-ended PET detector modules based on GAPD comparing to the single-ended one. The improvement is well predicted and characterized by the theoretical and simulates estimations. The proposed design could provide several merits. The improved linearity allows to use the GAPD with large-area microcells for PET application providing high photon detection efficiency (PDE). The increased LCE would allow to improve the time resolution by reducing rise time and the spatial resolution by increasing signal to noise ratio [13]. Furthermore, the proposed method could provide the DOI capabilities (excellent and uniform resolution of 3-4 mm) which were an additional and inherent benefit of dual-ended readout PET detector configuration.

The major drawback of the dual-ended PET detector module is that it requires the twice of GAPD and readout
electronics, compared to the single-ended one. Also, significant bias voltage and temperature dependence of GAPD require a careful tuning of the bias voltage settings and temperature stabilization for a pair of GAPDs consisting of the dual-ended configuration.

V. CONCLUSION

The dual-ended PET detector configuration could considerably improve the non-linearity properties of GAPD without modification of microcell size and, hence, such configuration could provide high LCE, as well as DOI capabilities, for high PET detector performance. This approach will allow to configure PET detector modules providing high resolution and sensitivity capabilities using GAPD with large-area microcells.

REFERENCES