On-chip single-photon spectrometer for visible and infrared wavelength range

V Kovalyuk1,2,3, O Kahl2,3, S Ferrari2,3, A Vetter3,4, G Lewes-Malandrakis4, C Nebel5, A Korneev6,7, G Goltsman6,7, W Pernice2
1Department of Physics, Moscow State Pedagogical University, 119992, Russia
2Institute of Physics, University of Münster, 48149, Germany
3Institute of Nanotechnology, Karlsruhe Institute of Technology, 76344, Germany
4Institute of Theoretical Solid State Physics, Karlsruhe Institute of Technology, 76131, Germany
5Fraunhofer Institute for Applied Solid State Physics, 79108, Germany
6Moscow Institute of Physics and Technology (State University), 141700, Russia
7National Research University Higher School of Economics, Moscow 101000, Russia

Abstract. Here we show our latest progress in the field of a single-photon spectrometer for the visible and infrared wavelengths range implementation. We consider three different on-chip approaches: a coherent spectrometer with a low power of the heterodyne, a coherent spectrometer with a high power of the heterodyne, and an eight-channel single-photon spectrometer for direct detection. Along with high efficiency, spectrometers show high detection efficiency and temporal resolution through the use of waveguide integrated superconducting nanowire single-photon detectors

1. Introduction
The detection of photons by superconducting nanowire single-photon detectors (SNSPDs or SSPDs) [1] is an inherently binary mechanism, revealing either absence or presence photons, but losing their spectral information. For some state-of-the-art microscopy techniques such as fluorescence resonance energy transfer (FRET) or fluorescence lifetime imaging (FLIM) wavelength discrimination is essential and required spectral demultiplexing prior to detection [2, 3]. Here we show our latest progress on the field of a single-photon spectrometer of the visible and infrared wavelengths range implementation. We use an approach adopted from quantum photonic integration to realize a compact and scalable on-chip single-photon spectrometer with waveguide integrated single-photon detectors (WSSPDs) [4] and implemented three nanophotonic configurations that allow us to produce a wide bandwidth heterodyne detection with ultra-high resolution greater than 109 [5,6] as well as the parallel detection on eight wavelength channels, but with reduced wavelength resolution up to 103 [7].

2. Device design and fabrication
The multilayer wafers consisting of silicon nitride (450 nm) and silicon dioxide (2.6 μm) thin films on top of a silicon carrier wafer were used as starting materials. On top of the wafers we deposited the ultrathin NbN superconducting film with a nominal thickness of 4 nm by a reactive magnetron sputtering in Argon and Nitrogen atmosphere. We reached a maximum critical temperature $T_c = 9.5$ K for films deposited at a substrate temperature $T_S = 800$ °C with partial pressures of Argon and Nitrogen of $6 \times 10^{-3}$ and $2.5 \times 10^{-4}$ mbar, respectively. The sheet resistance of the deposited NbN films measured at room temperature was 620 Ohms/sq.

We fabricated different types of on-chip spectrometers using several steps of e-beam lithography with dry etching and thin-film deposition. In the first step, Au-contact pads and alignment marks were formed using PMMA resist and standard lift-off technique. In the second step, U-shaped NbN nanowires were made with use of HSQ resist by reactive ion etching (RIE) in CF4. Finally, negative electron resist maN-2403 and etching in atmosphere of CHF3 were employed for waveguide formation. A schematic
view of fabricated nanophotonic circuits for quantum and spectral photonic applications is shown in Fig. 1.

The integrated devices include a waveguide and a detector parts. For the first two types of spectrometers, the waveguide part (in blue) includes two focusing grating couplers (FGCs) for 1550-nm light coupling, 50:50 Y-splitter for calibration of optical power as well as U-shaped superconducting NbN nanowire (80 nm width) as a single-photon detector (Fig. 1a,b). For a spectrometer of the third type (Fig. 1c), the waveguide part includes arrayed waveguide grating (AWG) [8], adapted to operate close to the central wavelength of 1550 nm, and 740 nm for IR and visible spectrometer implementations. The eight-channel of the spectrometer are terminated by WSSPDs connected to RF contact pads (highlighted in yellow). The available optical FGCs at the input of the circuit serve to calibrate the efficiency of the optical coupling, and at the output ones to separate the losses in AWG and detectors (dotted color arrows).

![Coherent detection vs Direct Detection](image)

**Figure 1 (a-c).** Schematic view of nanophotonic circuits for quantum and spectral photonic applications. The waveguide is highlighted in blue, RF contact pads and lithographic markers (crosses) are shown in yellow; S is signal laser; LO is local oscillator; dotted color arrows show the reference outputs for a calibration procedure. (a) Scheme of a nanophotonic device for coherent detection with low power LO. (b) Scheme of nanophotonic device for coherent detection with high power local oscillator. (c) Scheme for nanophotonic device for eight-channel spectrometer with arrayed waveguide grating as an optical demultiplexer and WSSPDs as detectors.

### 3. Operation principles

In all types of on-chip spectrometers presented here, the active non-linear element providing light detection are WSSPDs integrated with the silicon nitride optical waveguides [9]. However, the principle of operation of superconducting nanowires in these devices is different.

For the operation of the first type of spectrometer (Fig.1a) we routed to WSSPD two weak signals with slightly different frequencies: well-controlled local oscillator (LO) and unknown signal (S), whose spectrum needs to be measured. In this case, WSSPDs operates below the superconducting transition temperature and registers the total electromagnetic field of two sources (beating). Since the probability of photocounts in this mode is proportional to the optical power, the frequency of the “clicks” follows the beating of the total electromagnetic field. Knowing the frequency and phase of the LO and measuring the beating frequency (intermediate frequency), one can determine the frequency and phase of the unknown signal [5].

For the operation of the second type of device (Fig.1b), the LO power is significantly increased by heating the electronic WSSPD sub-system to the superconducting transition temperature. In this case, WSSPD operates as a hot-electron bolometer (HEB). If such a bolometer is biased by a direct current,
then the voltage follows the change in the electron sub-system temperature, which is proportional to the square of the amplitude of the beating [6]. The frequency and phase of the unknown signal is found by analyzing the voltage at the bolometer.

In the third type of spectrometer (Fig.1c), the unknown signal is divided by the wavelength by AWG connected to the eight WSSPDs. By measuring the photocounts in each of the channels, one can recover the original spectrum. To calibrate the device we used additional FGCs, connected with output waveguides through the integrated 50:50 Y-splitter. The light direction is indicated by dotted color arrows (Fig.1c).

4. Experimental results

4.1. On-chip efficiency and timing jitter

At first, using a tunable, fiber-coupled lasers and a calibrated photon flux, restricted by attenuators, we measured the efficiencies of devices. The nanophotonic devices placed on a motorized stage (AttoCube Systems) in a cryostat at 1.6 K temperature with 12-channel optical and 8-channel electrical access. The on-chip detection efficiency was measured as the ratio of WSSPD count rate with the exception of the dark count rate to the photon flux propagating in the waveguide. The on-chip detection efficiency is determined by the product of the internal detection efficiency (IDE) and the absorption coefficient. While the absorption of the NbN waveguide's evanescent mode by nanowire due to its length can be made close to unity, the internal detection efficiency is limited by the constrictions that arise in the fabrication of nanowires. For this reason, even for devices with the same geometry, the measured detection efficiency at the same wavelength can differ due to changing IDE. The measured on-chip detection efficiency for on-chip IR and visible spectrometer were found at the level of 19% and 21%, including internal losses of the AWG device and detectors. All detection efficiencies are given for dark count rate less than 10 s⁻¹. At the second stage, using a femtosecond laser sources we determined the timing jitter performance. The timing jitter values of the devices were measured as below 50 ps in both wavelength regimes. The timing jitter was limited by the room temperature readout scheme and independent of the wavelength range.

For the coherent spectrometer shown in Fig. 1a, the on-chip efficiency was defined as the minimal detectable signal at an intermediate frequency. By decreasing the signal at a fixed LO power below a pico-watt level, we were able to detect a signal at an intermediate frequency close to the quantum limit \( \Phi ph / RBW = 1.6-2.3 hv \). Here \( \Phi ph \) is the photon flux reaching the detector, and RBW is the resolution bandwidth of the spectrum analyzer, used for analyzing the voltage trace from WSSPD [5].

For the coherent spectrometer shown in Fig. 1b, we measured the conversion efficiency as the ratio of the power at the intermediate frequency to the power reaching the bolometer. We found the conversion efficiency of such a spectrometer at the level of -22 dB, as well as the conversion bandwidth up to 3.5 GHz [6].

After measuring the on-chip efficiency, the spectral resolution of the spectrometers was found.

4.2. Wavelength resolution

For coherent detection, the spectral resolution was limited by the stability of the LO. We obtained a line width at an intermediate frequency of \( \Delta f = 4 \) MHz, whereas in the homodyne scheme, when the role of the signal and the local oscillator was performed by the same laser source but shifted in frequency with the help of an acousto-optic modulator, we reached the signal width at an intermediate frequency equal to \( \Delta f = 1 \) kHz. Thus, the spectral resolution of the first two devices \( (f / \Delta f) \) was \( 10^6 \) and \( 10^7 \) for heterodyne and homodyne reception, respectively.

For the spectrometer shown in Fig. 1c, the resolution is determined by the configuration of the waveguide circuit [7, 8]. We designed the AWG with the spectral range of 16 nm and 45 nm and the channel resolution 2.2 nm and 6.4 nm for the IR and visible spectrometer, respectively. In this case, an increase in the resolution of the spectrometer leads to an increase in its dimensions, and, consequently, to an increase in optical losses.
4.3. Practical implementation
We investigated nanodiamond cluster created by drop-casting a colloidal solution of nanocrystals onto a microscope slide using the AWG visible range single-photon spectrometer. We analyze the emitted fluorescence spectrum using the eight-channel on-chip single photon spectrometer upon continuous-wave excitation at 532 nm. Taking advantage of the SNSPDs high timing resolution and fast response time, in a complementary experiment we replaced the exciting 532 nm continuous wave laser with a passively mode-locked laser, which produces pulses of 32 ps duration (FWHM) at 440 nm wavelength. In combination with the scanning confocal microscope setup, a lifetime map of the diamond nanocluster was obtained alongside the spectral information [7].

5. Conclusion
We implemented and studied three different single-photon spectrometers. The coherent spectrometers shown in Fig. 1a,b, allow to achieve a huge spectral resolution, which is not available for the direct-detection spectrometers of Fig 1c, making them suitable for applications where high spectral resolution is required, such as spectrometry of gas lines. In this case, an exact and smooth tuning of the local oscillator is necessary, which might leads to an increased acquisition time and post processing. The advantage of the first type of spectrometer over the second is the quantum limited sensitivity, as well as the low required power of the LO (below the picowatt level). While the second type of spectrometer has a wide conversion band reaching 3.5 GHz, but not capable of counting individual photons events. In addition, along with spectral information, signal phase information can be available for analysis.

The third kind of spectrometers presented here, based on direct detection can obtain both spectral and temporal information over several channels simultaneously. On-chip spectrometer with AWG arrays can be used similar to CCD arrays in conventional spectrometers. A similar type of integrated spectrometers can be realized adopting a wide variety of devices for light demultiplexing, such as, photonic crystals, planar diffraction gratings, etc. [10, 11]. These integrated circuits enable live monitoring of numerous fluorophores over a wide spectral range. Highly precise infrared and thermal imaging becomes possible owing to the huge spectral range of the SNSPDs. In addition demonstrated on-chip single-photon spectrometers can be used in high-speed quantum optical implementations, which require reliable detection of individual photons on tailored wavelengths. Further work will be related to the practical demonstration of the capabilities of the first two types of spectrometers for working with real single-photon sources (quantum dots, nanotubes, etc.) as well as combining all of the demonstrated approaches in a single device.

Acknowledgments
V. Kovalyuk acknowledges support by the Russian Science Foundation (project No. 16-19-10633; design, NbN film deposition and testing). A. Korneev acknowledges support of the Russian Science Foundation (project No. 17-72-30036; nanophotonic circuits modeling) and W. Pernice acknowledges support by the DFG grants PE 1832/1-1 & PE 1832/1-2 and the Helmholtz society through grant HIRG-0005 (fabrication of nanophotonic circuits and testing).

References
[1] Gol’tsman G N, Okunev O, Chulkova G, Lipatov A, Semenov A, Smirnov K, Voronov B, Dzardanov A, Williams C, Sobolewski R 2001 Appl. Phys. Lett. 79 6 705–707
[2] Okabe K, Inada N, Gota C, Harada Y, Funatsu T, Uchiyama S 2012 Nat. Commun. 3, 705
[3] Borst J W, Visser A J W G 2010 Meas. Sci. Technol. 21 102002
[4] Sprengers J P, Gaggero A, Sahin D, Jahanmirinejad S, Frucci G, Mattioli F, Leoni R, Beetz J, Lermer M, Kamp M, Hofling S, Sanjines R, Fiore A 2011 Appl. Phys. Lett. 99 181110
[5] Kovalyuk V, Ferrari S, Kahl O, Semenov A, Scherbatenko M, Lobanov Y, Ozhegov R, Korneev A, Kaurova N, Voronov B, Pernice W, Gol’tsman G 2017 Sci. Rep. 7, 4812
[6] Kovalyuk V, Ferrari S, Kahl O, Semenov A, Lobanov Y, Shcherbatenko M, Korneev A, Pernice W, Gol’tsman G 2017 *J. Phys. Conf. Ser.* 7 917 62042 1-6

[7] Kahl O, Ferrari S, Kovalyuk V, Vetter A, Lewes-Malandrakis G, Nebel C, Korneev A, Goltsman G, Pernice W 2017 *Optica* 4 5 557–562

[8] Smit M K, Member A, Van Dam C 1996 *IEEE J. Sel. Top. Quantum Electron.* 2 2 236–250

[9] Kahl O, Ferrari S, Kovalyuk V, Goltsman G, Korneev A, Pernice W H P 2015 *Sci. Rep.* 5, 10941

[10] Kyotoku B, Chen L, Lipson M 2010 *Opt. Express* 18 1 102–107

[11] Momeni B, Hosseini E S, Askari M, Soltan M, Adibi A 2009 *Opt. Commun.* 282 15 3168–3171