a low-cost solution for a large-area, low-noise SiPM pixel

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Outline

1. The Photo-Trap concept
2. Photo-Trap prototypes
3. Performance
4. Applications and future prospects
The need of Large Area SiPMs

Probably one of the main **drawbacks** of **SiPMs** is the **lack of large-area pixels**:

- SiPMs are typically available in **sizes** $\leq 6 \times 6 \text{ mm}^2$
- **Capacitance**, **dark count rate** (**DCR**) and **cost** increase with size
- Larger pixels (a few cm$^2$) can be achieved by **summing SiPMs**, but:
  - SNR degrades (single-phe resolution is often lost)
  - DCR still increases linearly with size...
  - ...and also cost
Photo-Trap

A low-cost, low-noise, large-area SiPM pixel

- A SiPM is coupled to a **Wavelength shifter (WLS) plastic**
  - \( \text{WLS area} \gg \text{SiPM area} \)

- A **dichroic filter** is placed at the **front**.
  - \( \text{High } T \text{ in the absorption band of the WLS} \)
  - \( \text{High } R \text{ in its re-emission band} \)

- **Reflectors** are placed at the **back** and **sides** of the WLS plastic

*Photo-Trap is an upgrade of the former EU project “Light-Trap” ([D. Guberman et al. (2019), NIM-A, 923, 19])
The Photo-Trap concept

300-400 nm photon

\[ n_{\text{air}} = 1 \]

\[ n_{\text{plastic}} \sim 1.5 \]

Dichroic filter

SiPM

WLS

Diffuse reflector
The Photo-Trap concept

300-400 nm photon

$n_{\text{air}} = 1$

$n_{\text{plastic}} \sim 1.5$

400-500 nm photon

Dichroic filter

SiPM

Diffuse reflector

WLS
The Photo-Trap concept

300-400 nm photon

\[ n_{\text{air}} = 1 \]

\[ n_{\text{plastic}} \sim 1.5 \]

Dichroic filter

SiPM

WLS

Diffuse reflector
Operation principle

(i) Incident photons with the *proper* $\lambda$ go through the filter, are absorbed by the WLS, re-emitted and remain *trapped* inside the pixel until they reach the SiPM.

(ii) Some of the absorbed photons may *escape* or be *re-absorbed* and will not reach the SiPM.

(iii) Photons at *other wavelengths* are *rejected*
Photo-Trap

- Pixel area $\sim$ 10-100 times area of a single SiPM.
- Pixel noise = noise of a single SiPM
- Pixel cost $\sim$ cost of a single SiPM (if the cost of the plastic and filter are low)
Prototypes
Proof-of-concept prototypes

Main components of our prototype pixels:

- **3 mm thick EJ-286 WLS from Eljen**
  - Sensitive at ~ 320 - 390 nm
  - Peak Emission ~ 420 nm
  - Decay time ~ 1.2 ns
  - Light Yield ~ 92%

- **Asahi ZUV0400 UV-pass filter**
  - T (0º AOI) > 95% @320-395 nm
  - R (0º AOI) > 98% @400-700 nm

- **ON MicroFJ−30035 SiPMs (3x3 mm²)**
  - Custom-made PCB to read a single SiPM or 4 in parallel (same area than a 6 x 6 mm²)

- **Berghof Optopolymer reflective film**
  - R~98% > 400 nm
Proof-of-concept prototypes
Prototype configurations

Prototype I
- WLS Area ~ 20 x 20 mm²
- SiPM Area ~ 3 x 3 mm²
- Area ratio ~ 42

Prototype II
- WLS Area ~ 20 x 20 mm²
- SiPM Area ~ 3 x 12 mm²
- Area ratio ~ 10

Prototype IV
- WLS Area ~ 40 x 40 mm²
- SiPM Area ~ 3 x 3 mm²
- Area ratio ~ 170

Prototype IV
- WLS Area ~ 40 x 40 mm²
- SiPM Area ~ 3 x 12 mm²
- Area ratio ~ 42
Performance evaluation
Optical Gain (G) / Trapping Efficiency (TE)

\[ G = \frac{\text{Nr of photons detected by Photo – Trap}}{\text{Nr of photons detected by a 'naked' SiPM}} \]

\[ TE = \frac{\text{Nr of photons that hit the SiPM}}{\text{Nr of incident photons}} \]

Note that

\[ G = \frac{S_{\text{WLS}}}{S_{\text{SiPM}}} \cdot TE \]

Note that

\[ PDE(\text{Photo – Trap}) \approx TE \cdot PDE(\text{SiPM}) \]
Optical gain/ Trapping efficiency

- Filter allows to increase the efficiency by > 25%

- With simulations we could identify some critical factors affecting the trapping efficiency:
  - Thickness of the gaps between WLS and filter/reflectors
  - Walls reflectivity and filter properties
  - Surface roughness…

Plot by C. Wunderlich
Optical Gain/Trapping efficiency

<table>
<thead>
<tr>
<th>Nr.</th>
<th>$S_{WLS}$ [mm$^2$]</th>
<th>$S_{SiPM}$ [mm$^2$]</th>
<th>$S_{WLS} / S_{SiPM}$</th>
<th>Optical Gain</th>
<th>Trapping efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>20 $\times$ 20</td>
<td>3 $\times$ 3</td>
<td>~42</td>
<td>~10</td>
<td>~24%</td>
</tr>
<tr>
<td>II</td>
<td>20 $\times$ 20</td>
<td>3 $\times$ 12</td>
<td>~10</td>
<td>~5</td>
<td>~50%</td>
</tr>
<tr>
<td>III</td>
<td>40 $\times$ 40</td>
<td>3 $\times$ 3</td>
<td>~170</td>
<td>~15</td>
<td>~10%</td>
</tr>
<tr>
<td>IV</td>
<td>40 $\times$ 40</td>
<td>3 $\times$ 12</td>
<td>~42</td>
<td>~12</td>
<td>~26%</td>
</tr>
</tbody>
</table>
Position-dependent sensitivity

3x3 mm² SiPM – 2x2 cm² WLS

3x12 mm² SiPM – 2x2 cm² WLS

3x3 mm² SiPM – 4x4 cm² WLS

3x12 mm² SiPM – 4x4 cm² WLS
Timing performance

Prototype III: 3x3 mm$^2$ SiPM – 4x4 cm$^2$ WLS

- Timing measurements performed using Advatech AMP-0611 preamp (~0.7 ns rise time) and pulsed LED

- Photo-Trap induces a **degradation of the timing performance** (w.r.t. the *naked* SiPM) which is due to:
  - Re-emission time profile of the WLS
  - Distribution of the total path traveled by photons before reaching the SiPM
    → **Timing** is better in pixels with lower $S_{WLS}/S_{SiPM}$
    → Distributing SiPMs in the WLS improves the timing

- For all the 4 prototypes, the **additional degradation** of the time resolution is of ~2-3 ns
Performance summary

<table>
<thead>
<tr>
<th></th>
<th>PMT</th>
<th>SiPM</th>
<th>Photo-Trap</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDE*</td>
<td>~35%</td>
<td>~50%</td>
<td>~5-25 %</td>
</tr>
<tr>
<td>Time resolution [ns]</td>
<td>~1</td>
<td>~0.1</td>
<td>~2-3</td>
</tr>
<tr>
<td>High-Voltage</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Compactness</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Ambient light exposure</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Sensitive to Magnetic field</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Largest Area [cm²]</td>
<td>~10²</td>
<td>~10¹</td>
<td>~10¹</td>
</tr>
<tr>
<td>DCR* [kHz/mm²]</td>
<td>~50</td>
<td>~0.2-5</td>
<td>~0.2-5</td>
</tr>
<tr>
<td>Capacitance/mm²</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Cost/mm²</td>
<td>Low-Medium</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

* “Educated” rough values at room temperature and ~375 nm

- WLS and filter should be optimized depending on the application (e.g.: background rejection)
- A wider sensitivity spectrum can be achieved by combining different WLS
- Distributing SiPMs in different positions of the WLS will improve sensitivity and timing (but also cost and readout complexity).
- Performance can probably be improved with a non “home-made” production
Applications and further developments
In general, Photo-Trap could be useful...

- When efficiency loss can be compensated with a larger detection area
- When wavelength shifting can increase the detection efficiency
- When low noise at room temperature is required
- When a sensitivity in a specific wavelength band is desired
- When cost is a limitation...

Amanor et al. (2018)
Further developments...

Photo-Trap was funded by a INFN CSN5 call for young researchers (22260/2020). Special thanks to J. Cortina (CIEMAT), the ‘father’ of this project and to all who participated in the developments of the Light-Trap: D. Estrada, J.L. Garcia, A. Mihi (ICMAB), J. E. Ward, E. Do Souto, O. Blanch (IFAE).
Bakcup
Wavelength shifter

Eljen EJ-286 WLS plastic

- Sensitivity at ~ 320 - 390 nm
- Peak Emission ~ 420 nm
- Thickness [mm]: 3
- Area [mm$^2$]: 20 x 20 / 40 x 40
- Substrate material: PVT/PS
- Decay time [ns] ~ 1.2
- Light Yield ~ 92%
Filter

Asahi ZUV0400 UV-pass filter

- Size: 50x50x1 mm³ (CA: 46x46 mm²)
- Wavelength cut ~ 400 nm
- T (0º AOI) > 95% @320-395 nm
- R (0º AOI) > 98% @400-700 nm
SiPM and Electronics

ON MicroFJ-30035 SiPMs
Active area: 3.07 x 3.07 mm²
Nominal chip size: 3.16 x 3.16 mm²

PreAmp home-made Boards
V1 for one SiPM
V2 connects 4 in parallel

Allows to switch between 2 Advatech preAmps:
AMP-0604 (x20 - x60 gain, ~5 ns rise time)
AMP-0611 (x10 - x20 gain, ~0.7 ns rise time)
Mechanics

### Berghof Optopolymer reflective film
- 2 mm thick film
- Diffuse reflection (R~98% > 400 nm)

### SS-998 Optical Grease
- For SiPM-WLS plastic coupling
- Refractive index ~ 1.47
- T~99.99% above 400 nm

### Pixel Holder
- Fast 3D-printed prototype that holds all components
- Designed to apply pressure from SiPM to WLS-plastic
Timing performance

3x3 mm² SiPM – 2x2 cm² WLS

3x12 mm² SiPM – 2x2 cm² WLS
Preliminary results: timing

3x3 mm$^2$ SiPM – 4x4 cm$^2$ WLS

3x12 mm$^2$ SiPM – 4x4 cm$^2$ WLS
Timing performance

3x3 mm$^2$ SiPM – 4x4 cm$^2$ WLS

3x12 mm$^2$ SiPM – 2x2 cm$^2$ WLS

SiPM  
~ 1.2 ns FWHM

Photo-Trap  
~ 3.4 ns FWHM
~ 3.0 ns Decay Time

SiPM  
~ 1.9 ns FWHM

Photo-Trap  
~ 3.2 ns FWHM
~ 2.8 ns Decay Time
Optical Wireless Communication (OWC)

Alternative to RF for wireless communication offering some advantages:

- “Unlicensed” band
- High data rate (potentially >Gbps)
- Directional (secure communication channel)
- LEDs are everywhere!

Turan et al., 2019, https://doi.org/10.1007/978-3-030-24892-5_8
Why Photo-Trap in OWC?

- LEDs have a large emitting angle → Large area and FOV is desired
- High Gain → Single-photon sensitivity → Allows for dimmer sources / Longer links
- Still has the advantages of traditional Pin diodes (compactness, robustness, low voltage operation…)
- Low cost per mm²
- Use of SiPMs in OWC has been explored. Also use of WLS. Never both of them together
- Low PDE ~ 20% (prototype @320-380 nm), but can be compensated with larger area
- Time resolution ~ 2-3 ns. Still good, but may limit maximum data rate
- Low Dark count rate ~2-10 kHz/mm² at ~20 C
- Large sensitive area ~400-1600 mm²
- High background rejection (can be optimized with the proper filter/WLS)