Infrared NbN superconducting single-photon detector for quantum cryptography and quantum information processing

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We present the overview of our recent results in research and development of superconducting single-photon detector (SSPD) practical applications such as quantum cryptography. By optimization of fabrication process and usage of high-quality silicon wafers with SiO_2 layer acting as a microcavity we managed to reach up to 35.6% detection efficiency at 1500 nm wavelength. Also we extended its wavelength range beyond 1800 nm by the usage of the fluoride ZBLAN fibres.

Quantum cryptography and quantum computing require efficient and fast single-photon detectors with low dark counts rate, and picosecond timing resolution (jitter). Although a significant progress in the development of InGaAs single-photon avalanche photodiodes (SPAD) was recently reported they still suffer from high dark count rate and relatively high jitter of several hundred picoseconds.

One of the novel single-photon detectors is superconducting single-photon detector based 100-nm-wide meander-shaped NbN strip (SSPD). The operation principle of such a detector is based on the local suppression of the superconductivity in the strip and formation of a resistive barrier [1, 2]. At the standard telecom wavelength of 1550 nm SSPD was successfully used in applications ranging from single-photon source characterization [3, 4] to quantum cryptograph [5]. In latter case the usage of the SSPD enabled a record length of the quantum key distribution, i.e. up to 250 km [6, 7].

Here we present a practical SSPD targeted to its applications quantum cryptography. Our recent research was inspired by the need of quantum efficienvy improvement. As the ultimate detection efficiency is limited by the NbN film absorption the straightforward way to overcome this limitation is to integrate the SSPD with a quarter-wave optical microcavity. Previously reported realizations [8, 9] featured the microcavity fabricated on the face side of the detector, i.e. the NbN film was deposited and patterned on the substrate, then a $\lambda/4$ dielectric layer was deposited on the patterned NbN film and finally the metallic mirror was placed on top of the dielectric layer. Although being reported above 60% quantum efficiency [9] such a detector is very difficult in practical usage: typically the light is fed to the SSPD by a single-mode optical fibre connected directly to the NbN meander. Cavity-integrated SSPDs require illumination through the substrate which in its turn require elaborated optics (lensed fibres, etc) and alignment techniques (such as active probe station).

Another approach was introduced in [10], i.e. to fabricate SSPD on Si substrate with SiO_2 layer. The Si/SiO_2 interface acted as a mirror. Although this approach gives a noticeable improvement in quantum efficiency it does not allow one to reach an ultimate almost unity absorption due to a relatively low reflectivity of this interface.

In our recent work we realized the latter approache: followed [10] and optimized our fabrication process to achieve maximum quantum efficiency of SSPD on high-quality silicon wafers with SiO_2 layer.

The SSPD was coupled to the optical fibre by precision alignment against the fibre core and subsequent mechanical fixing in a specially designed mount. Being cooled down to $\sim$2 K the SSPD did not exhibit any noticeable misalignment. We used three types of fibres for different wavelength ranges. In the range 600 nm – 1600 nm we used SSPD with the HP780 fibre which is single-mode for visible light. In the range 1000 nm – 1800 nm we used SMF-28e XB fibre which is a typical single-mode fibre for telecom wavelengths of 1300 nm and 1550 nm. Finally we used fluoride ZBLAN fibre to characterize the SSPD at 1800 nm wavelength which is beyond the transparency window of the silica.

Figure 1 presents system quantum efficiency measured in range from 800 nm to 1800 nm with different optical fibres: HP780 (1), SMF-28e (2) and fluoride-based ZBLAN fibre (3). Red squares represent detection efficiency measured with SMF-28e fibre and unpolaraized light, whereas red stars represent detection efficiency measured with polarized light with the polarization adjusted for maximum detection efficiency. One can see that with optimal polarization detection efficiency reaches 44.5% at 1300 nm wavelength and 35.6% at 1550 nm. Also the application of ZBLAN fibre enabled us to extend the spectral operation range beyond 1.7 μm, a cut-off for standard silica fibres. One can see that at 1750 nm wavelength on ZBLAN fibre quantum efficiency is as high as 17%. Such a detector was successfully used for the research into quantum dot emission near 2 μm wavelength [11].

Also we measured detection efficiency vs dark counts rate for our best device. The result is shown in fig. 2. Red circles correspond to 1300 nm wavelength, blue squares correspond to 1550 nm.

In conclusion, we presented the results of our recent efforts to improve SSPD's quantum efficiency and promote them to practical applications.

We improved the performance of the SSPD by fabricating it on high quality silicon wafer with SiO_2 layer acting as a cavity and SiO_2 / Si interface acting as a mirror. Such SSPD being fibre-coupled demonstrates up to 35.6% detection

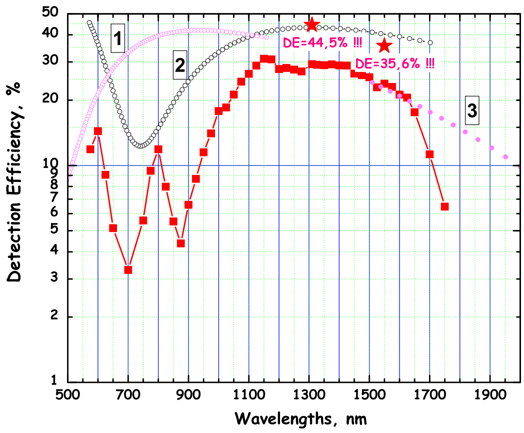

FIG. 1: Detection efficiency of the SSPD measured in wavelength range from 600 nm – 1800 nm with three different fibres: (1) HP780, (2) SMF-28e XB, and (3) ZBLAN fibre based on fluoride glass transparent beyond 1800 nm. Red squares represent detection efficiency measured with SMF-28e fibre and unpolaraized light, whereas red stars represent detection efficiency measured with polarized light with the polarization adjusted for maximum detection efficiency.

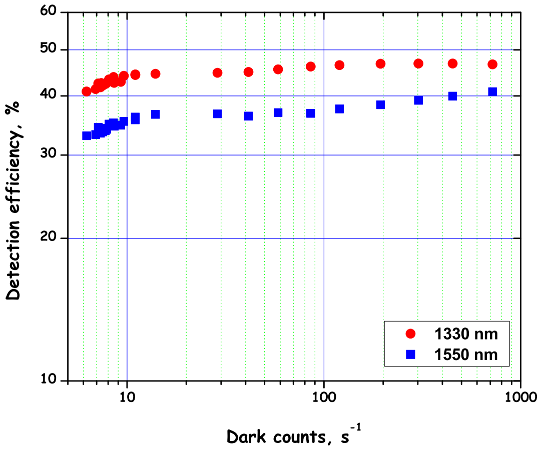

FIG. 2: Detection efficiency at 1300 nm (red circles) and 1550 nm (blue squares) vs dark counts rate measured for our best device.

efficiency (reduced to the fibre input) at 1550 nm at 10 dark counts per second, and we extended the wavelength range of the beyond 1800 nm by the usage of fluoride-based ZBLAN fibres.

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