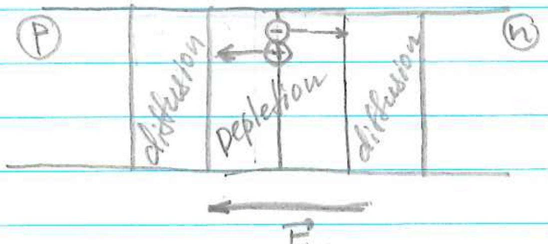
Photodetectors

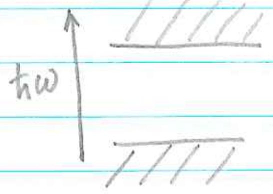
Thermal	Quantum
Convert light energy into ΔT, measure ΔT	Use "quantum" nature of EM field, photons

Until reecently, thermal detectors have been mostly used to detect powerful Optical filds (ultrafast laser pulses, > 1W lasers), or longer - wavelength radiation.

General principle of the quantum photodetector.

I. Regular p-n (or p-i-n) junction





In equilibrium, electrons tend to diffuse into p-doped material, and holes would drift into n-doped material, developing a voltage difference, that eventually counter balance the diffusion Thus, the junction "depletion" region is starved of charge carriers, and does not conduct.

Due to a photoelectric effect pairs of electrons and holes are created, producing a photo current that is measured.

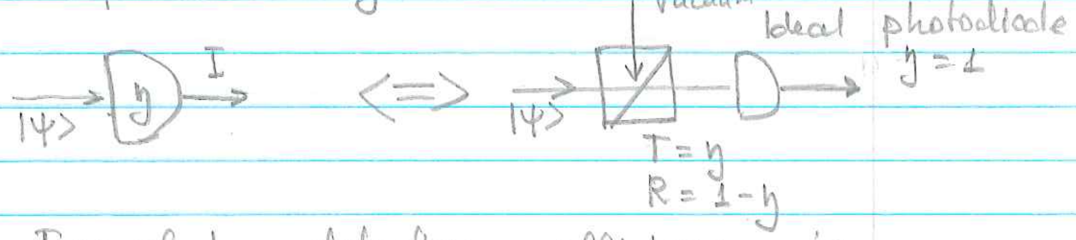
Ideally, each photon produces an electron, so the measured current is proportional to the number of photons in the optical field.

Characteristics of a real photodetectors

1. Spectral range: determined by the bandgap of the material
   Si: visible ($0.4-0.9\ \mu m$) (In-doped - $0.2-0.8\mu m$)
   Ge: near-IR ($1-2\ \mu m$)

2. Quantum efficiency $\eta = \frac{N_{photons}}{N_{electrons}}$
   regular photodione — 0.8-0.9
   can be improved to 0.95-0.98

Real photodiode $\eta < 1$



Imperfect detection efficiency is equivalent to a beam-splitter before an ideal detector.

3. Responsivity of the photodetector: ratio b/w photo current and incident optical power

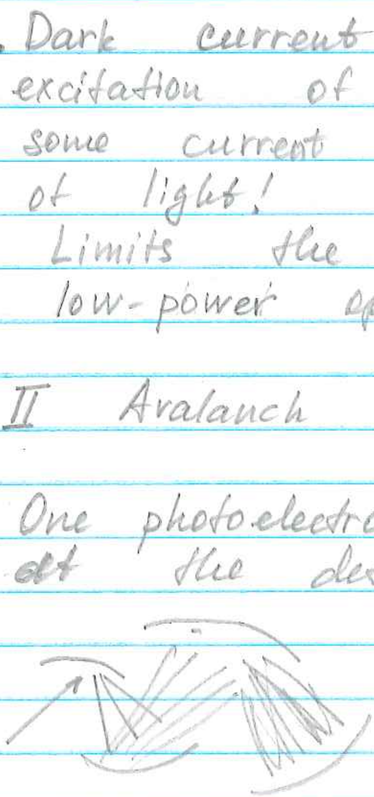
$$I_{pe} = e \cdot \underbrace{\frac{P}{\hbar\omega}}_{flux} \cdot \eta \cdot \underbrace{(1-e^{\alpha L})}_{absorption,\ ideally\ \simeq 1}$$

$$\text{Responsivity}\quad R = \frac{e\eta}{\hbar\omega}(1-e^{\alpha L}) \leq \frac{e}{\hbar\omega}\ \left(\begin{matrix}\text{ideal}\\ \text{detector}\end{matrix}\right)$$

4. Dark current – due to thermal excitation of carriers, there may be some current even in the absence of light!
Limits the ability to measure low-power optical fields.

II Avalanch photodetectors / photomultipliers (PMT)

One photoelectron produses many electrons at the detection point.



Electrons are accelerated by high voltage, so that each electron knocks out multipe $\bar{e}$ on each consequitive plate, exponentially increasing the number of electrons.

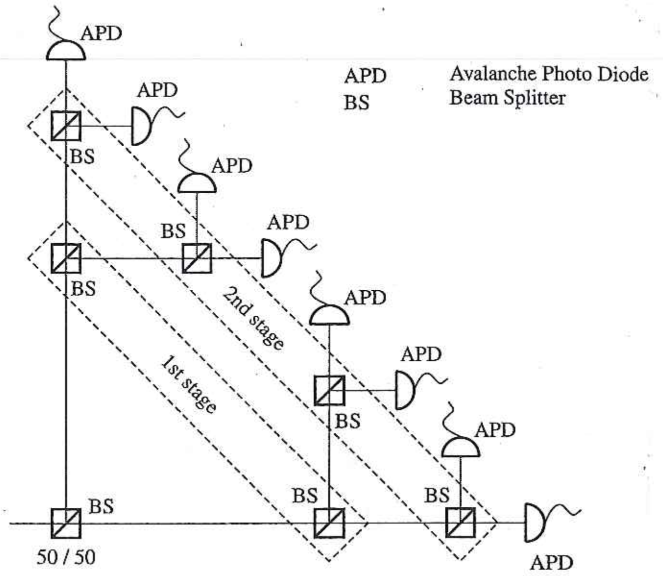
Pro: Very sensitive → can measure a single photon

Con: cannot distinguish the number of photons, not very high QE ($\leq 50\%$)

Possible solutions: multi-plexing

Spatial multiplexing

Fig. 5.7. Multiplexed detection schemes. Avalanche photodiodes respond to single photons, but cannot discriminate between one or more detected photons. Multiplexing is a way around this problem. The incident light is distributed to an array of avalanche photodiodes by an arrangement of beam splitters. Each individual detector rarely encounters more than one photon; so the whole device accurately measures the number of photons. Reproduced with permission from Silberhorn (2007).



Temporal multiplexing

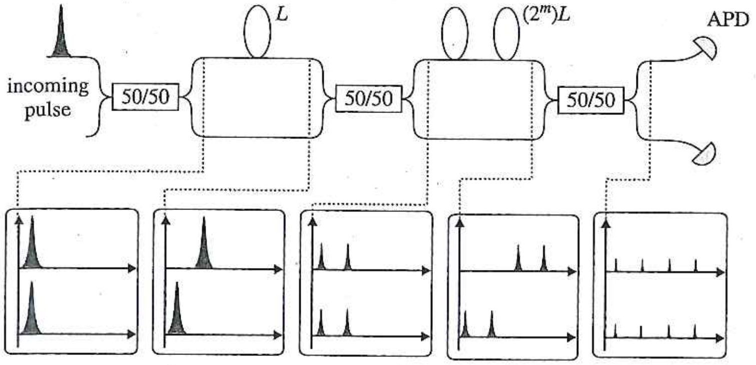


Fig. 5.8. Time-multiplexed detector. The fibre couplers and loops multiplex a pulse of light in time such that two avalanche photodiodes are sufficient for measuring the photon number. This simple scheme replaces the experimentally more complicated one of Fig. 5.7. Reproduced with permission from (Silberhorn, 2007).

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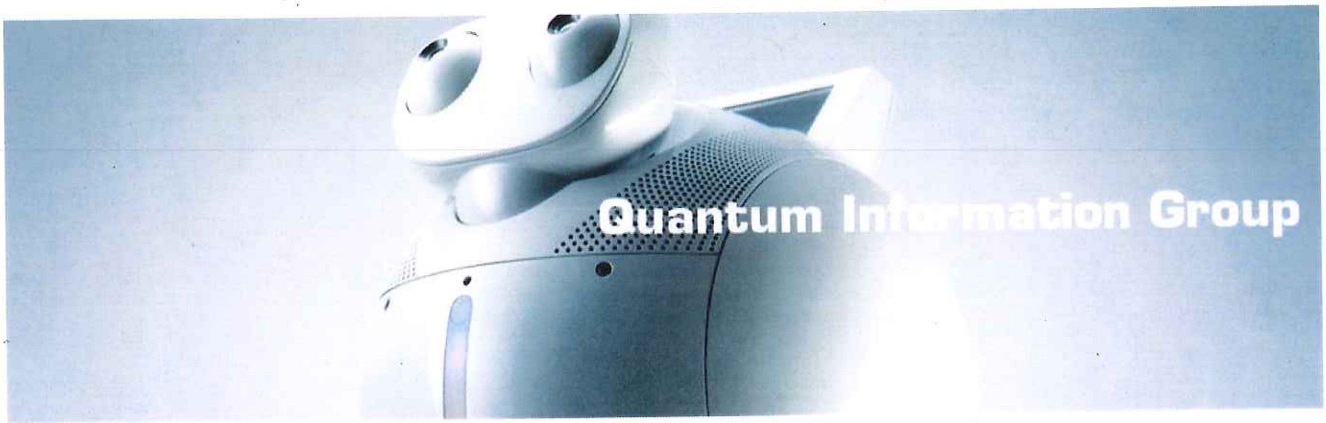
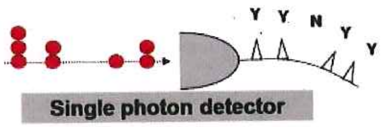
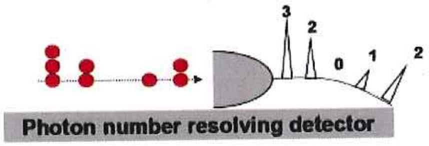


Photon Number Resolving Detector

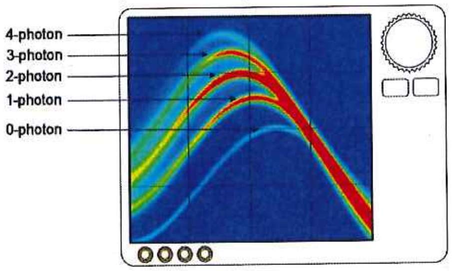
Single photon detectors which respond equally to one or more incident photons are relatively common. However, for many applications in quantum information technology we require a detector that can distinguish between different numbers of photons. We have realised a practical semiconductor device that can resolve the photon number in each incident light pulse.





A photon number resolving detector can be used to signal the successful operation of photonic gates used in quantum computers, as well as in quantum teleportation. Our detectors could also be used for quantum imaging and tomography, as well as the generation and characterisation of quantum light states. More generally, these detectors can make measurements limited only by the fundamental level of quantum noise, in low-light applications such as biomedical imaging, astronomy and optical range-finding.

Output of the Toshiba photon number resolving detector



Our detectors exploit small, unsaturated signals from avalanche photodiodes. Avalanche photodiodes are semiconductor devices which allow a single photon to generate a large photocurrent via avalanche multiplication, much like a single snowflake triggering an avalanche of snow. In a single photon detector this charge will grow until it saturates the device, giving a fixed output regardless of the number of incident photons. In our photon number resolving detectors we prevent this from happening by gating the detector, which limits the time for avalanche growth to less than 1 nanosecond. The output signal is proportional to the number of avalanches, which can be clearly discriminated, allowing the photon number to be determined. We have demonstrated this principle in uniform detectors [1,2] as well as using spatially-multiplexed devices, in which avalanches generated in separate zones within a single small-area diode are summed to give the photon number [3].

Because these detectors operate close to room temperature, are compact, scalable and simple to fabricate, our approach is ideal for a wide range of applications in quantum photonics.

Further Information:

[1] B. E. Kardynal, Z. L. Yuan and A. J. Shields, Nature Photonics 2, 425-428 (2008)
[2] O. Thomas, Z. L. Yuan, J. F. Dynes, A. W. Sharpe and A. J. Shields, Appl. Phys. Lett. 97, 031102 (2010)
[3] O. Thomas, Z. L. Yuan and A. J. Shields, Nature Communications 3, 644 (2012)

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