Characterization of a Superconducting nanowire single photon detector

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I hereby declare that this thesis was formulated by myself and that no sources or tools other than those cited were used.

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Acknowledgements

I would like to thank ...

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Contents

CHAPTER 1

Introduction

CHAPTER 2

Working principle of SNSPDs

In its essence, the SNSPD consists of four parts, seen in fig. 2.1. A saphire underground, a detection area made out of a superconducting nanowire in a serpentine winding and placed ont the saphire underground, a gold contact to supply a bias current through the superconducting nanowire and a fiber coupled to the detection area.
The sapphire layer is used to efficiently dissipate the heat when the wire heats up.
Moreover, the set up is first cooled below the critical temperature of the superconductor ($2 - 3$K), and a bias current is applied to the superconductor that is lower than the critical current.

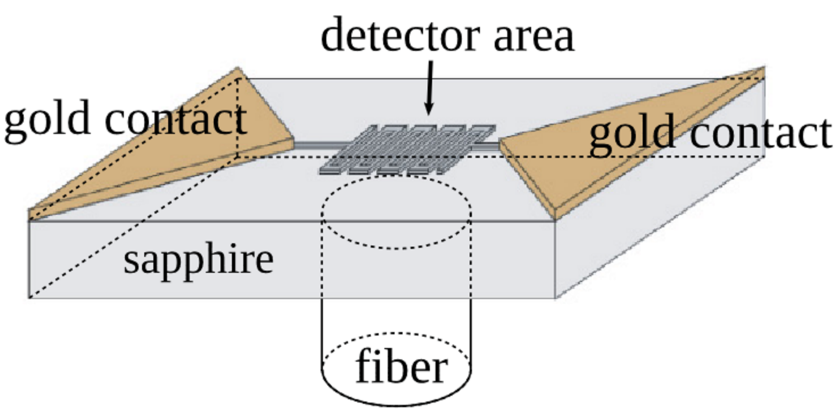

Figure 2.1: (a) Schematic structure of a superconducting nanowire single photon detector [1]

The detection process can be understood along the detection circle in fig. 2.2.
Single photons hitting a superconducting nanowire (ii) and break up individual Cooper pairs. This leads to a local reduction of the critical current below the bias current and in turn to a localised area where the superconductivity is interrupted, this local area forms the so-called ”hotspot” (iii). This hotspot forms a resistance area because the bias current exceeds the critical current. In response, the current flows around this hotspot (iv), whereby the local current density in the side areas next to the hotspot again exceeds the critical current, due to a higher current density. This excess also causes a

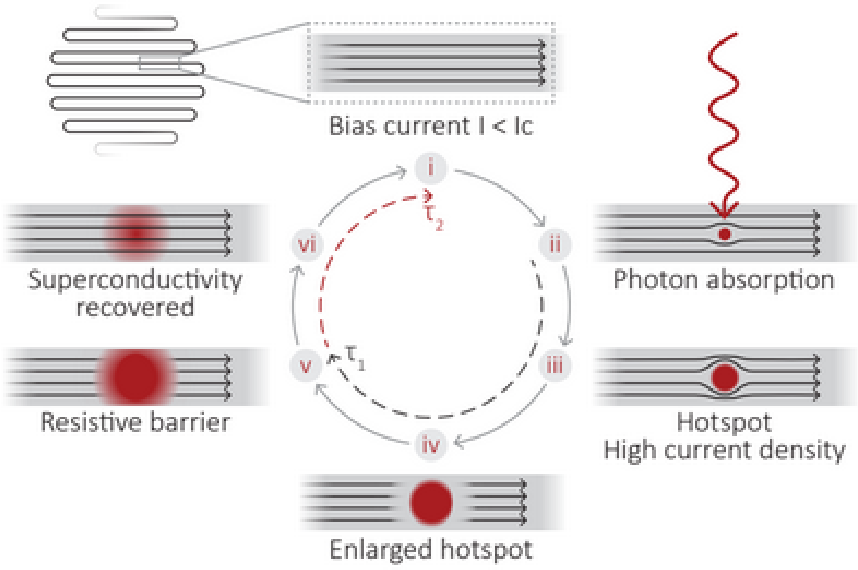

Figure 2.2: Schematic detection cycle of a superconducting nanowire single photon detector [2]

resistance in the side channels due to the critical temperature being exceeded (v). Ultimately, this increase in resistance can be measured in the form of a voltage pulse. The non-superconducting area is then cooled down by the cryogenic environment and returns to the superconducting state (iv—i).

One important technical detail is the fiber coupling of this detector because the efficiency and timing jitter depend on it. Depending on in which polarization the light hits the meander, the efficiency changes. When light hits the wire orthogonally polarized to the wire direction, the photon is less efficiently absorbed, than polarized parallel to the wire.
As seen in fig. 2.3 the coupled fibre in our characterized detector is parallel polarized to the nanowire. Moreover, to cover the whole light, shined out of the fibre, the geometry of the detection zone is constructed as a round plate and has roughly the same diameter as the fibre output (FC/PC). A smaller area would risk not absorbing each photon and a larger area would increase the time leading the signal to the computer unit.

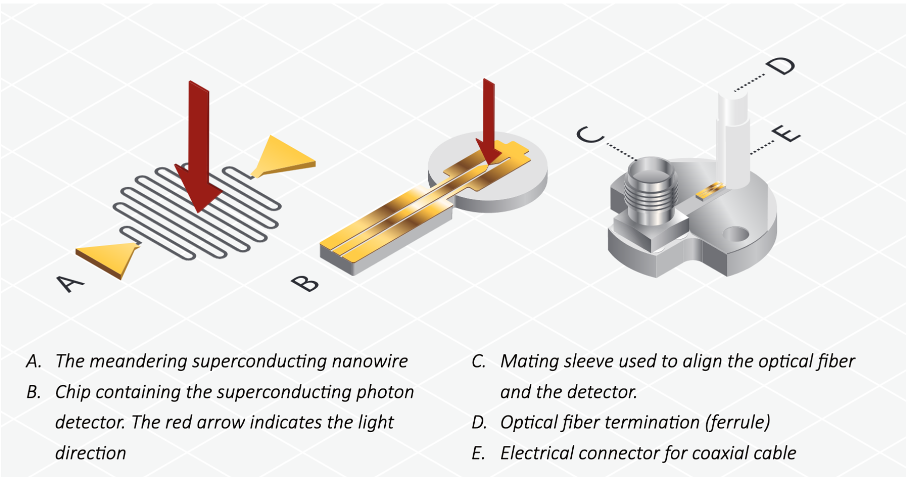

Figure 2.3: Scematic set up of the fiber coupling of a superconducting nanowire single photon detector Zitieren!

CHAPTER 3

Faint laser source for detector characterization

Counting photons one has to consider the characteristics of the emitter source as well. Here I focus only on the characteristics of a laser source affecting the characterization I made. For this first, I briefly sum up characteristics of a laser light source and its conditions it gives us for our detector characterization. Further, I make considerations regarding the inherent blindspots of laser light due to the randomness nature of photons in coherent light. Afterward, I introduce the setup I build for characterizing our SNSPD.

3.1 Characteristics of faint laser sources

Using a laser source enables us, considering the emitting light as monochromatic beam with angular frequency ω and constant Intensity I. The Photon flux of a laser is defined as the photon average number passing through a cross-section in unit time:

$$\Phi = \frac{IA}{\hbar\omega} = \frac{P}{\hbar\omega}\text{photons } s^{-1} \tag{3.1}$$

where I is the current of photon, A the cross-section, P the laser power and ω the angular frequency which depends on the wavelength.

The average number of registered counts $N(T)$ for a given detection time T by a detector is given by:

$$\text{N(T)} = \text{T}\Phi\eta = \frac{PT\eta}{\hbar\omega}\text{photons} \tag{3.2}$$

and hence the registered counts $\mathbb{R}$ per unit time by:

$$\mathcal{R} = \frac{\text{N(T)}}{\text{T}} = \eta\Phi = \frac{P\eta}{\hbar\omega}\text{photons } s^{-1} \tag{3.3}$$

where η is the efficiency of the detector system.

This detection count rate is restricted by the largest amount on the dead time of the detector.

$$\mathcal{R}_{\max} \propto \frac{1}{\tau_d} \tag{3.4}$$

Because the used laser has a minimum threshold power which corresponds to a photonrate above the maximum one, one has to attenuate the laser power in order to detect all events.

The photon statistic of coherent light, in our case (in reasonable approximation) of our laser light, is given by poisson statistics. This characteristic stems from discrete nature of photons and hence non-equidistant spacing between photons. Measuring single photons, one has to ensure that we have a neglectable amount of photons in the segment of the deadtime because else our light characteristics inherently forbid us measuring each of the incoming photons.

This is calculated by looking at the propability of measuring one photon per length segment, given by the deadtime. First, we consider one Length segment given by the deadtime τ_{d} and the measurement time τ_{m}:

$$L_{\mathrm{d}} = \frac{c}{\tau_{\mathrm{d}}} \tag{3.5}$$

$$L_{\mathrm{m}} = \frac{c}{\tau_{\mathrm{m}}} \tag{3.6}$$

Through this, we can calculate for a given measurement time the average photon rate per length segment L_{m} and further the probability of finding one photon in the particular line segment L_{d}:

$$\bar{n} = \Phi \frac{L_{\mathrm{m}}}{c} \tag{3.7}$$

$$p = \frac{\bar{n}}{\mathrm{N}} \tag{3.8}$$

Where $N = \frac{c}{L_{\mathrm{d}}}$ are the subsegments of the measured length segment L_{m}.

This enables us to calculate the probability p of finding n Photons per deadtime segment L_{d} and including this in our measurements.

3.2 Experimental setup

Though not measured by ourselves first, it is known from Zitat deadtime of the detector is around 20-25ns. This gives us a theoretical maximum detection rate of $\mathcal{R}_{\max} \propto \frac{1}{\tau_d} = 25 - 50\mathrm{MHz}$. In order to realize the laser attenuation the following setup was build:

The first coupling of the laser light was done in order to operate with the beam on a lower stage, because the laserbeam was due to its construction on an uplifted stage. Afterward the beam passes a pbs to filter the horizontal polarized E field out. Further a galile telescope was build out of one focal and one diffusing lens for minimizing the beam width so it fits fully on the surface of the AOM crystal. The first order of the AOM was set for flexible voltage modulation of the laser. A cover was used to filter out the first from the zeroth order of the AOM. Then a flip mount was placed, where Neutral density (ND) filers could be placed in and flexible placed in and out of the laser beam. The ND filters have the function to attenuate the laser light. At the end, before the laser light was again coupled in two waveplates where used to stabilize the light polarization regarding the slow axis of the fibre. Afterwards the light was coupled back into a fibre, so it can be send to the detector. It was important that the light was coupled in to a APC/PC to FC/PC optical fibre because the detector only had a FC/PC optical fibre input, in order to maintain higher efficiency coupling in the light.

Besides, this optical setup had to be protected from environmental light. For this, the room where the setup was running was shielded with alu foil which has a reflection coefficient of almost 90% at the operating wavelenght of 780nm. Morveverover a black box was build. It has the function to avoid further environmental light coupling into the fibre. Additionally, the optical fibre running from the optical setup to the detector was shielded with alu foil as well to avoid absoption from the optical fibre.

Neutral density (ND) filter calibration

We exactly need to know how many photons (related to Power) hit our detector. For this we need to measure the power (or number of photons) of the laser light we shining on the detector. The light we want to shine on the detector is very weak. So weak, we cannot measure it with powermeters or any other measurement devices (except with the uncharacterized detector) This weak power cannot reached by regulating the laser power down by the laser device (why not? laser minimum power function only with a power higher than required), but has to be done by Neutral Density filters. So our laser power we send to the detector depends on ND filter.

Now there are two challenges relying on ND filters. First, since the fabric values are not precise, the filters need to be calibrated ourselves. Second, one single ND filter cannot attenuate the laser power enough and therefore one has to stack several density filters on each other, since their OD values are adding up.

From these two constraints, we need to calibrate the ND filters carefully, to get precise and accurate OD values of the ND filters.

To get accurate results, we measure the OD value with two methods to rule out systematic errors in our results. The first method measures the OD values, where the ND filters are set in the flip mount as described in graph **??**. The second method measures the OD values after the fibre coupling directly in front of the powermeter outside the blackbox.

The attenuation of ND filters is quantized by the Optical density (OD) value. The measurement of the OD values done by sending light on the filter and measuring the power with and without the filter. The OD value is then calculated by the logarithmic value of the inverse transmission value. The transmission value is given by the proportion of the power with the filter compared without the filter.

Afterward, the final OD values of each method were averaged and the corresponding systematic and statistical errors are considered to get the closest to the true OD value for the ND filters.

Based one these OD values each measurement involving the laser was done.

- Basics of photon distribution of laser, attenuation, poisson statistics
- Set up for laser attenuation
- Single Photon Detection paper

CHAPTER 4

Characterization of our SNSPD

Vom Experiment aus Theorie erklären
schauen ob Unterkapitel passt

In literature, four central characteristics have emerged to quantize the quality of single photon detectors and make their performance comparable. These characteristics are the detector efficiency, the dead count rate, the recovery time and the timing jitter. In this thesis, I focus on the first three characteristics. In general, there are more than these introduced ones, like an after-pulsing or signal-to-noise ratio; however, these are the most important in the context of this thesis.

4.1 Dark Count Rate

The **dark count rate** (DCR) is the rate of measured detection events that were not intentionally sent to the source. It is measured in counts per Second and can be caused by statistical fluctuations in the measurement electronics or by scattered or ambient light from the environment. A low DCR is important because it allows differentiating between intended detected counts from the source and detected counts by environment and electronic noise.
It increases the count resolution and enables at lower frequencies still high signal-to-noise ratios. Moreover, SNSPDs DCR depends on the bias current applied to the nanowire. Since the deadtime and the efficiency depends on the bias current as well, one has to find the best adjustment, where low DCR is assured as well as a low deadtime and high efficiency.

Measurement setup

Evaluating the DCR needs measurements in two setups. First, a setup where the detector is unplugged from the source and covered fully in darkness.Like this one can assume no photons from the environment are hitting the detector. This enables measuring the DCR triggered by the electronics and the characteristic of the detector's operating mode. The later means, the probability detecting photons raises if the bias current increases due to the lower energy gap its needed exceeding the critical temperature.

Second, a setup where the detector is plugged to the faint laser source. This is done to compare this results with the first setup. We assume that the first setup has the lowest DCR. Comparing to it enables us to improve the setup as much as possible towards the first setup, hence we get the best signal to noise ratio.

Results and Discussion

First the DCR is measured from the detector with cap on ... covered best as possible in darkness, so one can compare how many photons are measured from the environment. The coverage was done in two ways. On the one hand the optical setup was put into a blackbox

The measurement setup is

4.2 Efficiency

In **efficiency**, there are three types of efficiencies that describe independent loss processes in detection. An efficiency can be equated with the probability that a quantum mechanically process under consideration will occur.
These three efficiencies are the coupling efficiency (η_K), the absorption efficiency (η_A) and the registration efficiency (η_R). The graph 4.1 shows schematically where the different loss process in the detection process appear. So, when a photon is sent to a detector via an optical fibre, not all photons can be coupled into the fibre due to material and symmetry properties. The probability of coupling is called the *coupling efficiency*.
When photons hit the detector, there is always a probability that the photon will not be absorbed by the detector. This is described by the *absorption efficiency*.
Finally, there is always a probability that the photon will not be registered by the measuring electronics. This is expressed with the *Registration efficiency*.

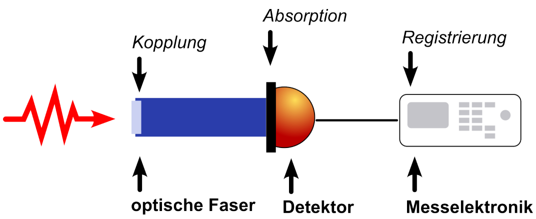

Figure 4.1: Sketch of the components in the detector setup where photonlosses appear and consequently a propability (η_K, η_A or η_R) has to be considered.

In literature, these terms are brought together in two efficiency terms: the device efficiency ($\eta_G = \eta_A \cdot \eta_R$) and the system efficiency ($\eta_S = \eta_A \cdot \eta_R \cdot \eta_K$). The device's efficiency η_G is that of the device itself and corresponds to photons sent to the detector in a free environment without any fibre coupling. The system's efficiency η_S also takes into account the coupling losses to the optical fibre. This is the case if the detector is connected to a fibre, as the device properties or the experiment does not allow photon detection in a free environment.

Measurement set up

The system detection efficiency η_s is measured in different ways, each is pointing out a different variable the efficiency is depending on. Each measurement was done in the setup explained in part 2.2.

First, we wanted to find the polarization axis were the maximum of the light is coupled to the slow axis of the fibre. This is explained by the technical fact that only the slow axis of the fibre is coupled to the output port of the detector. The explaination for this is the maximum η_A explained in part2.1. By adjusting the laser beam linear with a λ-4 plate first and afterwards rotating the λ-half plate in 10 degree steps it was possible to circulate the ligth axis and hence find the angle configuration were the maximum light was hitting the detector. This is important since measuring the efficiency aligned to a different axix would always put a systematic downshift error on the true efficiency of the detector

That measurment also confirms malus law ..

Second, the bias current und trigger voltage dependency was investigated. For this this polarization was aligned to the optimum. Afterwards, the bias current was swept from 0 to 35uA in 0.1uA steps and events within 200ms integration time were counted. This was done for four different trigger voltages.

Finally, measurements for different input count rates were done. This was done by exchanging the ND filters combination to get different photon counts. Here I covered up a range from the KHz regime up to the MHz regime. Moreover, this measurement shows the saturation point, were no additional efficiency is acquired by lowering the count rate.

Results and Discussion

4.3 Recovery time

The concept of **recovery time** is visually described in graph4.2.

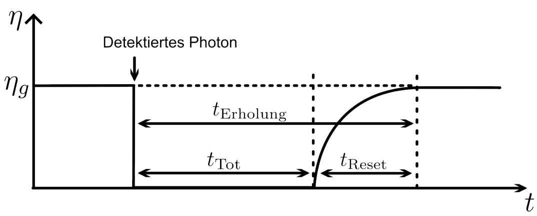

Figure 4.2: Schematic efficiency curve for the detection of a photon[3]. On the Y axis is the efficiency η, where η_G is the device efficiency. On the X axis is the time course of the efficiency
.

When a photon hits the detector of an EPD and is absorbed, the efficiency of the detector drops to zero and no further photon can be measured for a period of time. This elapsed time is called the dead time. The efficiency then rises again to its original device efficiency. This period is called the reset time. The characteristic curve between the two times forms the start of the increase to full efficiency. The sum of both times forms the recovery time.

Measurement set up

Results and Discussion

4.4 Discussion

Influence of timing jitter on efficiency and recovery time. - No Afterpulsing - Temperature 2.9 instead of 2.5Í

CHAPTER 5

Conclusion and Outlook

APPENDIX A

Appendix

In the appendix you usually include extra information that should be documented in your thesis, but not interrupt the flow.

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