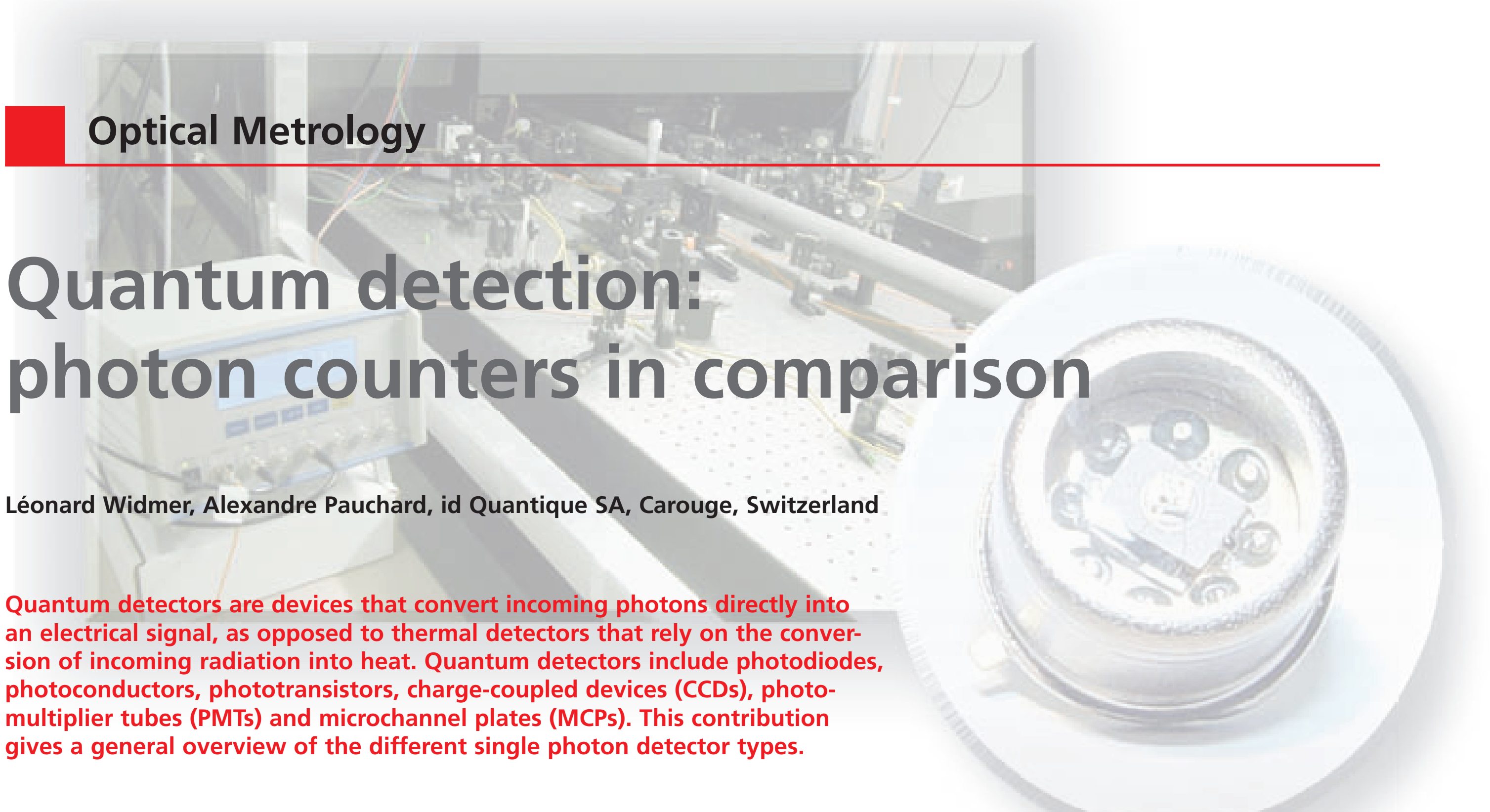

Quantum detection: photon counters in comparison

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Quantum detectors are devices that convert incoming photons directly into an electrical signal, as opposed to thermal detectors that rely on the conversion of incoming radiation into heat. Quantum detectors include photodiodes, photoconductors, phototransistors, charge-coupled devices (CCDs), photomultiplier tubes (PMTs) and microchannel plates (MCPs). This contribution gives a general overview of the different single photon detector types.

In a growing number of applications, the detection of single photons – the ultimate limit in detector sensitivity – is required. The availability of high performance photon counters is crucial to continued progress in the fields of quantum information processing, quantum communication, fluorescence analysis, chemical or biological luminescence analysis, single molecule detection, light detection and ranging (LIDAR) and optical time domain reflectometry (OTDR).

1 Non solid-state photon counters

Among the different photon detection methods, photomultiplier tubes (PMTs) and microchannel plates (MCPs) have been produced industrially for a half-century and have long since reached maturity.

Photomultiplier tubes (**figure 1**) have large active areas and are capable of detecting single photons. Consisting of a photo emissive cathode followed by an electron multiplier and an electron collector (anode), the timing resolution of conventional PMTs is limited to about 150 ps. A few PMTs have been optimised to operate in the near-infrared (NIR) wavelength range of 1000-1520 nm, but their quantum efficiency is poor – on the order of 1%.

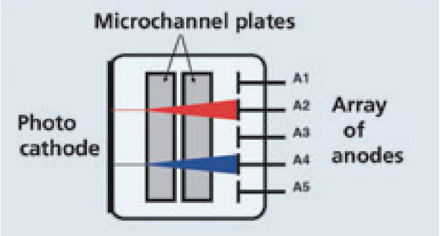

***Figure 2**: Principle of operation of a multi-anode MCP-PMT (image courtesy of Becker&Hickl)*

When high timing accuracy is required, microchannel plates (MCPs) (**figure 2**) are preferred. Consisting of millions of conductive capillaries fused together (with diameters in the range of 4 to 25 µm), some MCPs can achieve very low timing jitter of about 25 ps. However, the devices are very expensive and their count rates are limited to a few megahertz. In addition, MCPs are fragile and bulky, operate under very high bias voltages (up to 3000 V), and are limited to about 20% quantum efficiency in the visible range.

2 Solid-state photon counters

When operated in a linear mode (bias voltage below breakdown), avalanche photodiodes (APDs) are not sensitive enough to detect single photons because the achievable gain is too low. In a 100 Mb/s APD-based receiver operating at 1550 nm, sensitivity in the range of -54 dBm (BER = 1 x 10^{-6}) can be achieved, which corresponds to about 280 photons per bit.

In order to detect single photons, APDs need to be operated in the so-called Geiger mode. The idea is to bias the APD a few volts above the avalanche breakdown voltage, at which point the detector becomes extremely sensitive. When a photon is absorbed and triggers an avalanche process, it results in a huge increase in output current. This current then has to be quenched externally for the APD to return to a state where it is again sensitive.

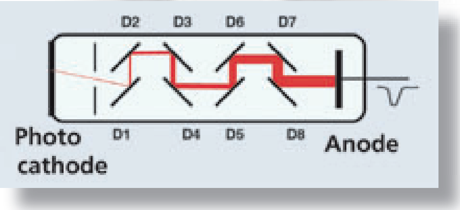

***Figure 1**: Schematic illustrating the principle of a conventional photomultiplier tube (PMT) (image courtesy of Becker&Hickl)*

There are a number of technological limitations to APDs, such as high dark count rate when thermal generation triggers avalanche events. Cooling the detector helps to minimize the impact of these spurious counts; however, electrical carriers can be trapped inside the crystal and released at a later time causing after-pulses. As the lifetime of trapping events increases when the temperature is reduced, there is a trade-off between minimising dark count and after-pulses.

2.1 APDs for the visible spectrum

Commercial photon counting modules based on silicon APDs have been available since the early 1990s. They cover a wavelength range from 350 nm up to 1060 nm and due to their excellent crystal quality achieve the best performance in Geiger mode, with dark counts in the range of a few counts/sec. To achieve maximum quantum efficiency in the red (70% at 700 nm), the devices have a thick depletion region of about 30 µm, resulting in very high timing jitter on the order of 500 ps. More recently, work has focused on reducing the depletion layer thickness to trade-off quantum efficiency in the red for better timing accuracy. The thin depletion layer thickness in the micrometer range results in an extremely low timing jitter of 40 ps (**figure 3** and **figure 4**).

2.2 APDs for the near-infrared spectrum

In the near-infrared spectrum, indium gallium arsenide / indium phosphide (InGaAs/

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Figure 3: *Si-APD in a standard TO5 package (diameter 8 mm), suitable for wavelengths from 350 nm up to 900 nm*

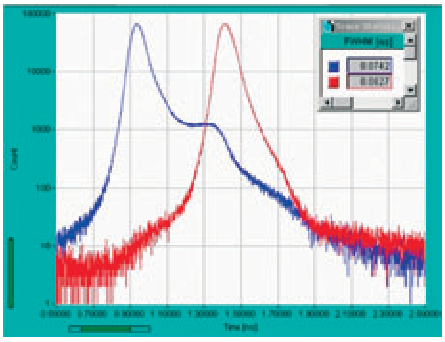

Figure 4: *Comparison of the timing resolution between an Si-APD (red) and an MCP (blue). The MCP has a resolution of 28 ps and the Si-APD a resolution of 47 ps, although the latter is smoother and decays faster*

InP) and germanium (Ge) APDs are the detectors of choice [1]. These devices can also be deployed in photon-starved environments when operated in Geiger mode. Their quantum efficiencies are in the range of 10 to 25% – a large improvement compared to PMTs. Due to the lower crystal quality of the InGaAs/InP and Ge material systems, the dark count rate of these APDs is much higher than that of silicon APDs. For the best InGaAs APDs, the dark count rate is in the range of 40 000 counts/sec when cooled to about -50°C. The APDs are operated in a "gated" mode: an excess voltage of a few volts is applied across the APD during a short gate period (typically 1 to 100 ns). Contrary to their silicon counterparts, InGaAs APDs suffer from a high density of after-pulsing, limiting the usable frequency to a few megahertz.

2.3 Up-conversion for NIR detection

The non-linear process of up-conversion can be exploited to go beyond the detection limits of InGaAs-based APDs. The basic idea, using frequency up-conversion, is to allow an infrared photon to be converted into a visible photon. The process of up-conversion uses sum frequency generation in non-linear optical crystals to combine a weak input signal with a strong laser pump to yield a higher frequency (in other words, shorter wavelength) output signal (**figure 5**). One can then use a Si-APD with much higher efficiency, lower noise and lower after-pulse probability, to detect the up-converted single photons. Contrary to InGaAs-based photon counters which only operate in gated mode, up-conversion-based detectors can operate in a continuous, free running mode. Several

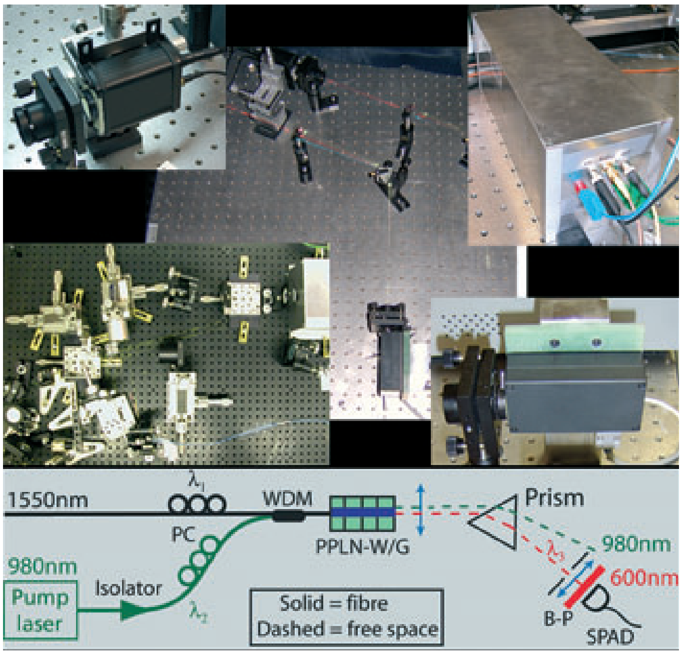

Figure 5: *Principle and implementation of up-conversion using a Periodically Poled Lithium Niobate (PPLN) waveguide. (image courtesy of Univ. of Geneva, GAP Optique)*

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research groups are currently working on up-conversion techniques [2].

Although very promising candidates for high-sensitivity detection at telecom wavelengths (1.3 and 1.55 µm), detectors based on up-conversion will require additional improvements to become viable alternatives to commercial detectors. If such obstacles as nonlinear noise, polarisation sensitivity, and the need for bulky optical components can be overcome, up-conversion holds the promise of fast and free-running operation, with higher detection efficiencies in the NIR than today's commercial products.

3 Superconducting detectors

Another way to improve the performance of single-photon counters beyond that of semiconductors is to take advantage of superconductivity. Superconducting single photon detectors (SSPD), are nanometre thin, ultra narrow superconducting coils operated scarcely below their critical specific current density at approximately 100 mK. By using the sharp super/normal conductivity transition of the tungsten structure, single photons can be detected. Such detectors have already been developed and are in use in some laboratories. However, they do not only have the ability to detect individual photons, as their analogue output current signal is proportional to the cumulative energy of the absorbed photons, thus also to their number, i.e. to the light intensity. The main barrier against the introduction of superconducting detectors is the need for cryogenic cooling, and the corresponding high price. Superconducting detectors are unlikely to be widely adopted unless high temperature superconducting materials become available. The devices could then be cooled thermoelectrically, reducing the overall detector cost.

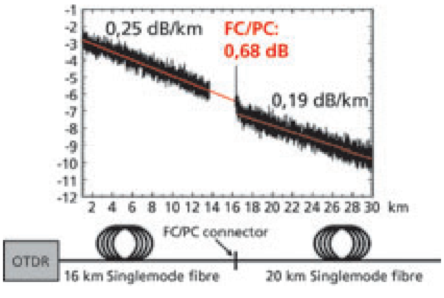

***Figure 7**: OTDR set-up. A series of optical pulses are coupled into the fibre under test, where discontinuities in the refractive index show up as strongly back-scattered light over background back-scattering in the fibre (image courtesy of Univ. of Geneva, GAP Optique)*

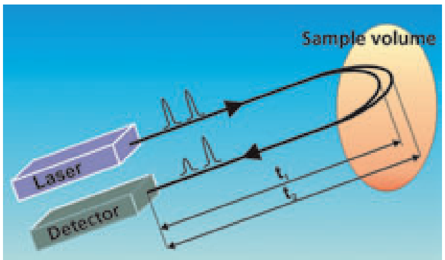

***Figure 6**: Typical LIDAR set-up. A laser sends single light pulses out to the target object and the back-scattered light is detected together with measurement of the transit time*

4 Typical applications for NIR single photon detectors

4.1 LIDAR

LIDAR (light detection and ranging) is a radar (radio detection and ranging) analogous method for distance and speed measurement as well as for remote diagnosis of atmospheric parameters. LIDAR systems for atmospheric measurement send laser pulses and detect the back-scattered light from the atmosphere. From the return time of the signals and the speed of light, the distance (range) can be computed (**figure 6**). With weak back-scattering signals, i.e. if the object lies very far away, single photon detectors are needed.

4.2 OTDR

OTDR, (optical time domain reflectometry) is a procedure for the characterisation of optical fibre. In practice OTDR plays an ever more important role particularly in optical communications technology. With optical time domain reflectometry, short laser pulses are sent into the optical fibre and the back-scattered light is measured over time. Scaling the back-scattered intensity logarithmically (**figure 7**) the losses (in dB/km) in the optical fibre can be accurately determined and precisely located, especially at splices and connectors.

4.3 Quantum information science

Quantum information science concerns communications techniques on the basis of quantum effects. It covers theoretical quantum physics and examines experimentally (**figure 8**) what can be achieved (or not) with quantum information. Sub-topics include quantum cryptography and quantum teleportation.

Quantum cryptography [3] or quantum key distribution (QKD) is a procedure which uses quantum mechanical phenomena to securely distribute a common random

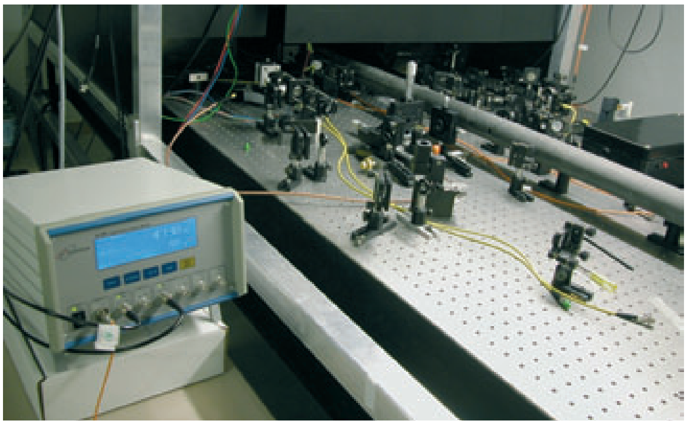

Figure 8: *Laboratory equipped for basic research in the field of quantum cryptography or quantum teleportation. (image courtesy of Univ. of Geneva, GAP Optique)*

number to two parties. The random number can then be used as secret keys, in order to transfer messages by means of classical symmetrical encryption. The advantage of quantum cryptography in relation to conventional key exchange consists of the fact that the security is based on the law of physics, and not on assumption over the efficiency of computers or algorithms. Different procedures for quantum cryptography exist, in particular the transmission of individual photons – for which efficient and reliable single photon detectors are needed.

Quantum physics guarantees the fact that "interception" of individual photons ("hearing" in the sense of the measurement of certain photon parameters) invariably introduces an observable disturbance – their presence proves indisputably that the signal was intercepted.

Quantum teleportation is a technology which transfers a quantum state to a remote place located anywhere. It is based on quantum entanglement, predicted by Einstein, Podolsky and Rosen in 1935 and called the "spooky action at a distance". Quantum teleportation does not transport energy or matter, nor does it permit communication beyond the speed of light. Two "entangled" quanta, photons for example, from a common place are sent in different directions. If one measures – with a suitable single photon detector – a particular state of one of the two photons, then the other photon jumps instantaneously into exactly the same quantum state. Classically, the second photon might be so far remote from the first photon that it could not have any knowledge of the measurement procedure. Only quantum mechanics allows the two photons to previously be in states other than that determined by the measurement. In this area there are still extremely exciting research results to be expected.

4 Summary

Single photon detectors differ by many criteria such as the size of the active surface, quantum efficiency, dark count, price, etc. At present, PMTs are the most widely used single photon detectors. They have the advantage of a large active area at an affordable price. Semiconductor photon counters are disadvantaged by their relatively small active area, have however a timing resolution as low as 40 ps, a high quantum efficiency and low power consumption. Other single photon detectors, which for example use superconducting or up-conversion, offer theoretically better solutions, but are not yet technically sufficiently mature to be commercialised.

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