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.

Bonn, ...

Date Signature

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Acknowledgements

I would like to thank ...

You should probably use `\chapter*` for acknowledgements at the beginning of a thesis and `\chapter` for the end.

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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 – 3K), and a bias current is applied to the superconductor that is lower than the critical current.

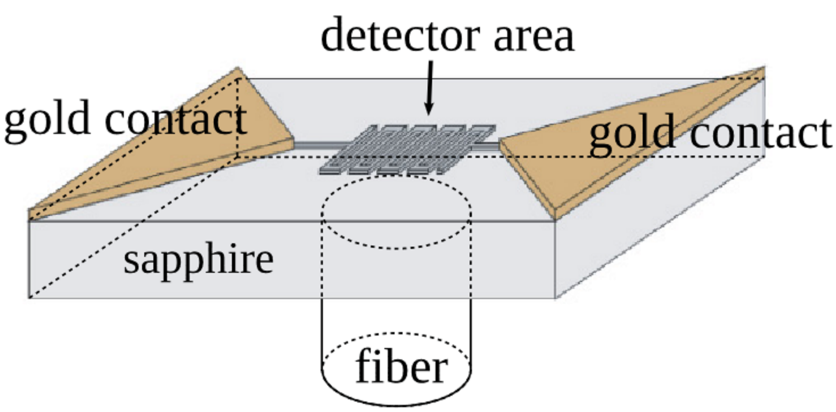

Figure 2.1: (a) Schematic structure of a superconducting nanowire single photon detector [1]

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

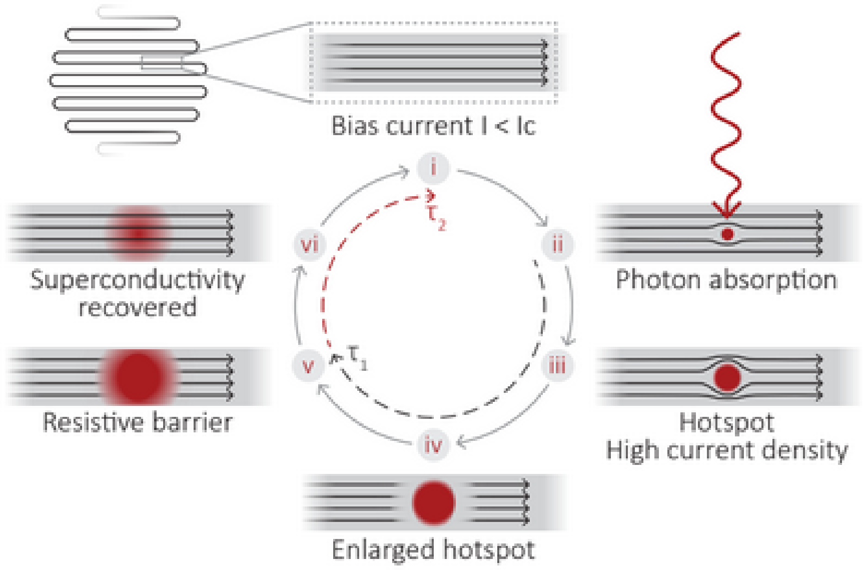

Figure 2.2: Schematic detection cycle of a superconducting nanowire single photon detector [2]

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.

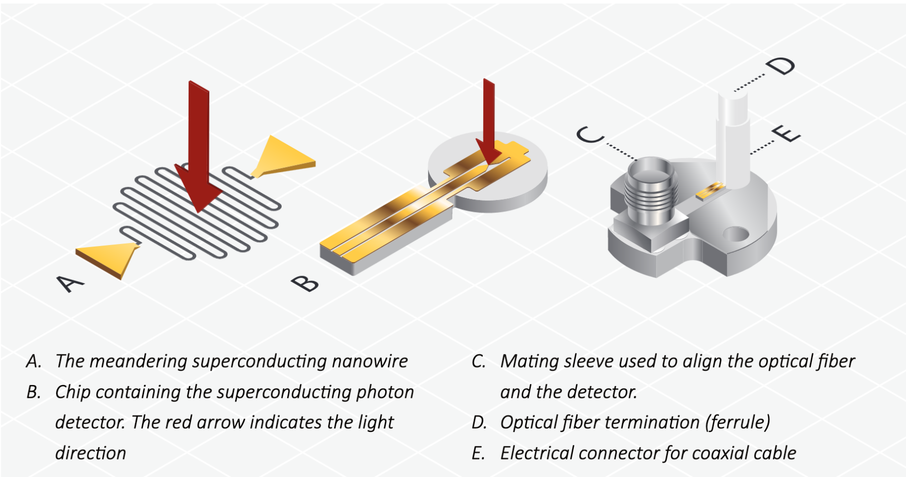

Figure 2.3: Scematic set up of the fiber coupling of a superconducting nanowire single photon detector Zitieren!

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.

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:

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

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

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

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.

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 $\mathcal{R}_{\max} \propto \frac{1}{\tau_d} = 25 - 50\mathrm{MHz}$.

- 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 the literature, four central characteristics have emerged to quantize the quality of single photon detectors and make their performance comparable. This 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** is the rate of measured detection events that were not intentionally sent to the source. The dark count rate can be caused by statistical fluctuations in the measurement electronics or by scattered or ambient light.

Measurement set up

Results and Discussion

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 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 that 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*.

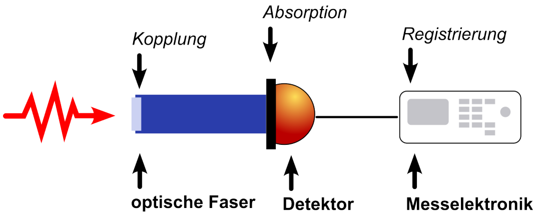

Figure 4.1: Sketch of the components in the detector setup where photons can be lost and consequently there is a probability (η_K, η_A or η_R) that the photon is not taken into account in the detection process.

These three 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 the efficiency would be if photons were sent to the detector in a free environment. The system's efficiency η_S also takes into account the coupling losses in 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

Results and Discussion

4.3 Recovery time

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

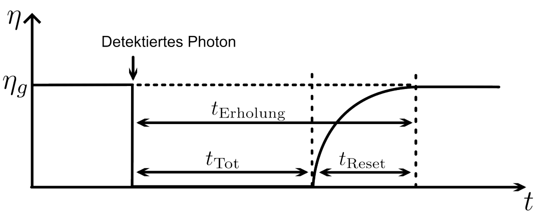

Figure 4.2: Schematic efficiency curve for the detection of a photon[3]. On the Y axis is the efficiency η, where η_G is the device efficiency. On the X axis is the time course of the efficiency
.

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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