A Novel Sub-Millimeter Resolution PET Detector With TOF Capability

Tianpeng Xu\textsuperscript{1}, Jie Wen\textsuperscript{2}, Qiang Wang\textsuperscript{2}, Qingyang Wei\textsuperscript{1}, Tianyu Ma\textsuperscript{1}, Yaqiang Liu\textsuperscript{1}, Yuan-Chuan Tai\textsuperscript{2}

\textsuperscript{1}Department of Engineering Physics, Tsinghua University, Beijing, China
\textsuperscript{2}Department of Radiology, Washington University in St. Louis, St. Louis, USA
Fast Timing Silicon Photomultipliers (SiPM)

Standard SiPM (2-terminal)

New Fast Timing SiPM (3-terminal)

Ultra fast rising edge for timing: coincidence resolving timing (CRT) ~ sub-200 ps for a pair of single pixels

Our work is to evaluate the performance of this new fast SiPM array.

Detector Module Design

- 20 x 20 LSO crystal block
- Acrylic Diffuser
- 4 x 4 fast SiPM array

Sub-millimeter

1.6 mm

TOF

Side view of detector module

Dimension of SiPM array

Single pixel
(3 x 3 mm² sensitive area)
Two Different Series: FM and FB

<table>
<thead>
<tr>
<th></th>
<th>FM30050</th>
<th>FB30035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Area</td>
<td>3 x 3 mm²</td>
<td>3 x 3 mm²</td>
</tr>
<tr>
<td>Microcell Size</td>
<td>50 um</td>
<td>35 um</td>
</tr>
<tr>
<td>Microcell Number</td>
<td>2656</td>
<td>4774</td>
</tr>
<tr>
<td>Peak Wavelength</td>
<td>500 nm</td>
<td>420 nm</td>
</tr>
<tr>
<td>PDE at $\lambda_p$</td>
<td>23%</td>
<td>31%</td>
</tr>
<tr>
<td>Gain $^*$</td>
<td>$4 \times 10^6$</td>
<td>$3 \times 10^6$</td>
</tr>
<tr>
<td>Dark Counts</td>
<td>10 MHz</td>
<td>7.5 MHz</td>
</tr>
</tbody>
</table>

$^*$ FM at 2V FB at 2.5V overvoltage

FB is better matched with LSO!

(Sensl, Ireland)
Front-End Readout Architecture

16 standard outputs → 4 outputs (A, B, C, D) for positioning & energy
16 fast outputs → 1 timing output
High compactness, Low cost, Low power consumption
How to Do Timing Determination?

Two different time pick-off methods:

- **Constant Fraction Discriminator (CFD)**
- **Leading Edge Discriminator (LED)**

**Experiment setup:**

- 30,000 events acquired
- Energy Window: 450keV ~ 650keV
- SiPM bias voltage: 2V~6V overvoltage(OV)
- Temperature: 26°C
Comparison of CFD and LED

The best CRTs at different OV for CFD and LED

LED is more appropriate for this fast timing SiPM detector than CFD.
Performance Evaluation of Detector Modules

- LED was used for time pick-off.
- Reference detector was working at 4V OV.

Block detector module VS Single pixel (reference detector)
FM Detector Module vs. Bias Voltage

Crystal flood map: (1M events) at 1V~4V overvoltage

1V (✓)  2V (✓)  3V (✗)  4V (✗)

Block Timing
(Energy Window: 350keV~650keV)

2V OV was used for all FM array evaluation.
FB Detector Module vs. Bias Voltage

Crystal flood map (1M events) at 3V~6V overvoltage

Block Timing (Energy Window: 350keV~650keV)

5V OV was be used for all FB array evaluation.
Crystal Flood Map

FM detector at 2V OV and FB detector at 5V OV (30M events)

Only 16 x 16 crystals of the 20 x 20 array are resolved.

Custom light guide is needed to resolve edge crystals.

Performance of custom light guide: Poster Session M11-47
Coincidence Timing Resolution

Timing Resolution across the 14 x 14 crystals in the middle.
Coincidence Timing Resolution

Histogram of CRT

Typical CRT Spectrum
Coincidence Timing Resolution

Estimation of CRT between two identical detector blocks:

CRT of two reference detectors: 280 ps

**reference detector:** \( \frac{280}{\sqrt{2}} = 198 \text{ ps} \)

CRT of detector block VS reference detector:

FM: 401 ps  
FB: 303 ps

**CRT between two identical detector blocks:**

\[
CRT_{FM-FM} = \sqrt{2} \times \sqrt{\left( CRT_{ref-FM}^2 - TR_{ref}^2 \right)} = \sqrt{2} \times \sqrt{401^2 - 198^2} = 493 \text{ ps}
\]

\[
CRT_{FB-FB} = \sqrt{2} \times \sqrt{\left( CRT_{ref-FB}^2 - TR_{ref}^2 \right)} = \sqrt{2} \times \sqrt{303^2 - 198^2} = 324 \text{ ps}
\]
Energy Resolution across the 14 x 14 crystals in the middle.

**FM**

**FB**

ER degrades due to the light loss.
Energy Resolution

Histogram of ER

Typical Energy Spectrum

FM
Average = 15.3 ± 1.4%

FB
Average = 11.3 ± 0.7%
Conclusions and Future Work

**Summary:**
- Our basic detector design provides excellent identification of sub-millimeter crystals, good timing resolution (block-block CRT: FM 493 ps and FB 324 ps), energy resolution (FM 15.3%±1.4%, FB 11.3%±0.7%).
- LED Performs better than CFD for this fast timing SiPM detector.
- FB-series SiPM has better performance than the FM-series due to higher PDE that is better matched with the emission spectrum of LSO.
- Our design does not require ASIC or high-speed digital sampling electronics, and can be easily implemented using conventional electronics.

**Future Work:**
- Better timing performance if readout individually (based on ASIC)
- Evaluate non-linearity effect of SiPM
Acknowledgment

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