Single-Photon Timing Resolution in Digital Silicon Photomultipliers

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Main objective of this talk

Discuss and propose a standardization methods for SPTR measurements in Digital SiPMs
Outline

- Definition of SPTR
- Digital SiPM architectures
- Setup examples
- Parameters and standardization
- Conclusions
Single-Photon Timing Resolution

“The timing response of a SiPM is represented as a statistical distribution characterized by its precision, accuracy, and bin size (LSB)”
Single-Photon Timing Resolution

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Single-Photon Timing Resolution

“The timing response of a SiPM is represented as a statistical distribution characterized by its precision, accuracy, and bin size (LSB)”
Conditions and techniques

• Single-photon light level
• Uniform illumination over the sensitive area
• TCSPC measurement technique
SPTR impact on applications (PET)

511 keV Gamma Photon

SCINTILLATOR

D-SiPM
SPTR impact on applications (PET)

- 511 keV Gamma Photon
- SCINTILLATOR
- D-SiPM

\[ Q: \text{total photoelectrons} \]
\[ T_r: \text{rise time} \]
\[ T_d: \text{decay time} \]
\[ \sigma: \text{SPTR} \]
SPTR impact on applications (PET)

511 keV Gamma Photon

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D-SiPM

Q: total photoelectrons
$T_r$: rise time
$T_d$: decay time
$\sigma$: SPTR
SPTR impact on applications (PET)

511 keV Gamma Photon

SCINTILLATOR

D-SiPM

\[ p_q(t) = \frac{R!}{(q - 1)!(R - q)!} \left[ 1 - F(t) \right]^{(R-q)} \left[ F(t)^{(q-1)} \right] f(t), \]

Q: total photoelectrons

\( T_r \): rise time

\( T_d \): decay time

\( \sigma \): SPTR

SORTING PROCESS
Digital SiPM architectures
Digital SiPM concepts

digital photon counter (DPC)

6400 SPADs

1 time stamp

T. Frach et al., NSSMIC 2009
Digital SiPM concepts

digital photon counter (DPC)

Multichannel digital SiPM (MD-SiPM)

6400 SPADs

TDC

1 time stamp

26x16 SPADs

48 TDC

48 individual time stamps

T. Frach et al., NSSMIC 2009

S. Mandai et al., NSSMIC 2012
Digital SiPM concepts

digital photon counter (DPC)

- 6400 SPADs
- 1 time stamp
- TDC

Multichannel digital SiPM (MD-SiPM)

- 26x16 SPADs
- 48 individual time stamps
- 48 TDC

3D digital SiPM (3DdSiPM)

- 1 SPAD per TDC
- N individual time stamps

References:

T. Frach et al., NSSMIC 2009
S. Mandai et al., NSSMIC 2012
Pratte et al. 3DIC-IEEE 2010

3D digital photon counter (3DdDPC)
Multichannel digital SiPM (MD-SiPM)
Digital Photon Counter (DPC)

- Each die has 4 pixels
- Two TDCs per die
- 4 sub-pixels
- 3200 or 6400 SPADs per pixel
- Programmable trigger and validation logic
- Individual SPAD cell masking circuitry
- TDC bin size: 24 ps

S. Brunner et al., JINST 2016

T. Frach et al., NSSMIC 2009
9x18 Array of MD-SiPMs

- 9 x 18 MD-SiPMs
- 432 TDCs

- 26x16 SPADs
- 26x16 Pixels
- 26x16 SPADs
9x18 Array of MD-SiPMs architectural overview

- a 2D 9x18 MD-SiPM array.
- 9 TDC banks with each having 48 TDCs.
- configuration memory and masking registers.
- readout logic and discriminator.

Augusto Carimatto; Shingo Mandai; Esteban Venialgo; Ting Gong; Giacomo Borghi; Dennis R. Schaart; Edoardo Charbon. ISSCC, 2015
3D digital SiPM

3D Integration
- high fill factor
- heterogeneous technologies integration

Teledyne Dalsa
Custom process

TSMC CMOS 65 nm
256 SPAD readout ASIC

Pratte et al. 3DIC-IEEE 2010
Digital SiPM overview

Array Readout → Out 1

A) Calibration and correction → Out 2
B) Timestamp sorting → Out 3
C) Dark count filter → Out 4
D) Multi-photon estimation → Out 5

Pratte et al. 3DIC-IEEE 2010

256 Pixels

Post-processing
Setup examples
Typical setup (MD-SiPM)

**picosecond Laser**
- power
- repetition rate
- wavelength
- pulse width (40 ps)

**Advanced laser diode systems.** EIG1000 AF.
Head: PiL040F, 405 nm, SANYO laser diode DL-5146-152
Typical setup (MD-SiPM)

- optical interface
  - NDF
  - diffuser
Typical setup (MD-SiPM)

MD-SiPM
- bias voltage
- temperature
- DCR
- .......

SYNC SIGNAL
Typical setup (MD-SiPM)

readout FPGA
- CLK source
- STOP/START

- ML507 Xilinx, Virtex-5
- human data [XCM-206Z]Xilinx Spartan-6 FGG676
- custom Microsemi AGL1000V2–CS281 board
Typical setup (MD-SiPM)

- acquisition computer
  - KDE
  - measurement error
  - calibration procedures

- custom USB-2.0 interface
- ethernet 1Gbps
- matlab/Linux
Typical setup (MD-SiPM)

- NDF
- diffuser
- fan
- MD-SiPM + readout
- picosecond laser head
- PC interface
- synchronization signal
SPTR measurement MD-SiPM

- excess bias voltage
- timing line settings

Sherbrooke’s SPTR setup

optical table
two 2x6' tables
one 2x8' table

PIN → att. → OPO → Mai Tai

PIN → Beam → DUT → Scope

high power

low power

photon starved
Sherbrooke’s SPTR setup

SP- Mai Tai Ultrafast Ti-Sapphire Laser
pulse width: < 100 fs
repetition rate: 80 MHz
wavelength: 690 - 1040 nm
average power: 3.0 W
Sherbrooke’s SPTR setup

SP- Optical Parametric Oscillator
pulse width: < 100 fs
repetition rate: 80 MHz
wavelength: 345 - 2500nm
average power: 100 mW - 1.0 W

PIN  att.  OPO  Mai Tai

Beam  DUT  Scope

low power  high power  photon starved
Sherbrooke’s SPTR setup

- PIN
- att.
- OPO
- Mai Tai
- Beam
- DUT
- Scope

Additional components:

- Variable attenuator
- High power optics
- Glen polarizer
- 1/2 wave plate
- Beam dump

Power levels:

- Low power
- High power

Power states:

- Photon starved
Sherbrooke’s SPTR setup

reference PIN diode
Becker & Hickl PHD-400
200 ps rise time

PIN  att.  OPO  Mai Tai

PIN  Beam  DUT  Scope

high power
low power
photon starved
Sherbrooke’s SPTR setup

low power

PIN → att. → OPO → Mai Tai

DUT → Beam → Scope

high power

photon starved

free space beam propagation
high-end Newport mirrors for ultrafast laser
Sherbrooke’s SPTR setup

**Beam conditioning setup**
- iris, shutter, filter, beam splitter, focusing optics

**high power**
- PIN
- OPO
- Mai Tai

**low power**
- att.

**photon starved**
- Beam
- DUT
- Scope

Jean-Francois.Pratte@USherbrooke.ca
Sherbrooke’s SPTR setup

- PIN
- att.
- OPO
- Mai Tai
- Beam
- DUT
- Scope

- high power
- low power
- photon starved

sample fixture
- automated XYZ-axis stage
- manual tilt, yaw and rotation axis
Sherbrooke’s SPTR setup

- **output signals**
- SMA cable (ref diode and DUT)
- oscilloscope
  - LeCroy SDA 6000A 20 GS/s, 6 GHz
  - Keysight MSOX91304A 80 GS/s, 13 GHz

**Diagram:**
- PIN
- att.
- OPO
- Mai Tai
- Beam
- DUT
- Scope

- **low power**
- **high power**
- **photon starved**

Jean-Francois.Pratte@USherbrooke.ca
Beam conditioning setup

- laser input for SPTR measurements
- neutral density filters (photon starved)
- beam focusing (down to ~2um spot size)
- XYZ motorized stage (array sweep, ~1um step)
Sherbrooke’s SPTR setup
**Typical SPTR acquisition**

A SPAD SPTR acquisition
- time delay between the SPAD output (pink) and the ref. signal (blue)
- histogram building (100k events)
- FWHM extract

\[
\sigma^2_{\text{mesured}} = \sigma^2_{\text{setup}} + \sigma^2_{\text{detector}}
\]

**Setup jitter**
- PIN ref diode pulse to pulse jitter
- include electronic jitter (SMA, scope)
- include Mai Tai / OPO pulse to pulse jitter (negligible)
- Value: 3-4 ps FWHM
SPAD + front-end SPTR

- TSMC 65 nm
- SPAD implemented for test purpose (and fun)
- 20 µm diameter

SPTR: 8.9 ps FWHM
DPC SPTR (measurement setup)

S. Brunner et al., JINST 2016
## DPC SPTR (results)

<table>
<thead>
<tr>
<th>DPC</th>
<th>Active area</th>
<th>Temp. [°C]</th>
<th>Inactive cells [%]</th>
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<tr>
<td>3200</td>
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<td>10</td>
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<td>16 ±2.4</td>
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S. Brunner et al., JINST 2016
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Masking level
Parameters and standardization
Timing propagation (architecture)

- quenching circuit
- detection circuit
- masking memory
- bias voltages

Timing line:
- detection circuit
- threshold bias voltage

Readout:
- event discriminator
- operation mode

TDC:
- single-shot resolution range
- LSB
- INL/DNL
Timing propagation (architecture)

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**TDC:**
- Single-shot resolution range
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Common architectural components

- Time-to-digital converters (LSB, INL, DNL, SSR)
  - several TDCs: best, worst, and median
- Operation mode
  - event discriminator, triggering system, reset system, measurement range
- SPAD-cell operation
  - masking [%], excess bias, quenching, TH, activated area
- Timing line settings and characterization
  - inverter, comparator TH, preamplifier
Timing measurement (setup)
Timing measurement (setup)

- **Laser:**
  - Pulse width
  - Power
  - Wavelength
  - Repetition rate

- **Optics:**
  - Attenuator
  - Diffuser
  - Optical parametric oscillator
  - Mirrors
  - Splitters

- **Digital SiPM**

- **Electrical Reference**

- **Readout FPGA**
Common setup components

• Optical components
  – light attenuator (SPAD rate, single-photon level)
  – light diffuser (uniformity). SPAD camera measurement
  – etc

• Laser system
  – pulse width, wavelength, CLK jitter, repetition rate

• D-SiPM controller and synchronization system with respect to the laser pulse
  – optical/electrical

• Measurement conditions: temperature, power, heatsinks, etc
Conclusions

• Digital SiPM standardization relies on two main aspects: the D-SiPM architecture and the measurement setup.
• In a standardization procedure, the common architectural parameters are established and specific features related to timing are also reported.
• The measurement setup can be divided into two types: high timing resolution (<100 ps) and standard timing resolution (>100 ps).
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References