Room temperature photon number resolving detector for infrared wavelengths

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Abstract

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Reference


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Room temperature photon number resolving detector for infrared wavelengths

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Abstract: In this paper we present a photon number resolving detector at infrared wavelengths, operating at room temperature and with a large dynamic range. It is based on the up-conversion of a signal at 1559 nm into visible wavelength and on its detection by a thermoelectrically cooled multi-pixel silicon avalanche photodiode, also known as a Silicon Photon Multiplier. With the appropriate up-conversion this scheme can be implemented for arbitrary wavelengths above the visible spectral window. The preservation of the poissonian statistics when detecting coherent states is studied and the cross-talk effects on the detected signal can be easily estimated in order to calibrate the detector. This system is well suited for measuring very low intensities at infrared wavelengths and for analyzing multiphoton quantum states.

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References and links
5. www.quantumcandela.net.
1. Introduction

Estimating the number of photons in a weak optical pulse is desirable for the implementation and/or the optimization of a large variety of applications. Research and clinical activities deal with the analysis of fluorescent compounds for the identification and quantification of chemical reagents or for tracking or investigating biological molecules. Such applications in the near or mid infrared region are extremely promising. For instance, reagents or for tracking or investigating biological molecules. Such applications in the near infrared spectroscopy, which can explore the vibrational and rotational spectra of molecules, is adopted for the investigation of complex systems, such as proteins, or for cancer diagnosis. These tasks need to measure, over a large range of values, low intensity optical pulses, which in most of the cases are non repetitive. Photon number resolving detectors (PNRDs) can greatly improve the accuracy and the rapidity of such single-shot measurements.
Table 1. Qualitative comparison between the main PNR detection approaches in the telecom regime. CIPD = charge integration photodiode; TES = transistor edge sensor; PND = parallel nanowire detector; Lin APDs = linear APDs; Non Sat APDs = Non saturated mode APDs. ‘Room temperature’ refers to temperatures achievable by thermoelectric cooling. With ‘Large Dynamic Range’ we mean a range between 0 and thousands of input photons.

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Other technological and commercial applications in the infrared, or telecom regime, like optical time domain reflectometry (OTDR) [4], can also gain in speed and sensitivity if fast and reliable photon counting is used. There is also an increasing demand for detectors that bridge the gap between single photon counting and macroscopic power levels [5]. Photon number resolving detection can also help in the investigation of multi-photon quantum states, by means of loss independent measurements of high order correlation functions [6] or with threshold detection conditions [7]. PNRDs can also be useful for quantum information applications [8], although these applications generally require extremely efficient detectors, though these only need to detect up to a few photons.

The main interest in PNRDs is the estimation of photon numbers in single shot measurements. Indeed, the photon number distributions can be reconstructed with just one single photon detector if a sample of identical photon pulses is available [9, 10]. Actually, even in this case, PNRDs can make the applications faster, since they provide more information per pulse with respect to single photon detectors. For the applications mentioned above, it is highly desirable to have PNRDs with a large dynamic range.

Table 1 qualitatively compares the existing PNRDs working at infrared wavelengths, in particular at the telecom ones. The charge integration photodiodes (CIPD) [11, 12] and transistor edge sensors (TES) [13–15] are very efficient and have good photon number resolution. However, they need cryogenic apparata for cooling, so they are expensive and cannot work as plug-and-play systems. Moreover, they work at quite slow repetition rates. Superconducting parallel nanowires detectors [16, 17] provide faster responses, but require cryogenic apparata as well. Avalanche photodiodes (APDs) in a linear mode, even with a very low noise equivalent power (NEP) [18], have a high minimum detectable number of photons (of the order of \(10^3\)), and APDs in non-saturated mode [19, 20], where weak avalanches are measured at an early stage of multiplication, have a limited photon number resolution. However, APD-based detectors work at room temperature, i.e. at temperatures that are achievable by thermoelectric cooling.

In this paper we present a PNRD that works at infrared wavelengths, with a large dynamic range, high readout frequency and which can operate at room temperature. This provides a practical detector well suited to measuring a large range of low intensities of light in a single shot fashion. It is based on the nonlinear up-conversion (UC) [21] of photons at 1559 nm into the visible regime and their detection by a multi-pixel APD detector, also known as Silicon Photon Multiplier (SiPM). The use of the UC for converting a telecom to visible wavelength is already known [21], but this time it is used to exploit the photon number resolving capability of the SiPM [22, 23]. Moreover, the UC process allows this approach to be adopted for a wide range of longer wavelengths [24]. In the following sections, we describe the detection scheme.
Fig. 1. Schematic of the up-conversion multi-pixel APD detector. Pulses from a diode laser at 1559 nm are attenuated (variable attenuator (VA) in the figure) and injected, together with a pump laser at 980 nm, into a PPLN waveguide (PPLN wg), where the up-conversion takes place. Polarization controllers (PC) are used for optimizing the nonlinear process. Light at 600 nm is then filtered by a dispersion prism and an interference filter (IF), and detected by the SiPM. The electrical signal is registered on the oscilloscope.

and the data acquisition process. A characterization of the detector is carried out by measuring its efficiency and noise, before we discuss its photon number resolving capability.

2. The up-conversion multi-pixel APD detector

2.1. Scheme of the detector

A diode laser at 1559 nm provides pulses of 1 ns-width that can be attenuated down to the single photon level, as shown in Fig. 1. The telecom signal is mixed with a cw pump diode laser at 980 nm (JDS Uniphase) in a fiber wavelength division multiplexer (WDM). The maximum emitted pump power is approximately 300 mW. After the WDM, the telecom signal and the pump are injected into a periodically poled lithium niobate (PPLN) waveguide (HC Photonics), where the non-linear UC of the signal takes place. The polarization of the input beams is controlled to satisfy the quasi-phase matching (QPM) conditions. This makes our system polarization dependent. Polarization-independent schemes with up-conversion have been recently proposed [25]. The waveguide has a length of 2.2 cm, a poling period of 9 μm, a nominal normalized internal efficiency of 500% W−1 cm2 and its input is fiber pigtailed.

The condition for QPM is obtained at 76.6 °C and converts the signal at 1559 nm to 600 nm. The upconverted light is collimated and then filtered by a dispersion prism and an interference filter (IF) at (600±20) nm. In this way we remove the remaining pump photons and their second harmonic generation signal at 490 nm, at which the SiPM is quite efficient. The signal is then focused onto a free space SiPM (Hamamatsu Photonics S11028-100(X1)) with 100 APDs arranged on an active area of 1 mm2 with a fill factor of 78.5%. The choice of the number of pixels is motivated by a series of experimental tests made with different SiPMs for finding a compromise between the dynamic range, the efficiency and the photon number resolution [26].

An internal Peltier cooler allows the detector to operate down to -34°C, corresponding to a breakdown voltage of 66.8 V, in order to minimize the thermal noise. A single pixel has a gain of $2.4 \times 10^6$ and a dark count rate of 370 Hz (measured with a discriminating level at half of the one photon equivalent signal) [27]. The electrical output is amplified with a 10 dB amplifier (Mini-Circuits, 0.1-500 MHz) and processed by a low-pass filter.
2.2. Data acquisition

Telecom wavelength optical pulses are sent to the detector with a 100 kHz repetition rate (see Fig. 1). Their intensity can be set by varying the attenuation automatically by software. The signal detected by the SiPM is measured with a 500 MHz oscilloscope, triggered by a PIN photodiode that detects a portion of light from the optical source. The amplitude of the SiPM output, in a relatively low photon number regime, is approximately proportional to the number of simultaneous avalanches in the detector [22, 23]. In Fig. 2 the superposition of the waveforms of the detected signal on the oscilloscope is shown. Their amplitudes take quite distinct

Fig. 2. Superposition of the waveforms of the detected signal on the oscilloscope.

Fig. 3. Top: pulse height histograms for coherent states with mean number simultaneous detections \( \langle n \rangle_{\text{det}} \) of 0.6, 5.0 and 10.4 respectively. Bottom: corresponding histograms of the relative frequencies of the simultaneous detections, fitted by poissonian distributions (red lines). \( n \) is the number of simultaneous detections.

Fig. 3. Top: pulse height histograms for coherent states with mean number simultaneous detections \( \langle n \rangle_{\text{det}} \) of 0.6, 5.0 and 10.4 respectively. Bottom: corresponding histograms of the relative frequencies of the simultaneous detections, fitted by poissonian distributions (red lines). \( n \) is the number of simultaneous detections.
values, distributed according to the poissonian distribution of the number of detected photons. Their duration is approximately 50 ns, making repetition rates of up to 20 MHz feasible. With different electronics the read-out frequency could be even increased, at the expense of reduced sensitivity. The timing jitter of the SiPM, which determines the timing resolution, is below 500 ps [27].

For each coherent state sent to the detector, we register $10^5$ traces from the oscilloscope and measure the height of the signal for each trace. The upper part of Fig. 3 shows the pulse height histograms for coherent states with mean number of simultaneous detections $\langle n \rangle_{det}$ of 0.6, 5.0 and 10.4 respectively. For the first two states one can notice a very good separation between the different amplitude levels, confirming the good sensitivity of the SiPM and the fact that all the pixels have similar gains. The distinguishability of the peaks gets worse for an increasing number of simultaneous detections: the uncertainty on the output voltage produced by the firing of $N$ pixels is approximately proportional to $\sqrt{N}$ times the standard deviation of the signal associated to one detection. For the coherent state with $\langle n \rangle_{det} = 10.4$, the peaks are still quite distinct, despite the appearance of a gaussian background due to the overlap of the tails of the detection signals.

For each state the data are organized in a histogram of the relative frequencies of the simultaneous detections, where the detection events are distributed in equal voltage intervals. Actually, the detected signal shows non linear effects beyond around 80 simultaneous detections. We determine the mean ($\langle n \rangle_{det}$) and the variance ($\sigma^2_{det}$) values of the data, that are then fitted with a poissonian distribution, as shown in the three graphs in the lower part of the Fig. 3.

### 2.3. Efficiency and noise characterization

The detector efficiency depends on the performance of the whole UC and filtering process and of the SiPM detection efficiency.

With the maximum available pump power, the signal at 600 nm measured after the IF is only the 11% of the telecom light at the input of the detector, due to the system losses. Only approximately 23% of the telecom light is coupled into the waveguide. A nominal value of 65% should be found for the coupling efficiency at telecom wavelengths. This discrepancy is due to the deterioration in time of the input fiber pigtailling. The telecom photons can be upconverted in the PPLN waveguides in principle with a 100% efficiency with a greater pump power [28]. However, the pump power effectively available for the UC is limited by the losses due to fibre splices, to the WDM and also to the waveguide coupling. Finally, the IF has a transmission of 85%.

To characterize the SiPM detection efficiency, we send telecom wavelength coherent pulses to the detector at 100 kHz. At this frequency the effects of afterpulsing are negligible. For a given $\langle n \rangle_{in}$ and in the absence of input light, we count the detection events overcoming a discriminating level chosen to be half of the one photon equivalent signal and estimate the probability of a detection $p_{DET}$ and of a dark count $p_{DC}$. In this way we can calculate the quantum efficiency as $QE = \frac{1}{\langle n \rangle_{in}} \ln(\frac{1-p_{DC}}{1-p_{DET}})$ [29]. We find $QE_{SiPM} = 24\%$ at a bias voltage of 68.1 V, corresponding to an excess bias voltage of 1.3 V. The excess bias voltage is calculated as the difference between the bias and the breakdown voltage. However, it is also possible to define the efficiency of a PNRD as $\eta = \frac{n_{det}}{n_{in}}$, where $\langle n \rangle_{det}$ and $\langle n \rangle_{in}$ are the mean numbers of simultaneous detections and of input photons per pulse, respectively. This quantity is more related to the photon number resolving character of the detector, because it takes into account not only the number of avalanches but also their amplitudes. We measured $\eta_{SiPM} = 36\%$ just for the SiPM, under the same conditions of bias voltage as for $QE_{SiPM}$. Notice that the definition of $\eta$ includes the effects of cross-talk that we will explain in detail in the next paragraph.

At this point we characterize the entire detection system and plot the total efficiency $\eta_{tot}$ as a
Fig. 4. Efficiency $\eta_{\text{tot}}$ of the UC multi-pixel APD detector as a function of the mean numbers of simultaneous detections $\langle n \rangle_{\text{det}}$.

function of $\langle n \rangle_{\text{det}}$, for an excess bias voltage of 1.3 V (Fig. 4). Up to $\langle n \rangle_{\text{det}} \approx 6$ the efficiency is approximately constant at 4%, which is what we expect from the individual values for the UC efficiency and $\eta_{\text{SiPM}}$. With this detection efficiency we have an energy resolution equivalent to 25 photons, corresponding to $3.2 \times 10^{-18}$ J at 1559 nm.

For higher values of $\langle n \rangle_{\text{det}}$, $\eta_{\text{tot}}$ decreases because of the saturation of the SiPM. Figure 5 shows the linear increase of the overall efficiency (for low values of $\langle n \rangle_{\text{det}}$) as a function of the excess bias voltage applied to the SiPM [(0.31±0.01)% per 0.1 V of excess bias voltage]. The value of this efficiency is limited by the lossy waveguide coupling due to the deteriorated fiber input pigtailling of our commercial device. However, it can be greatly improved by adopting optimized systems with pigtailling losses of less than 0.5 dB [28].

The noise of the detector has two different origins: the electronic noise of the SiPM, which is not produced by incident photons, and the detection of photons at 600 nm originating from other non linear processes (discussed in [30]), which take place inside the waveguide. We calculate the histogram of the detection frequency in the absence of the input telecom signal, from which we find that the noise corresponds to $\langle n \rangle_{\text{det}} = 0.023$. This value can be interpreted as a noise probability per shot. In order to evaluate the minimal sensitivity of our detector, we divide it by $\eta_{\text{tot}}$ and obtain 0.58. This is the approximate number of incident photons that give the same mean number of detections, if the detector had no noise and if they were sent in pulses of 1 ns width. The majority of this noise is due to the UC. Indeed, only 2% of the total noise is due to the SiPM.

### 2.4. Multi-photon detection

The multi-photon counting capability of a PNRD could be in principle characterized by performing a quantum tomography of the detector, according to the method described in [31]. However, in the case of large dynamic range PNRDs, the number of parameters to find numerically is very large, because probe states with large mean photon numbers have to be used for the characterization of the detector. This makes the numerical problem extremely complex and unstable. Therefore, more practical approaches need to be found for the characterization of PNRDs in a large photon number regime. In our case we investigate the preservation in the detected signal of the statistical properties of the input coherent states. If one sends Fock states to a perfectly efficient PNRD, with a sufficiently high photon number resolution, distinct outcomes for each state should be expected. In the case of a single shot measurement, one obtains
Fig. 5. Efficiency $\eta_{\text{det}}$ of the UC multi-pixel APD detector as a function of the excess bias voltage applied to the SiPM. The dotted line corresponds to a linear fit of the data.

Fig. 6. Experimental variances $\sigma^2_{\text{det}}$ as a function of the corresponding mean numbers of simultaneous detections $\langle n \rangle_{\text{det}}$. The dashed red line corresponds to ideally detected coherent states, for which $\sigma^2_{\text{det}} = \langle n \rangle_{\text{det}}$. In the inset the data for low $\langle n \rangle_{\text{det}}$ are shown. The blue line corresponds to the fit of the first data for the calculation of the cross-talk probability of the SiPM.

A specific output for only one specific Fock state. For a coherent state a poissonian distribution of outcomes is obtained, thus one can infer the number of photons of the initial pulse only up to the intrinsic uncertainty given by the poissonian statistics.

A good PNRD should preserve the statistics of the input states: the equality between the mean number of simultaneous detections $\langle n \rangle_{\text{det}}$ and the variance of the experimental data distributions $\sigma^2_{\text{det}}$ should be verified. In Fig. 6 we plot the experimental variances $\sigma^2_{\text{det}}$ as a function of the corresponding mean numbers of simultaneous detections $\langle n \rangle_{\text{det}}$.

The dashed red line in Fig. 6 corresponds to the condition of perfect poissonian detection distribution, that is $\langle n \rangle_{\text{det}} = \sigma^2_{\text{det}}$. The variances of the experimental distributions decrease for more than 20 simultaneous detections due to the saturation of the SiPM. The experimental
Fig. 7. Cross-talk probability as a function of the excess bias voltage applied to the SiPM. The error bars represent the statistical errors.

distributions of the number of simultaneous detections becomes narrower as \( \langle n \rangle_{\text{det}} \) approaches 100, the number of detector pixels.

The deviation of the experimental variances from the condition of perfectly detected coherent states, for \( \langle n \rangle_{\text{det}} \) below 15 (inset of the Fig. 6), deserves further discussion. We attribute this fact mainly to optical cross-talk effects between adjacent pixels. The avalanche process in one APD can induce the firing of one or more neighboring pixels, as the carriers released during the avalanche can emit radiative photons (the emission probability is approximately one photon per \( 10^5 \) carriers) [32]. We determine the cross-talk probability in our detector by considering the recent analytic results reported in [33]. The authors of [33] assume that the pixels can fire because of a primary origin, the detection of a photon, or a secondary one, for cross-talk or afterpulsing, which is essentially random (in our case the afterpulses are negligible.). Because of the latter effect, the experimental distributions of the number of simultaneous detections corresponding to input coherent states are compound poissonians with mean values \( \langle n \rangle_{\text{det}} = \frac{\langle n \rangle}{1-p} \) and variances \( \sigma^2_{\text{det}} = \frac{\langle n \rangle (1+p)}{(1-p^2)} \), where \( p \) is the probability of firing for secondary events and \( \langle n \rangle \) is the mean of the distribution in the absence of cross-talk. According to this model, the mean and the variance of the compound distributions increase in the presence of the secondary effect. The Fano factor \( F \), which is the ratio between the variance of the distribution of the simultaneous detections \( \sigma^2_{\text{det}} \) and the mean number of this distribution \( \langle n \rangle_{\text{det}} \), is thus expressed by the relation \( F = \frac{1-p^2}{1-p} \), from which \( p \) can be estimated. We measure \( F \) from the slope of the line fitting the data in the inset of Fig. 6. We limit the fit to low numbers of \( \langle n \rangle_{\text{det}} \), where the detector is unaffected by saturation. We obtained a cross-talk probability of \((31.4 \pm 0.6)\%\) at an excess bias voltage of 1.3 V.

The cross-talk probability increases as a function of the excess bias voltage (Fig. 7). A similar effect is reported in [34]. The probability for a pixel to fire due to cross-talk is related to its efficiency, but also on the quantity of photons released during the avalanche of a neighboring pixel, which depends on the amplitude of the avalanches. Both factors increase with the excess bias voltage.

The theoretical model adopted for describing the effects of cross-talk allows us to clarify the relation between the two definitions of efficiency \( \eta \) and \( QE \) used in this paper. Indeed, \( \eta = QE (1+p') \), where \( p' \) is the total probability of having detections due to cross-talk of second and multiple order, that is \( p' = \sum_{n=1}^{\infty} p^n = \frac{p}{1-p} \), which in our case is \((45.7 \pm 1.3)\%\) for the value of \( p \) determined previously. We calculate \( QE_{\text{SiPM}} = 25\% \), which is in good agreement with what
we measured directly. For the complete detector we have $QE_{tot}=2.7\%$ at an excess bias voltage of 1.3 V. Correcting the effects of cross-talk in the detected signal and in the efficiency enables one to calibrate the detector and to correctly estimate the number of photons in an optical pulse, measuring very low optical intensities.

3. Conclusion

In this paper we presented a photon number resolving detector working at infrared wavelengths, at room temperature and with a very large dynamic range. This demonstration is based on the UC of a signal at 1559 nm into the visible wavelength regime and detection by a thermoelectrically cooled SiPM. This scheme can be used for a wide range of infrared wavelengths with appropriate up-conversion. It has an energy resolution of $3.2 \times 10^{-18}$ J at 1559 nm and preserves the poissonian statistics of the input coherent states up to 20 simultaneous detections. The effects of cross-talk in the detected signal can be easily estimated in order to calibrate the detector. This approach is well suited for measuring a large range of low optical intensities in the infrared regime.

Acknowledgments

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