How to build your own picosecond light source

Martin Rongen
Workshop on Pico-Second Timing Detectors
May 2018, Torino

arXiv:1805.00822
(to be published in JINST)
ps-Neutrino Astronomy?

IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

IceCube
50 m

IceTap

86 strings of DOMs, set 125 meters apart

1450 m

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

2450 m

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

60 DOMs on each string

DOMs are 17 meters apart

Antarctic bedrock
The challenge at hand

- The calibration of single photon sensors (PMTs, SiPMs, ...) requires fast light sources

- PMT TTS $\sigma \sim 2\text{ns}$, SiPM SPTR $\sim 300\text{ps}$ → light source should be $<< 1\text{ns}$

- The $\$\€\€$ problem: Commercial laser or LED solutions cost $\sim 5k\€ + 1-5k\€$ per $\lambda$

- Usual pulsers in our field (Kapustinsky) only deliver multi-ns pulses

Can we build that ourselves?
Reverse biased (closed) transistors can exhibit an avalanche breakdown at high voltages (~80V) which is faster than the usual switching speed.

80ps rise time pulser based on this principle designed by Jim Williams 1994.
100GS/s measurements

- First evaluate speed of prototype pulser, with Tektronix MSO71254C 100GS/s 12.5GHz Oscilloscope and P7380A 8GHz (<55ps) probe
- Waveform is bipolar (good for sweep-out effect)
- 80ps rise time, with 170ps FWHM

![Waveform graph showing rise time and FWHM](image)
Sweep-out and biasing

- Charges can get trapped in depletion layer, resulting in long duration light curve after turn off
- Bias undershooting voltage charges are removed

- For brightness control a pulse height control is necessary
- Scaling sub-ns pulses is extremely difficult
- LEDs only “see” the voltage above the forward voltage → biasing is sufficient

DOI: 10.1063/1.4817538
The Pulser Module

- Combine pulse driver, biasing (with control ADC), internal / external trigger control and monitoring, and microcontroller in a handy package

- Light source (LED, VCSEL) on a separate SMA connectorized PCB with fiber connector for easy interchange
Vertical Cavity Surface Emitting Lasers

- Semi-conductor laser *technical blah blah* (I don't claim to understand it...)
- BUT it does not matter because to us it essentially behaves like a quick LED (two pins, apply a sufficiently large forward voltage and it will emit light)

- OPR2800V 850nm VCSEL (~5$ per piece):
  - 100ps 10%-80% rise and fall times
  - ~1.9V forward voltage, ~35Ω series resistance
  - 24° beam width, 0.3 mW/mA optical power

- Used for high speed fiber communication

- Only available for infrared → use fast LEDs below 800nm
Avalanche Photo Diode detector

- IDQ ID100-EDU 50um Avalanche Photo Diode detector
- ~400Hz dark noise rate

- 40ps typ., max. 60ps FWHM timing resolution (assuming a Gaussian → FWHM=2.355σ → σ=17-25ps)

- Given ≥1 photon detected triggers a digital output pulse (2V, 10ns)
**Time-to-Digital Converter**

- Texas Instruments TDC7200

- ~5€ per chip in single quantity
  ~100€ for a complete evaluation kit with TDC, oscillator, SMA inputs, micro-controller and software

- Counts clock cycles of a multiple-GHz ring oscillator (undetermined frequency), which is calibrated against an external precision 8 MHz clock

- Not as precise as DRS4 + dCFD (~5ps for TTL) but so much cheaper and easier

1. **Features**
   - Resolution: 55 ps
   - Standard Deviation: 35 ps
   - Measurement Range:
     - Mode 1: 12 ns to 500 ns
     - Mode 2: 250 ns to 8 ms
TDC performance

- Generate two TTL pulses spaced 100ns apart with QuantumComposer
- Measure time difference with TDC7200 → datasheet claim is correct!
Light curve

- Optical trigger jitter measured at maximum brightness (sample the first photon)
- Light curve measured by attenuating the pulse to 10% occupancy
- Light curve ~100ps std. when neglecting the long duration tail
  → see next slide

Trigger Jitter

850nm VCSEL triggered light curve

Instrument response function as measured by Becker & Hickl GmbH
Light curve

Although the fast APD has a narrow main peak, it also has an exponential tail that persists for hundreds of picoseconds. This diffusion tail, which is typical of APDs, is caused by the slow diffusion of photoexcited carriers from the neutral region into the high-field region of the device.

- „Fast lifetime measurements of infrared emitters using a low-jitter superconducting single-photon detector“
  - M.J.Stevens et.al.

- No IRF available at 850nm
- IR diffusion tail fitted as exponential and removed from measurement
<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>0pF</th>
<th>4pF</th>
<th>8pF</th>
</tr>
</thead>
<tbody>
<tr>
<td>370nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>375nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full dynamic range &amp; &lt;1ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>385nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;1ns but not full dynamic range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>405nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3V, &gt;1ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>430nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>no light</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>470nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+0.4V, &gt;1ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>565nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.0V, &gt;1ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>590nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+0.5V 600ps</td>
<td>-2.5V, 400ps</td>
<td>-2.5V, 550ps</td>
<td></td>
</tr>
<tr>
<td>LED performance matrix</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **385nm, 10pF**:
  - $\sigma \approx 280$ ps

- **VCSEL**:
  - -2.5V, 150ps
  - -2.5V, 270ps
  - -2.5V, 420ps

- **Full dynamic range & <1ns**:
  - 385nm

- **<1ns but not full dynamic range**:
  - 590nm

- **VCSEL**:
  - -2.5V, >1ns
Intensity Measurement

- 2.5V biasing
- 2.07e+06 photons per pulse (~10% systematic error)

PD3
S2281-01

Gain 1µV/fA

1.09GΩ

2.2nF

2.2nF

KEMET C0G GOLD MAX

Gain 101x

MAX4252
10.00KΩ

1.000MQ

100nF PPS

MAX4252

Cable to 16-bit ADCs
LSB=8–63µV

Gain 1x

AD8627

MAX4252

Pedestal 2.5V

Ref.

\[ QE_\lambda = \frac{R_\lambda}{\lambda} \cdot \frac{h \cdot c}{e} \approx (1240 \text{ W/A/nm}) \cdot \frac{R_\lambda}{\lambda} \]
Commercial availability
Summary and Outlook

- Williams pulser, biasing and careful triggering = great light source
- Using an APD+TDC setup the light curve is characterized at high precision
- Using a photodiode setup the average photon number per pulse is measured
- LEDs & VCSEL cover wide wavelength range at sub-ns timing precision & $10^4$ to $10^9$ photons per pulse
- Units are available for purchase
  & all design files have been released under the Creative Commons Attribution Non-Commercial Share-Alike 4.0 License

Be sure to visit [mrongen.de](#)

Custom picosecond light sources

Thank you for your attention!
Questions are welcome...