Liquid-nitrogen cooled, free-running single-photon sensitive detector at telecommunication wavelengths

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Abstract The measurement of light characteristics at the single- and few photon level plays a key role in many quantum optics applications. Often photodetection is preceded with the transmission of quantum light over long distances in optical fibers with their low loss window near 1550 nm. Therefore, photonic sources at telecommunication wavelengths are highly desired. Nonetheless, the detection of these states via avalanche photodetectors has long been facing severe restrictions. Only recently, demonstrations of the first free-running detector techniques in the telecommunication band have lifted the demand of synchronizing the signal with the detector. Moreover, moderate cooling is required to gain single-photon sensitivity with these detectors. Here we implement a liquid-nitrogen cooled negative-feedback avalanche diode (NFAD) at telecommunication wavelengths and investigate the optical properties of this highly flexible, free-running single-photon sensitive detector. Our realization of cooling provides a large range of stable operating temperatures and has advantages over the relatively bulky commercial refrigerators that have been used before. We determine the region of NFAD working parameters most suitable for single-photon sensitive detection enabling a direct plug-in of our detector to a true photon counting task.

1 Introduction

The observation of a light quantum is a demanding task since the detector should be able to resolve this tiny amount of energy via the heat absorption or the photoelectric effect and in a noiseless fashion convert it to a measurable electric signal. In addition to this, quantum features are extremely fragile and easily lost by any experimental imperfections prior to and at the detection. Nonetheless, in the past years, several photo-detector technologies have demonstrated the sensitivity to measure at the single-photon level \cite{1}. Moreover, many quantum optics applications require photon counters with at least partial photon-number resolution \cite{2}. In such experiments, superconducting detectors \cite{3,4} as well as visible light photon counters \cite{5} can be exploited with high efficiencies—however, at the cost of having to cool to temperatures of a few Kelvin. At room temperature only a few options are available, for example photo-multiplier tubes \cite{6} that suffer from large losses or hybrid detectors \cite{7} that require specific reconstruction techniques.

For photon counting tasks the most widely used detectors are avalanche photo diodes or shortly click detectors that are in Geiger mode sensitive to single photons but unable to resolve various photon numbers \cite{8}. This is due to the fact that a whole bunch of carriers is released after a photon impinges on the detector in order to gain a detectable electrical signal \cite{9}. This technology for the detection of light at the single-photon level is well-established and commercially available. In the region of visible light, click detectors can reach high quantum efficiencies and measure with a very low number of spurious counts \cite{10}. Additionally, in connection to a fiber-optic beam splitter network these detectors have lately been utilized as photon-number resolving detectors via time multiplexing \cite{11,12}.

Regarding a particular quantum optics application the selection of a suitable detector starts by determining the wavelength range of the investigated radiation. In the range of telecommunication wavelengths, which are ideal for long-distance transmission of light in optical fibers, click detectors have suffered from several drawbacks. Until recently these detectors have required narrow time-gating to suppress spurious counts, in other words, these detectors are active only for a short duration of time and the measured signal has to be synchronized with the gate. In a free-running mode – first demonstrated for the telecommunication band in Refs. \cite{13,14,15} – this synchronization can be omitted \cite{16,17}. The better temporal availability directly offers the possibility to
measure at higher rates. Additionally, free-running detectors make time-multiplexing and photon-counting via a fiber network more practicable at telecommunication wavelengths.

Apart from the wavelength sensitivity and efficiency, the temporal characteristics of a detector such as dead time, timing jitter, as well as the amount of spurious counts in terms of the dark counts and afterpulses are the figures of merit of click detectors [15]. While wavelength region and quantum efficiency mostly depend on the semiconductor’s properties the above characteristics are also influenced by the detector realization such as the stochastic process describing the carrier avalanche. However, also the external electronics can have great impact especially on the temporal characteristics of the detector [15]. For example the technique used for quenching the avalanche often limits the dead time of the detector and the read-out electronics the timing jitter. The rate of spurious counts often strongly depends on the bias voltage [16], which also sets the internal (avalanche) amplification. For a high signal-to-noise ratio we would like a high efficiency and low spurious counts, or in other words the lowest possible noise equivalent power (NEP, or better noise-equivalent photon count rate). The NEP has to be controlled, otherwise the detector looses its single-photon sensitivity [15]. To complicate things, these properties are temperature dependent and can thus be manipulated by cooling the detector. Cooling typically increases the detector efficiency at a given dark count rate [16]. However, care has to be taken since this comes at the cost of an increasing probability of afterpulses [17] and a shift in the wavelength sensitivity of the detector towards shorter wavelengths.

Here, we present a highly practical realization of a liquid-nitrogen (LN$_2$) cooled single-photon sensitive detector at telecommunication wavelengths. It is based on a commercially available fiber-coupled negative-feedback avalanche diode (NFAD) (PNA-300-1) from Princeton Lightwave. The integrated feedback resistor makes this diode intrinsically passively self-quenched and our implementation of deriving an output signal follows Yan et al. [16]. Our solution of cooling the detector with liquid nitrogen has several advantages. A wide range of temperatures can be chosen, the system is compact and easily movable. It does not require any bulky cooling apparatus and it efficiently prohibits humidity from condensing on the detector heads. This paper is organized as follows. In Sec. 2 we present the chosen cooling technique and study its temperature characteristics. In Sec. 3 we investigate the optical properties of our implementation. We examine both the efficiency of the detector as well as the NEP at different temperatures in terms of the dark count rate in order to find the working parameters for the most suitable operating point. Sec. 4 summarizes our results and highlights the findings of our studies.

2 Detector realisation

Our realization of a free-running, single-photon sensitive detector is based on LN$_2$ cooling. A schematic picture of our implementation having a height of approximately 80 cm is shown in Fig. 1. We put our fiber-coupled NFADs in a capsule placed on top of a 34 cm long metal rod of stainless steel, which is set into a partially filled dewar of LN$_2$ such that the detectors sit above the surface of the liquid. We can pack two NFADs with small circuit boards in one capsule including a heating coil placed in between them as depicted by the inlay in Fig. 1. All wiring is routed via a stainless steel tube to a connection box at the top of the tube. A vented bushing allows evaporated nitrogen to escape the dewar and holds the construction straight.

We employ simulations with a commercial solver to investigate the heat transport inside the dewar and at its opening. This is especially important as the NFADs have to be protected from condensed water. In order to gain the proper parameters for the simulation, we make a one day test run, in which the temperature of the detector housing is kept constant at $-80^\circ$C. We observe an LN$_2$ evaporation rate of approximately 150 g/h. At this rate a single dewar fill of 15 – 20 kg yields an operating time of 96 h. A small amount of condensed water, which forms during the test run near the vent, can be easily collected with a tissue placed loosely at the neck of the dewar. The long term test also shows that a heating power of approximately 6.5 W is required to keep the operating temperature stable.

The simulated dewar shape and size correspond to the dimensions of our real dewar with a 35 l interior space.
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Fig. 2 Simulation of temperature distribution (left) and the heat transfer (right) in the LN$_2$ filled dewar and its surroundings, when heating is applied. The strength of the stream is shown by the flow velocity. The pathlines illustrate the traces of individual fluid particles. The time difference between two arrowmarkers within one trace is kept constant.

filled to a specific level with LN$_2$. The boundary conditions are the measured evaporation rate, an environment temperature of 25°C and 1 bar pressure. To simulate the effect of the heating coil, 7 W of power is deposited in the heating area inside the detector capsule.

Our simulation in Fig. 2 firstly shows as expected that with the chosen parameters a temperature of 199 K can be achieved on the horizontal plate in the detector capsule, where the NFAD-detectors are attached. Secondly, it can be clearly seen that the heat is transported not only via conduction but also via convection that causes a small eddy inside the dewar. More interestingly, there is a continuous flow of evaporated nitrogen from the dewar to outside, which prohibits the condensation of water and the forming of ice on the detector house and the cooling rod. A similar eddy inside the detector capsule cools and protects the NFADs itself.

Although the strength of the heat transport is strongly dependent on the amount of LN$_2$, a stable operating temperature can be achieved by a commercial temperature controller that regulates the heating power. In a second 3 h long test at −80°C we measure the temperature stability of our diodes and find that the operating temperature can be set with a stability of ±0.002 K.

3 Experimental investigations

In order to determine the most suitable working range of our single-photon sensitive detector we investigate its main figures of merits. For this purpose we use a continuous-wave (CW) laser (from Yenista) with a maximal power of 4 mW and tunable between 1520 − 1600 nm as our light source. The laser beam is attenuated to the few-photon level with a stack of neutral density filters.

The weak light is then coupled via a single-mode fiber coupler to the two NFADs and their electrical response is measured via a multi-channel time-to-digital converter (TDC) that serves as a counter of the detected clicks. We investigate here the properties of one single NFAD although each individual detector has its own specific characteristics.

By blocking the optical input we start by investigating the spurious counts and measure the dark count rate with respect to the bias voltage and the detector’s temperature. As the electrical response of the NFADs shows a highly complicated pulse shape we choose to measure the dark counts with two different threshold values for the TDC counting the clicks. Our results in Fig. 3 show the working range of the detector in terms of the bias voltage and the achieved dark counts various temperatures. We further note that the threshold value can be chosen rather freely between two values we used in our measurements as they both deliver the same tendency of the measured counts. Looking closer at the errorbars of the measured dark counts, one clearly recognizes that with diminishing temperature the statistical error in the dark counts increases. At approximately 1 kHz dark count rate we find almost Poissonian fluctuations at −60°C whereas at −90°C the errorbars are one order of magnitude larger than those expected for Poissonian click statistics. We claim this to be due to the increasing afterpulse probability since the lifetime of the trapped carries increases with decreasing temperature.

Second, by employing the optical input we determine the detector efficiency at different dark count rates that are fixed by choosing a proper bias voltage. For CW light
the detector efficiency can be extracted via \[ \eta = \frac{E_{ph}}{P\mu} \left( \frac{R_{det}}{1 - R_{det}\tau} - \frac{D}{1 - D\tau} \right), \] (1)
in which \( E_{ph} \) describes the energy of a photon at 1550 nm, \( P \) is the mean power of the CW laser and \( \mu = (3.97 \pm 0.15) \cdot 10^{-12} \) the amount of the attenuation. In addition to this, \( R_{det} \) represents the detected click rate, \( D \) is the measured dark count rate at the selected bias voltage and \( \tau = 100 \pm 50 \text{ ns} \) is the detector dead time extracted from another measurement. At each chosen dark count rate we measure the detector efficiency at different laser powers up to a maximum of about 60 kHz detected click rate in order to ensure that the extracted efficiency remains intact at different photon fluxes and does not vary due to artificial spurious counts. In Fig. 4 we show the extracted efficiencies measured at different operating temperatures with respect to the chosen dark count rates. Clearly, the lower the temperature the better an efficiency is achieved at 1550 nm at a given dark count rate.

Quite as important is the single photon sensitivity of the detector that can be investigated via the noise equivalent power (NEP) given by \[ \text{NEP} = \frac{E_{ph}}{\eta} \sqrt{2D}. \] (2)
The lower the NEP the more sensitive the detector is at the single-photon level. Furthermore, Eq. (2) represents the trade-off between the detector dark-count level and the achieved efficiency. Our results at 1550 nm in Fig. 5 show that the efficiency of the detector grows faster than the dark count rate throughout the whole studied regime of the employed bias voltages for a given temperature. Moreover, our results deliver a clear lower bound of approximately 200 – 300 Hz of dark counts, above which the detector should be operated in order to work with a useful sensitivity. The values obtained here for the NEP follow the tendency of the latest developments reported

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**Fig. 3** Dark counts in terms of the bias voltage \( U_B \) for a low and high threshold voltage (shortly \( U_{Th} \)) at different operating temperatures (marked with \( T \)) from \(-60^\circ C\) to \(-90^\circ C\).
for avalanche photodetection at 1550 nm and are gradually approaching those typical in the visible wavelength range at room temperatures although being still one order of magnitude away from what is commercially available for visible light with slight cooling \cite{9,15,20}.

Finally, in order to be suitable for the investigation of several different kinds of quantum light sources, a detector with a broad spectral band is highly desired. Since the properties of semiconductor materials are highly dependent on temperature, we investigate the upper cut-off wavelength of our detector that is expected to shift towards shorter wavelengths when the temperature is decreased. For this purpose we measure the relative spectral sensitivity while trying to keep the dark count rates constant at different temperatures. Due to the stray light impinging the detector we can only control the background rate during the measurement that was kept between 0.9 – 1.6 kHz. We investigate the relative sensitivity with respect to the temperature for different wavelengths between 1560 nm and 1600 nm. At each wavelength we normalize the detector efficiency against that at −60 °C. From our results in Fig. [6] we conclude that cooling down to −90 °C is desired below 1590 nm in order to gain the best operation while at 1600 nm cooling below −70 °C increases the sensitivity of the detector only modestly. While we have not directly measured the upper cut-off wavelength, the observed behavior is consistent with its shift towards shorter wavelengths.

4 Conclusions

Free-running single-photon sensitive detectors for the telecommunication band are of great importance for many quantum optics applications. Still today, most of these single-photon-sensitive detectors are plagued with low detection efficiencies and require special conditions to work. We implemented a highly practical and flexible cooling with liquid-nitrogen for two fiber-coupled, commercially available NFADs. By utilizing a temperature controller, extremely stable operation of the detector is possible. We investigated several figures of merit of our detector. In order to gain the best single-photon sensitivity we extracted the lower bound for the dark count level and measured the corresponding efficiencies. Further, we investigated the spectral boundaries of our detector. Our results deliver a set of working parameters for the most suitable operation of these detectors in quantum optics applications. Moreover, our detector has the potential to be employed in photon counting applications via time-multiplexing with a fiber network.

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