World Record in TCSPC Time Resolution: Combination of bh SPC-150NX with SCONTEL NbN Detector yields 17.8 ps FWHM

Abstract: We present an ultrafast TCSPC setup consisting of a bh SPC-150NX TCSPC module and a SCONTEL superconducting NbN detector. The combination delivers an instrument response function (IRF) with a full width at half maximum of 17.8 ps. The RMS value of the overall single-photon timing jitter is about 7.9 ps.
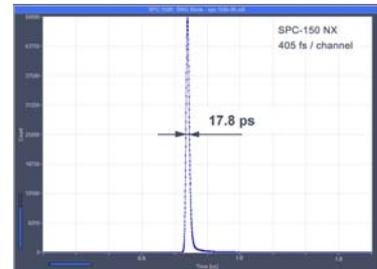
Detector

Superconducting single photon detectors (SSPDs) consist of an ultra-thin superconducting film in the form of a nanostrip. The strip is normally shaped as a meander [3, 10, 11]. For operation as an optical detector, the superconducting strip is biased by a DC current close the critical value. The absorption of a photon results in the formation of a region with a non-equilibrium concentration of quasiparticles. The current density then exceeds the critical level, and a resistive region forms across the nanostrip. The resulting voltage pulse indicates the detection of the photon. The mechanism is described in detail in [11]. Superconducting NbN detectors have extremely low timing jitter, and a spectral sensitivity range from the visible to the mid-IR range. The dark count rate of an SSPD is extremely low, typically below 1 count per second, and there is no afterpulsing. The active area of the detectors is on the order of 10 um^2.

The SCONTEL SSPD detection system [7] is available both in a liquid-He cooled version and with a closed cycle refrigerator as shown in Fig. 1, left. The spectral sensitivity of two slightly different detector types is shown on the right.
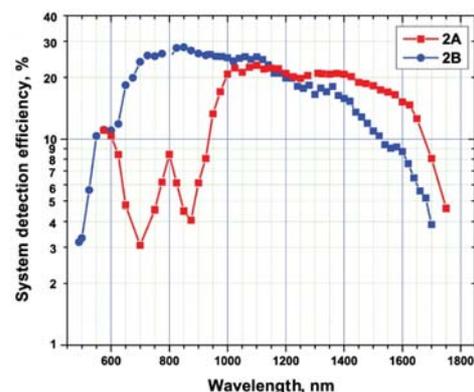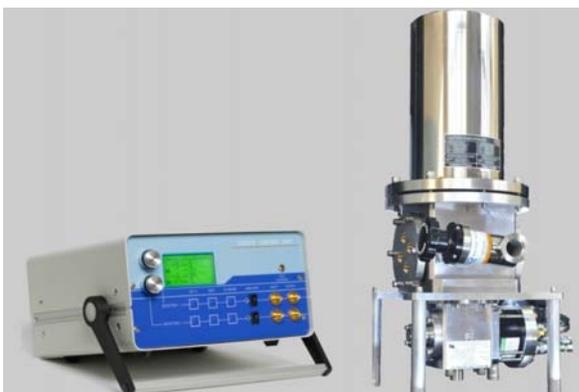
Fig. 1: Left: SCONTEL superconducting NbN detector, amplifier and controller unit and closed cycle cooler. Right: Spectral sensitivity curve. From [7].

Experimental setup

For the experiment we used a SCONTEL TCORPS-UF-10 superconducting NbN detector, both in the liquid-He cooled version and in the version with a closed-cycle refrigerator [7]. The test light source was an AVESTA Project EFO-80 laser. The laser emits pulses at a wavelength of 1560 nm

and at a repetition rate of 50 MHz. It has two outputs, one with a pulse width of 1ps, the other with a pulse width of 300 fs. The 1 ps output was used to generate a synchronisation signal for the TCSPC device via a fast photodiode. The 300 fs output was attenuated by a F2A FHA2 series optical fibre attenuator, and then coupled into the detector. The entire system was connected by single-mode optical fibres.

The single-photon response pulses from the detector were amplified by standard low-noise GHz bandwidth RF amplifiers. The total gain was 40 dB (1:100), resulting in a pulse amplitude of about 200 mV. The amplified pulses were connected to the counting input of a bh SPC-150NX TCSPC module. Compared to the commonly used SPC-150 the SPC-150NX has a 4 times higher discriminator bandwidth and 2 times faster TAC ranges [1]. The minimum time channel width is 405 fs, the electrical IRF width is 3.6 ps FWHM. The count rates used in the experiments were between 100 kHz and 2 MHz.

Results

The instrument response function of entire system, including laser, fibre system, detector, reference photodiode, and TCSPC device is shown in Fig. 2. The full-width at half maximum (FWHM) of the IRF is 17.8 ps.
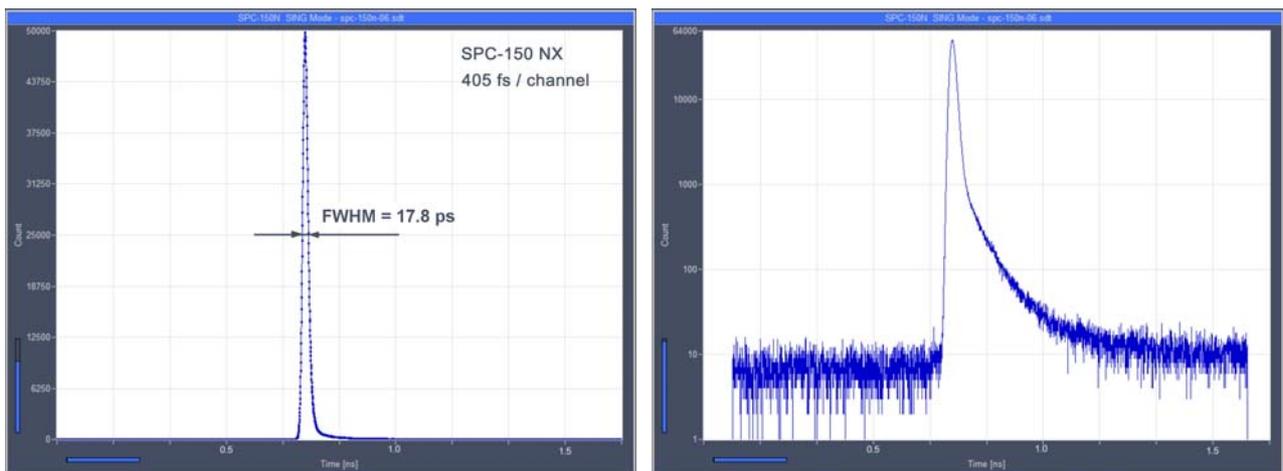
Fig. 2: Instrument-response function of the detector-TCSPC combination. Left: Linear scale. Right: Logarithmic scale. Both recorded with bh SPC-150NX TCSPC module, time per channel 405 femtoseconds.

The logarithmic display shows that the IRF has a low-amplitude tail of about 2% of the peak amplitude and about 150 ps duration. We do not know whether this is a property of the detector, a slow tail in the laser pulse shape, or a dispersion effect in the fibre system. A calculation of the RMS of the effective transit time jitter for channels with counts more than 1% of the peak value yielded about 7.9 ps.

The timing stability of the detector - TCSPC combination was excellent. Fig. 3, left, shows two recordings taken with a time of 5 minutes in between. The curves (blue and red) are almost indistinguishable. For comparison, Fig. 3, right, shows two recordings with a 30 mm difference in optical fibre length.
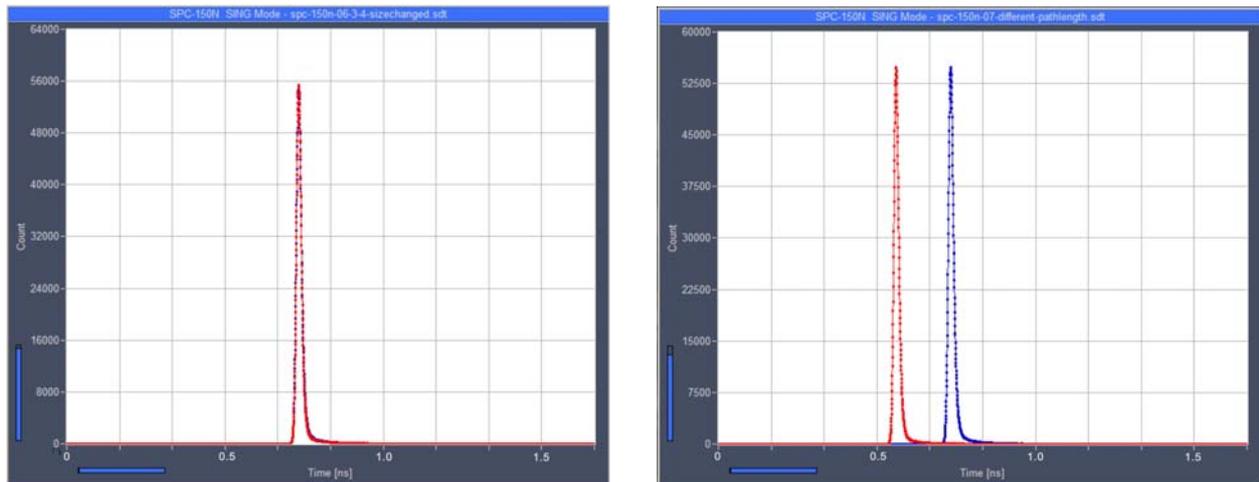
Fig. 3: Left: Two separate recordings, blue and red, taken with 5 minutes between the measurements. The timing drift is less <1 ps. Right: Two recordings, 3 cm path length difference

Discussion

Evaluations of the time resolution of TCSPC with NbN detectors have been performed and published earlier. Hadfield (2008) states an IRF width of 68 ps FWHM [2]. Rosenberg et al. (2013) reported a time resolution of 60 to 80 ps, unfortunately without describing the optics and the TCSPC setup [5]. Pernice et al. (2012) reached an FWHM of 50 ps with a TCSPC device of 19 ps RMS timing jitter [4]. Liu et al. (2014) obtained an IRF width of 75.7 ps FWHM with a multi-mode fibre in front of the detector [3]. With a single-mode fibre they obtained 52.2 ps FWHM.

An NbN detector of Single Quantum, (The Netherlands), although specified with 75 ps, delivered 48 ps FWHM with a bh SPC-150 module. However, the pulse width of the test laser (a supercontinuum laser with an AOTF) was not accurately known. An extrapolation of the results for 40 ps laser pulse width yielded an estimate of 25 ps for the detector alone [1]. Toussaint et al. (2012) reported 35 ps FWHM for a detector made by Karlsruhe Institute of Technology, Germany [9]. The test result later improved to 22.2 ps [1, 10]. From these data, the authors estimated a timing jitter of 19.8 ps FWHM for the detector alone.

Measurements of the timing jitter of SSPD detectors have also been performed with ultra-fast sampling oscilloscopes. Verevkin et al. (2004) used an oscilloscope of 50 GHz sampling rate and obtained 18 ps FWHM [11]. In a similar measurement setup, Pernice et al. (2012) obtained 18 ps FWHM, Schuck et al. (2013) obtained 18.4 ps, and Tarkhov et al. (2008) 16 ps [4, 6, 8]. It should be noted, however, that these values are for the detector alone, not for a detector-TCSPC combination. There is also another significant difference: The oscilloscope calculates centroid values from the recordings of subsequent pulses, and builds up a histogram of these values. The TCSPC device directly triggers at the edge of the detector pulses. The effect of high-frequency noise is different in both cases: Centroiding partially averages out the noise, edge triggering does not. To our knowledge, the 17.8 ps FWHM we obtained is the fastest IRF reported for any detector-TCSPC combination yet.

The question is whether the 17.8 ps we obtained can be further improved. Theoretical considerations show that the timing jitter in the buildup of the quasiparticle avalanche may be well below 10 ps FWHM. The electrical response of the TCSPC module (for noise-free input pulses) is

less than 4 ps FWHM. We therefore believe that the largest part of the timing uncertainty is induced by electronic noise. Using preamplifiers with lower noise figure does not significantly improve the situation. Good amplifiers have a noise figure of less than 2dB. That means the input-referred noise is only 25 % higher than the thermal noise of the 50-Ohm input matching resistor. In other words, most of the noise comes from the resistor. The only way to reduce it is cooling. Resistor noise scales with the square root of the temperature. Cooling with liquid nitrogen (70K) may therefore reduce the noise by a factor of two. Normally the entire amplifier has to be cooled because the matching resistor is part of the amplifier chip. That means only amplifiers based on MESFETs can be used - bipolar transistors do not work at 70 K.

Another way to improve the resolution would be to increase the amplitude of the single photon pulse of the detector itself. However, simply increasing the detector bias current does not help. Above a certain level, the dark count rate increases steeply [11, 7], and at higher current superconductivity is lost altogether. It is possible that the amplitude can be increased by modified detector design but this has not been practically proved yet.

References

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