SINGLE-PHOTON DETECTOR MODULE

APPLICATION NOTE

Single-photon detection with InGaAs/InP avalanche photodiodes

Introduction

When most people think of detecting single-photons, photomultiplier tubes probably spring to their mind. Indeed, for a long time these were the detectors of choice in ultrasensitive detection and spectroscopy. Today, however other types of detectors allow to reach a single-photon sensitivity. Special semiconductor devices called single-photon avalanche diodes (SPAD) have been developed, optimised for this regime and are commercially available. Silicon SPADs exhibit very good performance between 600 and 900 nm: quantum efficiencies for detecting single photons around 60%, dark counts in the absence of light below 100 counts per second and sub-nanosecond timing resolution. The excellent performance of silicon SPADs has enabled significant progresses in luminescence studies, astronomy, sensor applications and fundamental research in physics.

However, if one wishes to pursue photon counting at the longer telecom wavelengths of 1300 nm and 1550 nm, the situation is no longer so easy. Although near-infrared photomultiplier tubes having a spectral response extending to 1700 nm exist, their quantum efficiency does not exceed a fraction of a percent. For 1300 nm photons, germanium APD's have been extensively studied. In order to have a reasonable dark count rate, these detectors must be cooled, usually with liquid nitrogen, to a temperature below 150 K, making them impractical for most applications. Furthermore, the cut-off wavelength of these APD's when cooled is around 1450 nm, making them unsuitable for use as photon counters for 1550 nm photons. More recently new approaches employing superconducting materials have been proposed and tested. However, because of their cooling requirements– 4 K or lower – these detectors are impractical for most applications.

The 0.73 eV bandgap of InGaAs, lattice matched to an InP substrate makes single-photon sensitivity possible up to a wavelength of 1650 nm. Quite a few groups have therefore turned their attention to using commercially available InGaAs/InP APD's, originally developed for optical communication applications, for photon counting at 1300 nm and 1550 nm. This research has proved quite fruitful, and there are many applications emerging in optical metrology, in eye-safe range finding, and in future quantum technologies. id Quantique is bringing the first commercial single-photon detection system employing InGaAs/InP APD's into laboratories.

This application note describes the principle of single-photon detection using InGaAs/InP APD's. It presents then the id 200 Single-Photon Detection System and finally mentions applications.

Transforming single-photons into macroscopic current pulses

Photodiodes are semiconductor devices designed to transform light into an electric current and are used as detectors in numerous applications. The simplest photodiode is the so-called p-i-n junction diode, which operates at zero or low reverse bias and provides no internal current gain. Although p-i-n diodes can be used for sensitive detection when followed by a low-noise electrical amplifier, they feature too much noise for detecting single-photons.

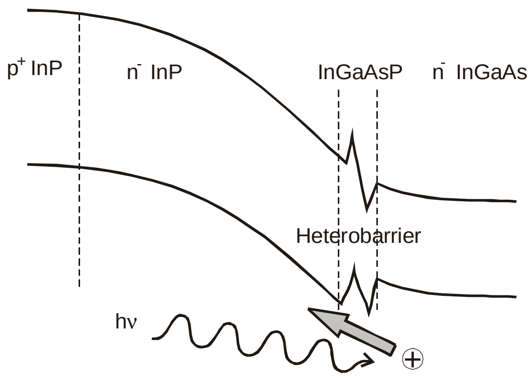

Figure 1

An avalanche photodiode (APD) is basically a p-i-n diode specifically designed for providing an internal current gain mechanism. When reverse biased, the APD is able to sustain a large electric field across the junction. An incoming photon is absorbed to create an electron-hole pair. The charge carriers are then swept through the junction and accelerated by the strong electric field. They can gain enough energy to generate secondary electron-hole pairs by impact ionisation. These pairs are in turn accelerated and can generate new electron-hole pairs. This multiplication phenomenon is known as an avalanche.

In the case of InGaAs/InP APD's the photon are absorbed in a narrow bandgap InGaAs layer (see Figure 1). The photogenerated hole is then injected into the wider bandgap InP multiplication layer. Separate absorption and multiplication layers are designed to optimise the avalanche behaviour and minimize the excess noise factor associated. This also ensures that tunnelling breakdown in the narrow bandgap InGaAs layer occurring at field values lower than the threshold for avalanche multiplication does

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not impair functioning. Because of the bandgap difference between InGaAs and InP, a grading quaternary InGaAsP layer is used to smooth the band discontinuity, which could otherwise trap charge carriers and slow down timing response.
For conventional optical communication applications, the reverse voltage applied is below the so-called breakdown voltage, the point where a self-sustaining avalanche current can be initiated by thermal fluctuations or tunnelling effects. The output signal is a linearly amplified copy of the input signal.
Figure 2 represents the I-V characteristics of an APD and illustrates how single-photon sensitivity can be achieved. This mode is also known as Geiger mode. The APD is biased, with an excess bias voltage, above the breakdown value and is in a metastable state (point A). It remains in this state until a primary charge carrier is created. In this case, the amplification effectively becomes infinite, and even a single-photon absorption causes an avalanche resulting in a macroscopic current pulse (point A to B), which can readily be detected by appropriate electronic circuitry. This circuitry must also limit the value of the current flowing through the device to prevent its destruction and quench the avalanche to reset the device (point B to C). After a certain time, the excess bias voltage is restored (point C to A) and the APD is again ready to detect a photon.

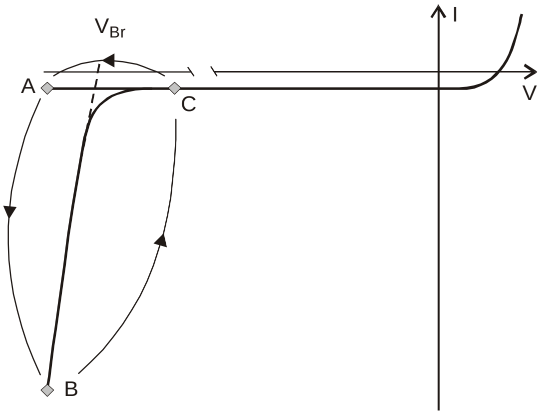

Figure 2

The actual value of the breakdown voltage depends on the semiconductor material, the device structure and the temperature. For InGaAs/InP APD's, it is typically around 50V. The detection efficiency but also the noise of an APD in Geiger mode depends on the excess bias voltage (see below). Typical values range from one to a few volts.

Avalanche photodiode biasing

While several biasing modes have been proposed and tested, the best performance in the case of InGaAs/InP APD's is obtained with gated operation.
In this approach, the excess bias voltage across the APD is briefly raised above the breakdown voltage when a photon is expected. The duration of this gate is typically a few nanoseconds. Two such gates are separated by a longer hold-off time (typically more than 500 ps), during which the bias voltage is kept well below the breakdown voltage. Because of the possibility of applying a high excess bias voltage, this technique makes it possible to achieve high detection efficiencies and good timing resolutions. In addition, the fact that the detector is activated only for a short time period, allows to limit afterpulse effects and to discriminate photo-counts from noise counts which are not coincident. Gated mode operation can also be used in a scanning mode, to investigate the profile of the arrival time of photons.

Performance

Quantum detection efficiency
The performance of an APD in single-photon detection mode is characterized first by its quantum detection efficiency. This quantity corresponds to the probability for a photon impinging on the photodiode to be detected. The Geiger mode quantum detection efficiency results from three different factors:
- The optical coupling efficiency from the optical fiber onto the active area of the detector
- The probability that a photon is absorbed in the InGaAs layer
- The probability that the photogenerated carrier triggers an avalanche when crossing the multiplication zone

The quantum detection efficiency increases when the excess bias voltage is raised. At 1550 nm, a 10% detection efficiency is typical, although value as high as 30 – 40% have been reported.

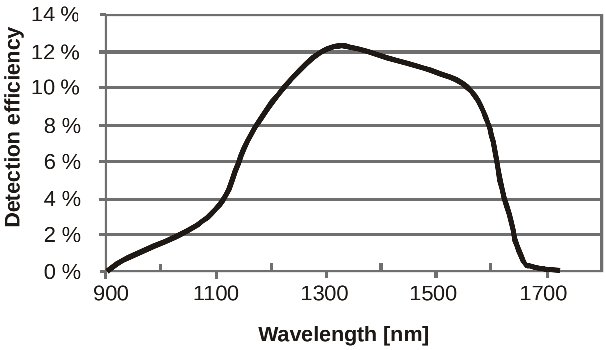

Figure 3

Figure 3 shows the detection efficiency as a function of the wavelength of the photons. Single-photon detection is possible between 1100 and 1650 nm.

Dark counts
In an APD, avalanches are not only caused by the absorption of a photon, but can also be randomly triggered by carriers generated in thermal, tunneling or trapping processes taking place in the junction. They cause self-triggering effects called dark counts.
The easiest way to reduce dark counts is to cool the detector. This reduces the occurrence of thermally generated carriers. At low temperature, dark counts are thus dominated by carriers generated by band to band tunneling and more importantly trapped charges (see below). Raising the excess bias voltage increases the occurrence of dark counts. The operation point, in terms of bias voltage, must thus carefully be selected.
In gated mode, one typically quantifes this effect as a dark

count probability per nanosecond of gate duration. Figure 4 shows this dark count probability as a function of the detection efficiency at a temperature of 220 K. At 10% efficiency, the dark count probability is typically 5 10^{-5} ns^{-1} or less.

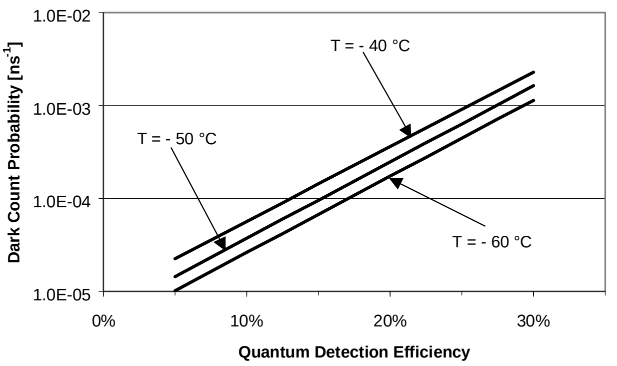

Figure 4

Afterpulses

Perhaps the major problem limiting the performance of present InGaAs/InP APD's is the enhancing of the dark count rate by so-called afterpulses. This spurious effect arises from the trapping of charge carriers during an avalanche by trap levels inside the high field region of the junction, where impact ionization occurs. When subsequently released, these trapped carriers can trigger a so-called afterpulse. The lifetime of the trapped charges is typically a few µs. The probability of these events is also proportional to the number of filled traps, which is in turn proportional to the charge crossing the junction in an avalanche before the quenching takes place. The total charge can be limited by ensuring prompt quenching of the avalanches.

It is also important to note that reducing the operation temperature of the APD increases the lifetime of the trapped charges. The cooling temperature must thus carefully be chosen to minimize the total dark count probability. Although it depends on the counting rate, this optimal temperature is typically around 220 K for current InGaAs/InP APD's.

So far, the cure to get rid of the dark count enhancement by afterpulses has been to use the gated mode detection scheme (see above). If the voltage across the APD is kept below the breakdown voltage for a sufficiently long time interval, longer than the trap lifetime, between two subsequent gates, trap levels are empty and cannot trigger an avalanche. With typical trapping time in the µs range, however, the upper repetition frequency of InGaAs/InP APD's is limited to a few MHz. Using a deadtime to inhibit gates for a time long compared to the trapped charges lifetime after each avalanche also proves useful.

Timing resolution

For many applications, the timing resolution of the detector is also important. It depends on the time it takes for a photogenerated carrier to be swept out of the absorption zone into the multiplication zone.

Timing performance typically improves with an increase of the excess bias voltage. In order to quantify it, one sends short (shorter than 100 ps) and weak pulses on the detector. The spread of the onset of the avalanche pulses is then monitored with a time-to-amplitude converter. At a 10% detection efficiency, a timing resolution of about 400 ps FWHM is typical (see Figure 5). In the future, optimisation of the photodiode structure could lead to improvements.

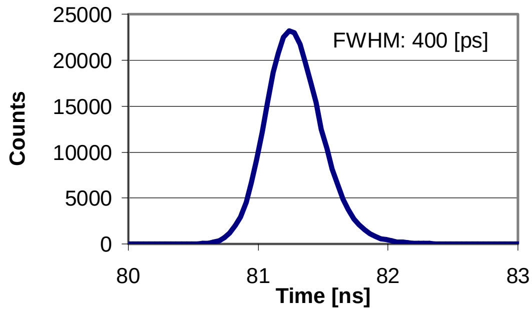

Figure 5

id Quantique's Single-Photon Detector Module

The single-photon detector module is a comprehensive system developed to make photon counting beyond 1 µm simple and efficient. Figure 7 shows the block diagram of the module.

Figure 6

The core of the detector consists of a pigtailed (singlemode optical fiber) InGaAs/InP APD. In order to reduce dark count probability, the APD is cooled using a thermoelectric cooler. The operation temperature is selected to optimize the performance and accurately controlled.

The APD is operated in so-called gated mode, where a voltage pulse is applied to raise the bias beyond breakdown upon triggering. While the duration of the gate pulse can be adjusted by the user, its amplitude is fixed. It is selected, along with the temperature, to yield a given quantum detection efficiency and dark count probability. A *gate out* signal (coincident with the gate and same duration, NIM level) is available on the front panel. It can be used for synchronization purpose or as a start signal for a time-to-amplitude-converter.

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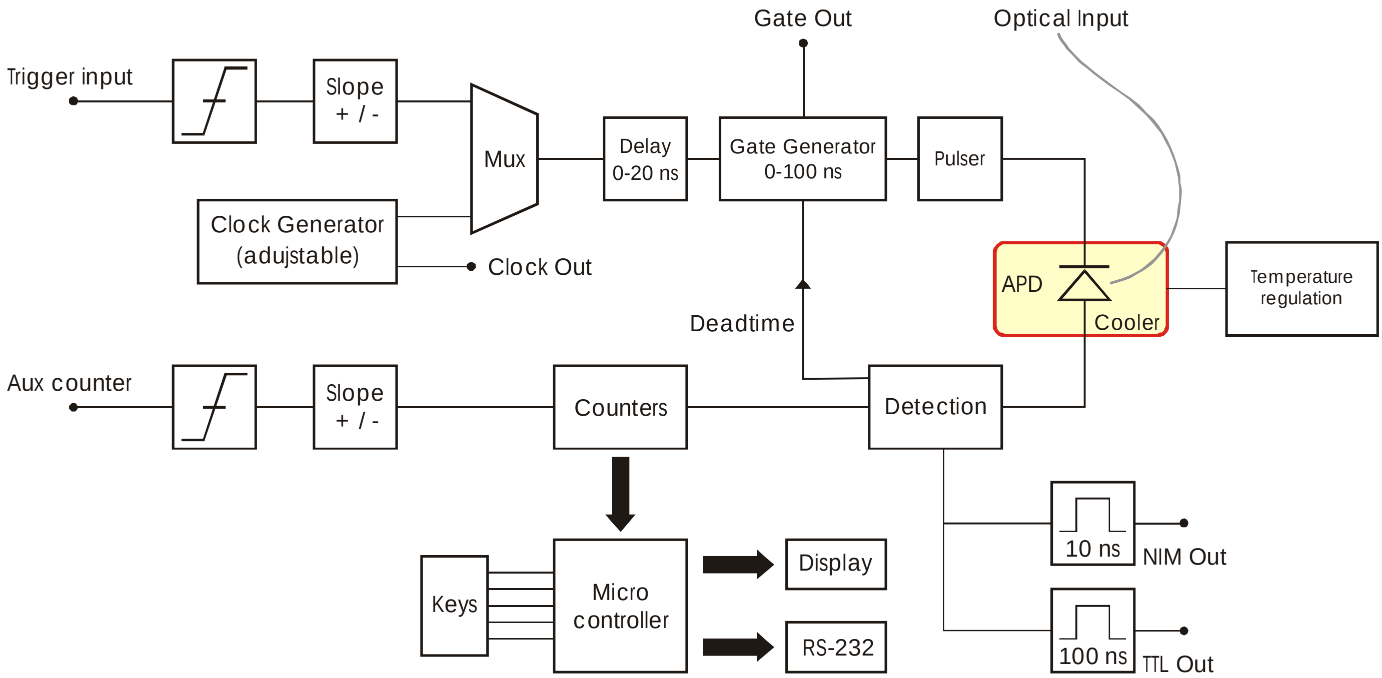

Figure 7 Block diagram of the module

There are two possible sources for the trigger signals. First it can be provided by an external device and fed to the module through the trigger input connector. The level, impedance and slope can be adjusted. Alternatively, the trigger signal can also be generated by the internal clock generator. In this case, the signal is also available on a *clock out* front panel connector for synchronization of other devices (e.g. pulsed laser source). The frequency of the internal generator is adjustable. An electronic delay line can be used to delay this signal (0 – 20 ns), before it is sent to the gate pulse generator. This feature is useful to precisely synchronize the arrival time of the photon with the gate.
Sensing electronics is used to detect the avalanches and to produce logical electronic pulses. Both a NIM level (10 ns duration) and a TTL level (100 ns duration) are available on two separate front panel connectors. The NIM pulse is typically used for timing purposes, while the TTL one serves with counters or acquisition cards.
A variable deadtime can be selected to reduce afterpulse occurrences. With this feature trigger signals are inhibited for a certain time, which is adjustable, after each avalanche.
The front panel consists of an optical fiber connector (FC/PC), electronic connectors for input/output (BNC), a keypad, and a display. The keypad is used to navigate through a user-friendly menu structure in order to set the different parameters.
The module also comprises three counters. The first one monitors the trigger signal, the second one the detection signal, while the third one, an auxiliary counter, can be used to count any type of signal. A front-panel connector is available for this counter (level, impedance and slope can be adjusted). The values recorded by the counters can be displayed on the front panel display both as a frequency and as a number of counts (in this case, a chronometer allows to monitor the integration time).
The module can be connected to a PC through a RS-232 connector. This option allows to remotely operate the detector. All the parameters can be adjusted and the values of the counters monitored.

Operation modes

In this section, four typical applications of the single-photon detection module are presented to illustrate its operation.

Triggered mode

This example illustrates a typical time correlated single-photon detection measurement.
A short laser pulses source is triggered by a delay generator. The light pulse is sent through the optical device under test onto the APD.
The delay generator also provides a trigger signal to the detector module. This signal, possibly delayed, is used to generate the gate pulse activating the APD. The duration of this gate pulse is set to 50 ns. The detector will thus detect photons within the time window defined by the arrival of the trigger signal and this duration.
The internal counter displayed on the front panel can be used to monitor the output of the detector. As mentioned above, the counts can arise both from photons and from dark counts. By disconnecting the fiber on the panel of the module and blocking the optical input of the detector, one can measure the dark counts. This quantity can then be subtracted from the overall signal to obtain the counts arising only from photons.

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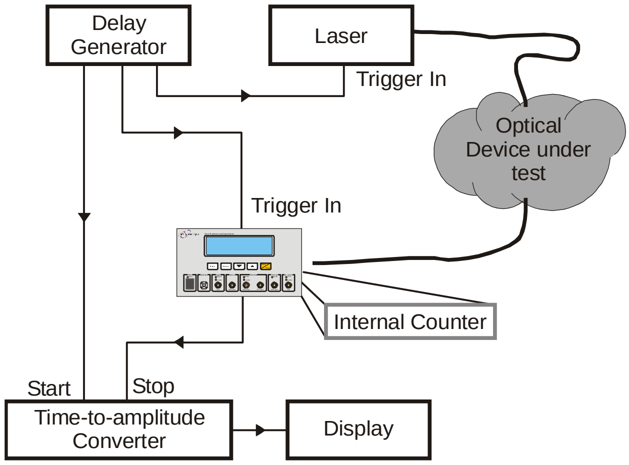

Figure 8 *Detector Module* operation in triggered mode.

In certain cases, it is interesting to obtain precise information on the time of arrival of the photons within the 50 ns gate. This can be achieved by connecting the NIM output of the module to the STOP of a time-to-amplitude converter (the START signal comes from the delay generator). One obtains thus a time spectrum of events recorded within the gate.
If the optical signal of interest is temporally restricted to a small region of the 50 ns gate window, it may be beneficial to reduce the gate window in order to limit the dark counts.

Self-triggered mode

This second example is similar to the first one. The difference is that the detector module replaces the delay generator. Its internal frequency generator is used as a source of trigger signal for the gating of the APD and provides an external synchronization signal to trigger the laser.

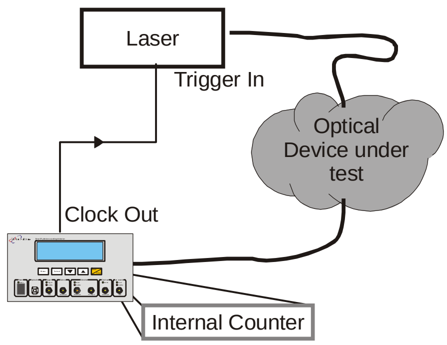

Figure 9 *Detector Module* operation in self-triggered mode.

Coincidence measurements with two detector modules

The third example illustrates a typical coincidence measurement using two detector modules. A delay generator triggers an optical device generating correlated photons. These are sent to separate detector modules using optical fibers. The delay generator also triggers both detector modules. The gate duration is set to 50 ns. The counts on a single detector can be monitored using the internal counter of each module. The detection signal of one module is sent to the START input of a time-to-amplitude converter, while the signal of the second module is sent to the STOP input. The converter produces a time spectrum of the coincidences.

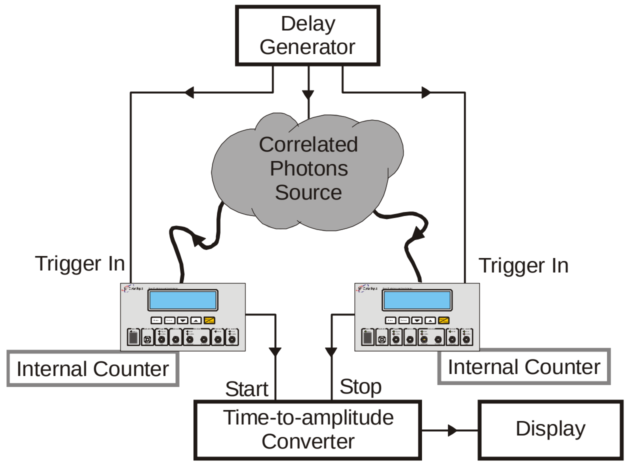

Figure 10 Coincidence measurement with two *Detector Modules*.

Coincidence measurements with a single detector module

The fourth example illustrates a coincidence measurement using a single detector module. A delay generator triggers the optical device generating correlated photons. One of the optical fibers is connected to an optical delay line (an optical fiber spool). Both fibers are then connected to the two ports of a balanced coupler, whose output goes to the module. Please note that such an arrangement results in a factor of four reduction in the coincidences counting rate.

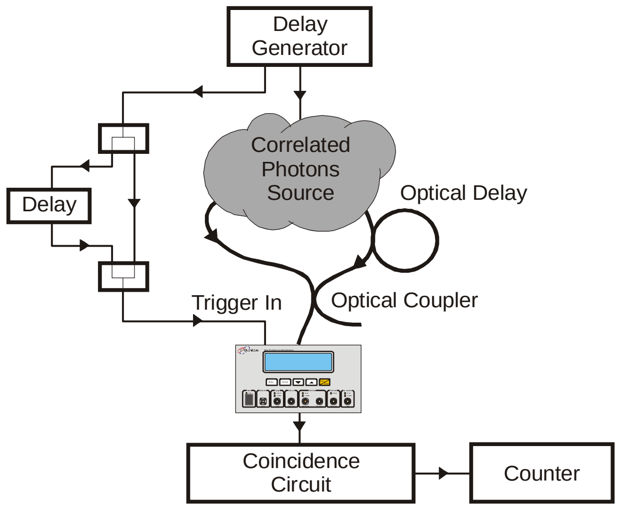

Figure 11 Coincidence measurement with a single *Detector Module*.

The delay generator also generates a trigger signal for the detector module. This signal is first fed into a fan-out circuit. One of the output signals is delayed using an electronic

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delay generator. This delay corresponds to the optical delay introduced in the path of one of the photons. The two electronic signals are then recombined using an OR gate, before being fed into the trigger input of the module. The APD is thus gated twice, at times corresponding to the arrival of each photon.
The time delay between the photons must be sufficiently long to ensure low afterpulse probability in the second gate. A duration of typically 2 µs is appropriate (2 µs corresponds to 400 m of optical fiber). One must be careful not to degrade the timing resolution by introducing electronic jitter or dispersion effects in the optical delay.

Applications

The field of applications of single-photon detection beyond 1 µm is very broad and constantly expanding. Two applications are briefly mentioned.

Telecom instrumentation

Geiger mode operation of APD's enables to increase the sensitivity and improve the resolution of optical time domain reflectometers. Although typical resolution for standard OTDRs are in the meter range, centimetre resolution over kilometres spans are achievable with the timing resolution of InGaAs/InP APDs. Commercial devices are available.
Similarly, free space reflectometry applications (LIDAR) taking advantage of the fact that the wavelength of 1550 nm is considered "eye-safe" have also been proposed[7].

Quantum optics

Detecting single-photons – the elementary quanta of light – is a key technology for quantum optics. Working at telecom wavelengths allows to take table-top applications and to repeat them over long distances. Recent fundamental experiments include long distance quantum teleportation[8].
Quantum cryptography is also an important application[9]. It allows to exchange a cryptographic key whose secrecy is guaranteed by the laws of quantum physics. The bits of the key are encoded on single-photons, which are quantum systems. Their interception necessarily translates into perturbations. Eavesdropping can thus not go undetected.

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