Superconducting single-photon detectors designed for operation at 1.55-μm telecommunication wavelength

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Abstract. We report on our progress in development of superconducting single-photon detectors (SSPDs), specifically designed for secure high-speed quantum communications. The SSPDs consist of NbN-based meander nanostructures and operate at liquid helium temperatures. In general, our devices are capable of GHz-rate photon counting in a spectral range from visible light to mid-infrared. The device jitter is 18 ps and dark counts can reach negligibly small levels. The quantum efficiency (QE) of our best SSPDs for visible-light photons approaches a saturation level of ~30-40%, which is limited by the NbN film absorption. For the infrared range (1.55 μm), QE is ~6% at 4.2 K, but it can be significantly improved by reduction of the operation temperature to the 2-K level, when QE reaches ~20% for 1.55-μm photons. In order to further enhance the SSPD efficiency at the wavelength of 1.55 μm, we have integrated our detectors with optical cavities, aiming to increase the effective interaction of the photon with the superconducting meander and, therefore, increase the QE. A successful effort was made to fabricate an advanced SSPD structure with an optical microcavity optimized for absorption of 1.55 μm photons. The design consisted of a quarter-wave dielectric layer, combined with a metallic mirror. Early tests performed on relatively low-QE devices integrated with microcavities, showed that the QE value at the resonator maximum (1.55-μm wavelength) was of the factor 3-to-4 higher than that for a nonresonant SSPD. Independently, we have successfully coupled our SSPDs to single-mode optical fibers. The completed receivers, inserted into a liquid-helium transport dewar, reached ~1% system QE for 1.55 μm photons. The SSPD receivers that are fiber-coupled and, simultaneously, integrated with resonators are expected to be the ultimate photon counters for optical quantum communications.

1. Introduction

Modern quantum communications (QC) provide a unique possibility of ultrafast, extremely low power, and unconditionally secure information exchange. Practical QC systems require high-counting rate and very sensitive photon detectors with precise timing characteristics and low dark counts.

Superconducting single-photon detectors seem to be very prospective for these purposes as they demonstrate a unique combination of the picosecond response time and high quantum efficiency (QE) in the NIR range. We have already reported the development of the superconducting single-photon detector (SSPD), based on ultrathin, submicron-width NbN structures [1-3]. The SSPD's operation is based on photon-induced resistive hotspot formation in the current-carrying ultrathin and ultranarrow superconducting stripe [4]. The devices are operated at 2 – 5 K and are capable of GHz-rate photon
counting in a spectral range from visible to mid-infrared. Advances in the fabrication process and low-temperature operation lead to QE as high as ~30-40% for visible-light photons, which is the saturation value, limited by optical absorption of the 4-nm thick NbN film. For 1.55 μm photons, QE reaches ~20% and decreased exponentially with the wavelength reaching ~0.02% at the 6-μm wavelength [5].

In this paper we present results of the SSPDs development for implementation in practical QC systems. To further enhance the SSPD efficiency at 1.55 μm we have performed an approach to integrate our detectors with optical resonant cavities. Independently, we have successfully coupled our SSPDs to single-mode optical fibers. We also present a fiber-based single-photon receiver, designed for applications in practical QC systems.

2. Device design and fabrication

Our detector chips are thin-film structures deposited on 350-μm-thick sapphire substrates and intended for connection to an external coplanar waveguide (figure 1 left). The active element of the detector is a meander-structure made of ultrathin (4-nm-thick) and ultranarrow (~100-nm-wide) NbN stripe, covering 10x10-μm² area with the filling factor ~0.5 (figure 1 right). The NbN superconducting films were deposited on sapphire substrates by DC reactive magnetron sputtering whereas the meander element of the detector was patterned by the direct electron-beam lithography followed by reactive-ion etching. The coplanar waveguide, serving also as large contact pads of the detector was made of gold with a titanium sublayer deposited by the vacuum resistive evaporation at room temperature, and patterned by optical lithography [6].

Figure 1. The image of the detector chip with lateral size 4x5mm² (left). The SEM image of a SSPD active structure, consisting of a 4-nm thick and 100-nm-wide NbN meander-type stripe (black), and covering 10x10 μm² area (right).

To enhance the SSPD efficiency at 1.55 μm, we have performed an approach similar to [7], i.e. to increase the absorption of the detector at 1.55 μm by integrating it with optical resonant cavities. An optical microcavity optimized for absorption of 1.55 μm photons was designed as an one-mirror resonator consisting of a λ/4 dielectric layer and a metallic mirror.

The microcavity was deposited on the top of the NbN SSPD meander. The resonator was formed by the dielectric SiO₂ layer and metal mirror made of gold or palladium. A schematic geometry and a photo of the integrated detector structure are shown in figure 2.

Microcavity layers were deposited using a magnetron sputtering system at a pressure below 6x10⁻⁶ mbar. Thin films of Au or Pd were deposited in a DC mode and SiO₂ in RF mode. The deposition rates were 1.92 nm/s for Au, 1.85 nm/s for Pd and 0.4 nm/s for SiO₂. The thickness of the SiO₂ layer was 256 nm optimized for absorption at the 1.55-μm wavelength considering the refraction coefficient of SiO₂ measured as 1.46. The metal layers made of Au or Pd were about 1000 nm thick.
3. Spectral sensitivity
We have performed experiments to investigate the spectral sensitivity of the SSPD with resonant optical cavity comparing to the detectors with no cavity. For the experiments in the NIR (0.6-2µm) we used a grating spectrometer; the optical radiation was delivered to a cryostat with the SSPD as a free-propagating beam and reached the SSPD through the sapphire substrate. QE of the SSPD in the NIR range was measured as a ratio of a photoresponse number to a number of incident photons.

Our experimental data show that the SSPD QE decreases with the increase of wavelength; a spectral dependence of QE demonstrates a rather steep slope (open squares in figure 3). To reveal the resonant component, we normalized the QE spectral dependence of a SSPD with λ/4 cavity (QE1(λ) – solid circle in figure 3) to the QE spectral dependence of a SSPD without λ/4 cavity. A result of normalizing for the experimental data is shown in figure 4 (open triangles).

First tests performed on relatively low-QE devices integrated with microcavities, showed that the cavity enhances SSPD QE at the wavelengths near the resonator maximum. QE at the resonant frequency was of the factor up to 3 higher than that for a nonresonant SSPD. A divergence between expected and measured maximums of QE dependence shows, that the cavity was not fully optimized for 1.55-µm wavelength. That can be explained by a difference between expected and real refractive indexes of the λ/4 dielectric layer.

4. Fiber-coupled SSPD
We have designed an integrated two-channel, single-photon receiver based on fiber-coupled SSPDs. The receiver was designed to be immersed in a standard liquid helium transport dewar. Two SSPDs were placed at the bottom flange of a cryogenic insert (figure 5a). For fiber-coupling of the SSPDs we used photoresist rings (figure 5b), fabricated on top of the detector by a photolithography process. The
cross section through the coupling mechanical support for our fiber-detector consisting of the photoresist ring and two bridge-like aluminum holders is presented in figure 5c. The estimated coupling efficiency of the fiber-detector set up in our design is about 30%.

Our experiments demonstrated that the direct fiber-coupling implemented in our receiver did not significantly reduce the time resolution of our NbN detectors. The real time counting rate of the receiver is $\sim$1 GHz. The measured jitter was 35 ps (a histogram at the top of figure 5d). The value was somewhat longer than the best, 18 ps, result obtained in our non-fiber NbN detectors [3], but still much better than in other SPDs.

Figure 5. Design of fiber-coupled receiver (a-c) and the receiver timing jitter (d).

5. Conclusions

We have developed an advanced SSPD structure with an optical microcavity optimized for absorption of 1.55 $\mu$m photons. The design of advanced SSPD structure consists of a quarter-wave dielectric layer, combined with a metallic mirror. First measurements demonstrate, that implementation of the one-mirror resonant cavity allows to increase detector QE at the resonant wavelength by factor of 3-to-4 compared to that of the detector without microcavity.

We have fabricated and tested a fiber-based single-photon receiver, designed for applications in practical QC systems. The estimated coupling efficiency of the fiber-detector set up in our design is about 30%. The completed receivers, inserted into a liquid-helium transport dewar, reached $\sim$1% system QE for 1.55 $\mu$m photons.

The SSPD receivers that are fiber-coupled and, simultaneously, integrated with resonators are expected to be the ultimate photon counters for long-distance fiber-based optical communications and quantum cryptography.

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