8.7 ps FWHM IRF Width from Ultrafast SPAD

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Abstract: We tested an ultra-fast four-element low-jitter Si single-photon avalanche diode (SPAD) of EPFL, Neuchâtel, for TCSPC time resolution and timing jitter. With a bh SPC-150-NXX TCSPC module we obtained IRF (instrument-response function) widths of 8.7 ps to 9.2 ps FWHM for the individual detector elements. These values correspond to a single-photon timing jitter of about 5.2 ps RMs. With these values, the detector is the fastest high-performance SPAD currently known, surpassed only by superconducting single-photon detectors (SSPDs).

Motivation

Time resolution is the most important and most spectacular parameter of a TCSPC system [1]. With an intrinsic timing jitter of <3 ps FWHM, the bh TCSPC modules are unsurpassed in time resolution. They have been shown to deliver IRF widths of 19 ps FWHM with ultra-fast hybrid detectors [2] and 4.4 ps FWHM with superconducting single-nanowire detectors [3]. SPADs, in comparison, deliver IRF widths in the range of >25 to several 100 ps [1]. We were therefore curious whether a SPAD especially designed for low timing jitter would break the 25 ps limit. Details of the SPAD are described in [4].

Results

The test setup followed the usual design principle. As a test light source we used a Toptica Femto Fibre Pro femtosecond fibre laser with a wavelength of 780 nm and a repetition rate of 40 MHz. The beam was widened to about 3 mm diameter and attenuated by absorptive ND filters. Optical elements which could introduce temporal pulse dispersion were strictly avoided. The attenuated beam was fed directly to the SPADs. The associated detector electronics delivers photon pulses of about ±200 mV at four separate differential outputs [4]. The photon-pulse signals of the diode under test were connected to the inputs of a bh SCP-150 NXX TCSPC module. To exploit the differential output capability of the SPAD we used a differential discriminator in the TCSPC module [5]. The synchronisation signal for the TCSPC module was taken from the Sync output of the laser. Results are shown in Fig. 1.

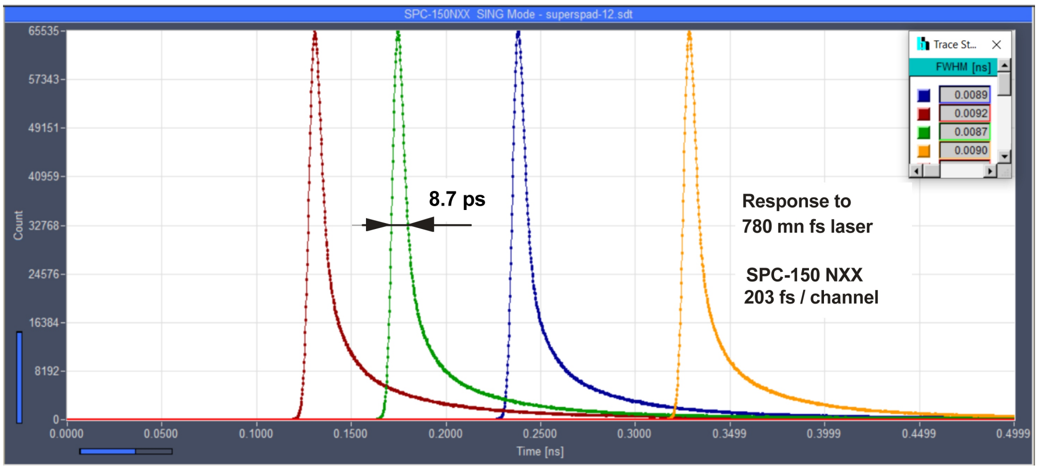

Fig. 1: Response of SPADs to 780-nm femtosecond laser. SPC-150 NXX TCSPC Module with 203 femtoseconds per channel, display scale 50 ps per division. FWHM of fastest SPAD is 8.7 ps.

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The IRF width for all detector elements is smaller than 10 ps, FWHM. The fastest SPAD has an IRF width of 8.7 ps FWHM, the slowest an IRF width of 9.2 ps FWHM. Translated into RMS jitter, these are about 5.2 ps. As typical for all SPADs, the response function has a diffusion tail [1]. Considering the long test wavelength, the diffusion tail is remarkably short and and has a low amplitude. The IRF of the fastest diode is shown in logarithmic scale in Fig. 2. A fit with a triple-exponential model delivers decay times of 4 ps for the main peak, and 32 ps and 151 ps for the diffusion tail. The amplitudes are 87,4%, 11,4% and 1.2%, respectively.

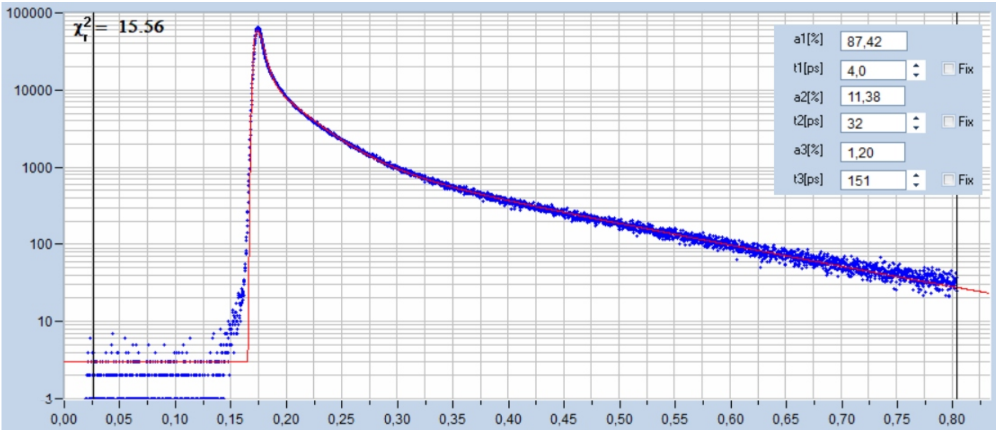

Fig. 2: IRF at logarithmic scale, fit with a triple-exponential decay model. Tail decay times are t2 = 32 ps (amplitude 11.4%) and t3 = 152 ps (amplitude 1.2%). Fit with bh SPCImage NG data analysis software.

The dependence of the IRF on the count rate is shown in Fig. 3. IRFs at three count rates, 32 kHz, 730 kHz, and 1.1 MHz, were recorded. The IRFs for 32 kHz and 730 kHz are undistinguishable, the IRF for 1.1 MHz is slightly off by 0.6 picoseconds.

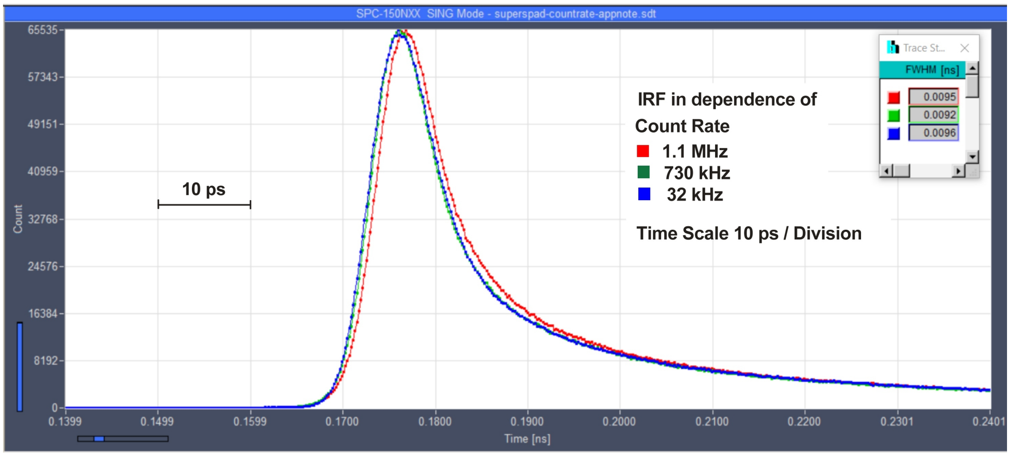

Fig. 3: IRFs for three different count rates

A possible application to photon migration in turbid media is demonstrated in Fig. 4. The figure shows light curves after the laser pulses have propagated through 0.2 mm, 0.5 mm, and 0.8 mm of paper. The pulses are broadened by multiple scattering. The shape of the transmitted-light curve bears information on the scattering and absorption coefficients in the propagation medium [1]. Under normal circumstances, objects thinner than about 1 mm cannot be investigated by the technique because the light curves become too narrow for exact analysis. Not so for the ultra-fast SPAD: The widths of the curves are 36 ps, 71 ps, and 124 ps, which is large compared with the IRF width of 9 ps.

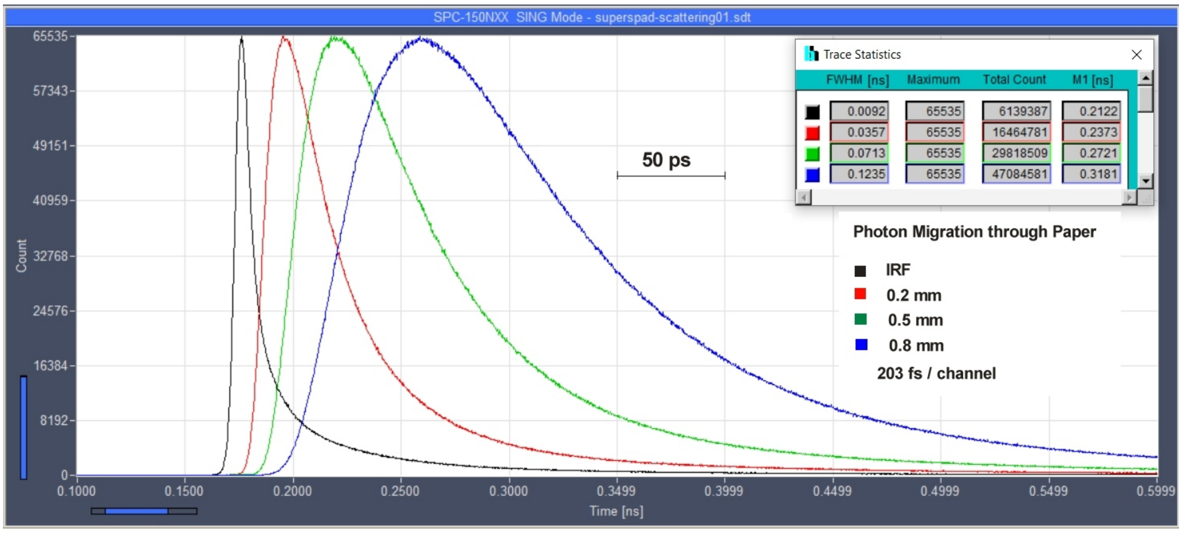

Fig. 4: Photon migration through thin layers of paper. IRF, 0.2 mm, 0.5 mm, and 0.8 mm.

Remarks

The effective IRF width of a TCSPC system contains the transit-time jitter in the detector, the intrinsic jitter of the TCSPC module, and possible jitter of the synchronisation with the laser. It is thus likely that the SPAD is slightly faster than the FWHM values given above tell. Corrected for the internal TCSPC jitter of 3 ps FWHM (about 1 ps RMS), and an estimated synchronisation jitter of 1 ps the detector IRF would be about 8.5 ps wide. Another source of timing jitter is electrical noise. Noise sources abound: The computer, switch-mode power supplies, radio transmitters, wireless LAN, and ground loops between different power sources. An indication that noise plays a role is the fact that differential detector connection yielded a slightly better timing resolution than single-ended connection: Differential operation yielded about 9 ps, single-ended operation about 11 ps. Moreover, detector jitter tests with an ultra-fast oscilloscope yielded a jitter of 7.5 ps FWHM [4]. The oscilloscope samples the detector pulses at high rate, and calculates the centroids of the pulses. With every pulse sampled several times some of the noise averages out. We therefore believe that the time resolution can still be improved by careful design of the experiment setup.

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