Photon detection at subwavelength scales

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Summary

Light is one of the tools by which humans understand the world and nature surrounding them. For instance, what we see with our eyes is the scattered or reflected light from objects, which provides us with necessary information in daily life. Much of the understanding of the world around us can be gathered by using the classical description of light as an electromagnetic wave.

Light is also one of the tools in pioneering scientific research by which insight and understanding is obtained at a deeper level. Besides the classical behavior of light as a wave, light also shows features of a particle, usually called a photon. This particle description is essential for modern topics such as quantum optics and quantum information. Whatever description is applicable, ultimately the light will interact with a material object, be it the eye, a camera or a single-photon detector and the nature of this interaction is a research topic by itself. This thesis focusses on understanding light-matter interaction for nanoscale objects with a strong emphasis on superconducting nanowires capable of detecting single photons.

Superconductivity is a phenomenon where materials exhibit exactly zero electrical resistance when cooled below their characteristic critical temperature, provided that the current through the material does not exceed the critical current. The superconductor material in this thesis is NbN, which becomes superconducting for temperatures below 10 K. The NbN material is shaped as a single nanowire on a substrate, and a current just below the critical current is applied. Under these conditions absorption of the energy of a single photon is sufficient to drive the nanowire from the superconducting state to the normal state. Once the wire is in the normal, resistive state a voltage pulse is generated and amplified that signifies the detection of the triggering single photon. For lower bias currents multiple photons are needed to trigger the nanowire.

The typical dimensions of the nanowires studied in this thesis are 50-200 nm wide and $\sim$ 5 nm thick, being 5-20 times narrower and 200 times thinner than the wavelength of light. While the wave description of light provides an adequate description of light absorption for nanoscale objects the physical processes that take place on the nanoscale require further investigation. A direct observation of such a nanoscale light-matter interaction requires focusing light

to length scales smaller than the width of the nanowire, far below the diffraction limit. To gain access to these length scales scanning near-field optical microscopy (SNOM) techniques are necessary. Conventional SNOMs use a sharp metal tip or a subwavelength aperture to concentrate the light that is subsequently scattered to a far-field detector. The efficiency of such a SNOM is limited because the amount of light scattered from objects much smaller than the wavelength is exceedingly small.

The low efficiency of SNOMs makes it difficult to use them to explore physical phenomena at the single photon level. An idea, put forward in this thesis, is to use the NbN nanodetector to detect light directly in the near-field. Compared to a conventional SNOM, this configuration uses the much more efficient process of nanoscale absorption that scales with the volume of the nanoparticle. A NbN superconducting single photon detector can be small and can be integrated on top of a nanofabricated pyramid or pillar to create a scanning, single-photon sensitive probe. In this way a multi-photon probe with deep subwavelength resolution can be achieved. Based on the numerical simulations in Chapter 5 we estimate that a 50×50 nm sized NbN detector can be used as a near-field scanning probe that is two orders of magnitude more sensitive than a conventional, aperture based probe. This high efficiency hints at a strong near-field light-matter interaction. However, the perturbation of the emission rate of a nearby quantum dot is smaller than with conventional SNOM probes.

New experiments that aim at investigating the detection mechanism of SSPDs can be designed by using the technique of quantum detector tomography. Most measurements that characterize SSPDs measure the count rate as a function of the power of the light incident on the detector and bias current applied to the detector. Detector tomography uses the measured count rate as a function of the mean photon number of the incident light to determine the absorption efficiency and the probabilities to detect exactly one, two, three etc. photons. The description of the detector response in this photon number basis is a complete quantum description of the detector and is an essential step in understanding the detection mechanism of SSPDs. The accuracy and robustness of this type of tomography is investigated in Chapter 2, showing that the parameters that characterize the quantum response of the detector can be estimated to an accuracy better than 2%.

Detector tomography separates the physical process of optical absorption from the process that leads to a measurable voltage pulse. The physics of this latter process is still under active investigation, but should not depend on the polarization of the incident light: once the photon is absorbed the energy is transferred to the electrons of the superconductor and the polarization information is lost. Surprisingly, our tomography experiments show that the probabilities to detect one photon after the absorption efficiency is factored out **do** depend on the polarization of the incident light.

Repeating the polarization-dependent tomography experiment for various wavelengths and combining this information with the numerically calculated polarization and position dependent absorption of the wire allows us to recover the position-dependent internal detection efficiency of a single nanowire. The result shows that the edges of the wire are more photo-sensitive than the center. This qualitatively agrees with models of the detection process that include the effect of photon-assisted vortex entry. In these models photon detection at the edge is favored because absorption of the photon lowers the energy barrier for vortex entry. Once the vortex enters the superconducting material the dissipation of the moving vortex triggers the detector.

The experimentally determined local detection efficiency of a nanowire cannot be completely explained by the current models. However, good quantitative agreement with the measured polarization-dependent quantum efficiency of meandering wire SSPDs can be obtained if both the polarization-dependent optical absorption and the measured local detection efficiency is taken into account. This strengthens the emerging picture of a local detection efficiency for NbN detectors, but a direct experimental observation is still lacking.

As a first step towards a direct determination of the local detection efficiency we have numerically simulated the response of a NbN nanowire in a scattering SNOM using the local detection efficiency as input. In these simulations, a rounded, conical tip is placed above a NbN nanowire, with a fixed gap of 5 nm between the tip and the nanowire. The tip-nanowire system is illuminated from the side and the tip functions as an antenna that concentrates the light around its apex. In such a configuration the tip acts as a point-like light source scanning over the nanowire, and the tip-position dependent SSPD response is calculated. Because the absorbing detector functions as a resistive load to the antenna a question arises if the resonance required for a subwavelength resolution probe is degraded by the presence of the tip.

The simulation results show that, besides the intrinsic property of the position-dependent detection efficiency, the detector response in the SNOM also depends on the tip geometry and tip position. The localization of the incident light around the tip originates from the coupling of the light and the free electrons in the tip. Thus, the tip geometry plays an important role in the SSPD absorption. The tip with a smaller semi-angle and radius produces a higher free electron density and consequently a stronger electric field (or light) intensity at its apex. As a result more absorption occurs in the detector. The length of the tip determines the plasmonic response of the electrons in the metal tip, and the intensity of the light in between the apex and the detector shows a resonant behavior as a function of the tip length. A spatial resolution of ~ 20 nm can be achieved when the tip moves across the edge of the nanowire where the signal is enhanced by a maximum in both the local

detection efficiency and the optical absorption of the tip-nanowire geometry.

With both photon number resolving ability and high spatial resolution of 20 nm, new types of near-field optical microscopy arise. A nanowire SSPD can be fabricated on top of a micrometer-sized pyramid or pillar, and the edge can be used as a sensor in near-field detection, with a spatial resolution of about 20 nm. By tuning the bias current we can make the detector work in different photon-number regimes, opening the possibility to extract quantum information (i.e., photon number states) in the optical near-field.