Single-photon Detector Overview

• Key metrics
• PMTs
• APDs
• Superconducting
  • TES
  • Nanowire
Key Metrics

- efficiency – how likely to detect a photon
- dark counts – how much noise in the absence of light
- deadtime – how long after detection before ready
- afterpulsing – how often is there a secondary signal
- jitter – what time resolution does a detection have
- latency – how long to get a signal out
- photon-number resolving?
- operating temperature
- $$$
Invited Review Article: Single-photon sources and detectors

M. D. Eisaman, J. Fan, A. Migdall, and S. V. Polyakov
National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA
and Joint Quantum Institute, University of Maryland, College Park, Maryland 20742, USA

(Received 14 December 2010; accepted 7 June 2011; published online 27 July 2011)

We review the current status of single-photon-source and single-photon-detector technologies operating at wavelengths from the ultraviolet to the infrared. We discuss applications of these technologies to quantum communication, a field currently driving much of the development of single-photon sources and detectors. © 2011 American Institute of Physics. [doi:10.1063/1.3610677]
**Photomultiplier Tube**

![Diagram of Photomultiplier Tube](image)

### Table: Photomultiplier Performance

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Operation temperature (K)</th>
<th>Detection efficiency, (\eta)%, (\lambda) (nm)</th>
<th>Timing jitter, (\delta t) (ns) (FWHM)</th>
<th>Dark-count rate, (D) (ungated) (1/s)</th>
<th>Max. count rate (10^6/s)</th>
<th>PNR capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT (visible–near-infrared)</td>
<td>300</td>
<td>40 @ 500</td>
<td>0.3</td>
<td>100</td>
<td>10</td>
<td>Some</td>
</tr>
<tr>
<td>PMT (infrared)</td>
<td>200</td>
<td>2 @ 1550</td>
<td>0.3</td>
<td>200 000</td>
<td>10</td>
<td>Some</td>
</tr>
</tbody>
</table>
## Avalanche Photodiode

![Avalanche Photodiode Diagram](image)

### Table of Parameters

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Operation temperature (K)</th>
<th>Detection efficiency, wavelength (η%, λ (nm))</th>
<th>Timing jitter, δt (ns) (FWHM)</th>
<th>Dark-count rate, D (ungated) (1/s)</th>
<th>Max. count rate (10^6/s)</th>
<th>PNR capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si SPAD (thick junction)</td>
<td>250</td>
<td>65 @ 650</td>
<td>0.4</td>
<td>25</td>
<td>10</td>
<td>None</td>
</tr>
<tr>
<td>Si SPAD (shallow junction)</td>
<td>250</td>
<td>49 @ 550</td>
<td>0.035</td>
<td>25</td>
<td>10</td>
<td>None</td>
</tr>
<tr>
<td>InGaAs SPAD (gated)</td>
<td>200</td>
<td>10 @ 1550</td>
<td>0.370</td>
<td>91</td>
<td>0.01</td>
<td>None</td>
</tr>
<tr>
<td>InGaAs SPAD (self-differencing)</td>
<td>240</td>
<td>10 @ 1550</td>
<td>0.055</td>
<td>16 000</td>
<td>100</td>
<td>None</td>
</tr>
</tbody>
</table>
Superconducting Transition Edge Sensor (TES)

Calorimetric detection of UV/optical/IR photons

Fiber coupled self-aligned TES < 1% coupling loss

Superconducting Nanowire Single-photon Detectors (SNSPDs)

![Image of detector](image.png)

Figure 2.1: Scanning Electron Microscope (SEM) image of a detector. The highlighted region is what we expect to be the active area for photon detection. The image was supplied by K. Rim from the Institute for Micro- and Nanoelectronic Systems.

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Operation temperature (K)</th>
<th>Detection efficiency, wavelength $\eta$(%), $\lambda$ (nm)</th>
<th>Timing jitter, $\delta t$(ns) (FWHM)</th>
<th>Dark-count rate, $D$ (ungated) (1/s)</th>
<th>Max. count rate ($10^6$/s)</th>
<th>PNR capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNSPD</td>
<td>3</td>
<td>0.7 @ 1550</td>
<td>0.06</td>
<td>10</td>
<td>100</td>
<td>None</td>
</tr>
<tr>
<td>SNSPD (in cavity)</td>
<td>1.5</td>
<td>57 @ 1550</td>
<td>0.03</td>
<td>...</td>
<td>1000</td>
<td>None</td>
</tr>
</tbody>
</table>
Superconducting Nanowire Single-photon Detectors (SNSPDs)

Detector type | Operation temperature (K) | Detection efficiency, wavelength, $\eta(\%)$, $\lambda$ (nm) | Timing jitter, $\delta t$ (ns) (FWHM) | Dark-count rate, $D$ (ungated) (1/s) | Max. count rate (10^6/s) | PNR capability
--- | --- | --- | --- | --- | --- | ---
SNSPD | 3 | 0.7 @ 1550 | 0.06 | 10 | 100 | None
SNSPD (in cavity) | 1.5 | 57 @ 1550 | 0.03 | ... | 1000 | None
Parallel SNSPD | 2 | 2 @ 1300 | 0.05 | 0.15 | 1000 | Some

Figure 2.1: Scanning Electron Microscope (SEM) image of a detector. The highlighted region is what we expect to be the active area for photon detection. The image was supplied by K. Rim from the Institut für Mikro- und Nanoelektronik, Stuttgart.
Multi-photon detection using a conventional superconducting nanowire single-photon detector

Clinton Cahall, Kathryn L. Nicolic, Nurul T. Islam, Gregory P. Lafyatis, Aaron J. Miller, Daniel J. Gauthier, and Jungsang Kim

We present the first evidence of multi-photon detection using a conventional superconducting nanowire single-photon detector, indicating number resolution up to four photons. The observed multi-photon detection statistics are consistent with the predictions of our model. © 2017 Optical Society of America

Fig. 2. Histograms of the peak height of differentiated detection waveforms. Each data set is fit with a sum of Gaussian functions, where the integral of each peak is constrained to follow the expected Poisson statistics. The arrows with corresponding error bars show predicted values of the peaks from the electro-thermal model and finite-bandwidth amplifiers.
Multi-Photon Detection with SNSPDs

- Photon absorption creates a resistive ‘hot-spot’
- Bias current is diverted to a parallel load resistor
- Rise time of the pulse depends on hot-spot resistance
- Multi-photon events lead to faster rise times

Detector Bias, SNSPD

\[ R_{hs} \sim L_k / R_{hs} \]
Readout Circuit and Output Waveforms

SNSPD

Amp

Coax

Differentiating Circuit

Normal Waveform

Differentiated Waveform

3-Photon

2-Photon

1-Photon

Voltage (mV)

Time (ns)

3-Photon

2-Photon

1-Photon

Voltage (mV)

Time (ns)
Single-photon Vision

- Can you SEE single photons?
- At this moment you are detecting \( \sim 10^{16} \) photons every second. But could you see just one?
- No one knows. Past experiments suggested a minimum threshold as high as 8, as low as 1 or 2.
- Now we can give a definitive answer…

PGK, Anthony Leggett
Ranxiao Frances Wang (UIUC Psychology)

**Michelle Victora, Julia Spina (GS)**
Recordings from single rods

Figure 2: (a) A single rod photoreceptor cell from a toad, in a suction pipette. Viewing is with infrared light, and the bright bar is a stimulus of 500 nm light. (b) Equivalent electrical circuit for recording the current across the cell membrane. (c) Mean current in response to light flashes of varying intensity. Smallest response is to flashes that deliver a mean ~ 4 photons, successive flashes are brighter by factors of 4. (d) Current responses to repeated dim light flashes at times indicated by the tick marks. Note the distinct classes of responses to zero, one or two photons. From [Rieke & Baylor 1998a].
“Heralded” Single-Photon Source

Spontaneous Parametric Downconversion:

\[ \omega_p \rightarrow \omega_s \rightarrow \omega_i \]

\[ k_p \rightarrow k_s \rightarrow k_i \]

Heralded single-photon source diagram:

- Pump laser (Nd:YAG 6 kHz)
- BBO (BBO crystal for nonlinear optical processes)
- Bandpass filter
- 25-m SMF (Single-Mode Fiber) for optical delay
- FPGA (Field-Programmable Gate Array) for computer control
- Totally external modulator (TREMO) to produce signal and heralded single photons
- PC (Personal Computer) for processing
- PBS (Polarizing Beam Splitters) for polarization control
- HWP (Hänsch-Wallman Prisms) for waveplate operation

Observer viewing station:
- Visual field with fixation cross
- LED for right and left light signals

P(n) distribution:
- P(1) = 0.999999999...
- P(2) = 0.000000001...

Random results displayed to observer.
700-nm fixation light

505-nm targets

40°

30 cm

10-μm diameter spots at 20° on the nasal and temporal retina of the left eye
Single-Photon Vision Experiment

Researcher area

Subject area

Single-photon source

Computer

Observer presses a key to indicate on which side the photon appeared, with 3 confidence levels.
Single-Photon Vision Experiment

Current Status:
Weak LED and N-photon trials show SOME subjects can reliably detect <30 incident photons (~3 at the retina)

Temporal integration time of the eye longer than expected (~800 ms)

New single-photon trials underway

Can YOU see single photons?
http://research.physics.illinois.edu/QI/Photonics/vision/
“Each photon then interferes only with itself. Interference between two different photons never occurs.”

-P.A.M.* Dirac

On Hanbury-Brown Twiss correlations: “…if such a positive correlation did exist, it would call for a major revision of some fundamental concepts in quantum mechanics.”

-Brannen and Ferguson

*Paul Adrien Maurice
Hanbury Brown and Twiss '56

Pound and Rebka '57

Coincidence rate vs Delay time
Hanbury-Brown and Twiss

“Michelson Stellar Interferometry” -- Measure field-field correlations

“HBT Interferometry” -- Measure intensity-intensity correlations
Evaporatively cooled metastable He (which one??)
Comparison of the Hanbury Brown–Twiss effect for bosons and fermions

T. Jeltes\textsuperscript{1}, J. M. McNamara\textsuperscript{1}, W. Hogervorst\textsuperscript{1}, W. Vassen\textsuperscript{1}, V. Krachmalnicoff\textsuperscript{2}, M. Schellekens\textsuperscript{2}, A. Perrin\textsuperscript{2}, H. Chang\textsuperscript{2}, D. Boiron\textsuperscript{2}, A. Aspect\textsuperscript{2} & C. I. Westbrook\textsuperscript{2}

Figure 2 | Normalized correlation functions for $^4\text{He}^+$ (bosons) in the upper plot, and $^3\text{He}^+$ (fermions) in the lower plot. Both functions are measured at the same cloud temperature (0.5 \textmu K), and with identical trap parameters. Error bars correspond to the square root of the number of pairs in each bin.