

# TITLE PAGE

**Citation Format:**

M. Caldarola, A. Fakhree, T. Palo, V. Damagatla, L. Di Sieno, A. Pifferi, A. Dalla Mora, L. Kobayashi Frisk, and T. Durduran, "Custom SNSPD For Hybrid Time-Domain Diffuse Optics," in Diffuse Optical Spectroscopy and Imaging X, D. Contini, Y. Hoshi, and T. D. O'Sullivan, eds., Proc. of SPIE-Optica Vol. 13935, 1393511 (2025); <https://doi.org/10.1117/12.3098384>

**Copyright notice:**

Copyright 2025 Society of Photo-Optical Instrumentation Engineers (SPIE). One print or electronic copy may be made for personal use only. Systematic reproduction and distribution, duplication of any material in this publication for a fee or for commercial purposes, and modification of the contents of the publication are prohibited.

**DOI abstract link:**

<https://doi.org/10.1117/12.3098384>

# Custom SNSPD For Hybrid Time-Domain Diffuse Optics

Martin Caldarola<sup>a</sup>, Amin Fakhree<sup>a</sup>, Tommaso Palo<sup>b</sup>, Vamshi Damagatla<sup>b</sup>, Laura Di Sieno<sup>b</sup>, Antonio Pifferi<sup>b</sup>, Alberto Dalla Mora<sup>b</sup>, Lisa Kobayashi Frisk<sup>c</sup>, Turgut Durduran<sup>c, d</sup>

<sup>a</sup>Single Quantum B.V., 2629HH, Delft, The Netherlands; <sup>b</sup>Politecnico di Milano, Dipartimento di Fisica, 20133 Milano, Italy; <sup>c</sup>Institut de Ciències Fotòniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona (Spain); <sup>d</sup>Institució Catalana de Recerca i Estudis Avançats (ICREA), 08015 Barcelona (Spain)  
m.caldarola@singlequantum.com

**Abstract:** We present a superconducting nanowire single-photon detector (SNSPD) system designed for diffuse optics applications. We describe the specifications of the detectors and we show results from time-domain diffuse correlation spectroscopy and near infrared spectroscopy.

© 2025 The Author(s)

## 1. Introduction

Diffuse optics (DO) is a powerful and fully non-invasive technique to monitor diffusive media (such as tissue) up to a depth of few cm. Generally speaking, the time-domain (TD) technique ensures the higher information content with respect to the other domains. Indeed, it allows to disentangle the contribution of absorption from the reduced scattering one using a single acquisition. Moreover, the information on the mean penetration depth reached by photons is encoded in the photons arrival time. On the other hand, the main disadvantage of the TD optical technique is due to the inherent low signal recorded (due to the need to count single photons) which results in a poor signal-to-noise ratio of acquisitions.

For TD-DO applications, to enhance the available signal and approach the limits of the technique, some conditions for the design of the detector chain should be met such as, for example, the high quantum efficiency, the high temporal resolution as well as a low dark count rate (for larger dynamic range). All those features are needed for both Time-Domain Near-Infrared Spectroscopy (TD-NIRS) [1] and Time-Domain Diffuse Correlation Spectroscopy (TD-DCS) [2]. Those techniques may be used separately (e.g., recover of the tissue components with NIRS and to detect the flow for TD-DCS) or, even better, in conjunction (e.g., to recover both oximetry and flowmetry, respectively). As a first step toward a multimodal imaging capable of improving the imaging of tissues, we conceived (within the fastMOT project) a 10000 pixel tomography system based on Superconducting Nanowire Single-Photon Detectors (SNSPDs). In this work, we present the characterization and the results obtained with single-pixel SNSPDs specifically built for both TD-NIRS and TD-DCS applications. For the TD-NIRS, thanks to the very high dynamic range of the SNSPDs, it was possible to implement a non-contact configuration for the measurements, opening also the way to new possible applications (such as for example, monitoring for thermal treatment or healing or reperfusion of tissue through bioresorbable fibres, even in conjunction with the monitoring of the microflux with TD-DCS).

## 2. Characterization of the SNSPD system

With the application of diffuse optics in mind, we developed specific detectors aiming for TD-DCS and TD-NIRS. The first set of detectors is coupled to single-mode fibres and are optimized for detecting photons at 1064 nm and 785 nm, as this two wavelengths have been shown useful for DCS and can be used for NIRS [3].

Table 1. SNSPDs main specifications

| Number of detectors in the system | Wavelength [nm] | Detection efficiency [%] | Dark count rate [cps] | Timing Jitter [ps] | Coupling optical fibre |
|-----------------------------------|-----------------|--------------------------|-----------------------|--------------------|------------------------|
| 4                                 | 785             | >72                      | < 10                  | < 40               | Single Mode            |
| 4                                 | 1064            | >70                      | < 10                  | <31                | Single Mode            |
| 2                                 | 785             | >31                      | <2000                 | <56                | Multi-Mode             |
| 1                                 | 1064            | 34                       | <2000                 | 72                 | Multi-Mode             |

Table 1 depicts an overview of the complete system, consisting of eleven detectors in total, with a combination of multi-mode and single-mode fibre-coupled SNSPDs. The obtained specifications are superior to the equivalent for Avalanche PhotoDiode (APD) or Silicon-based single Photon Avalanche Diode (SPAD), particularly in the case of photons at 1064 nm, where the efficiency of silicon based devices is usually below 5%. Moreover, the timing precision of SNSPDs is below 75 ps, which is a factor of 2 or 3 better than commercially available APDs. This point is particularly relevant for time-domain diffuse optics technics, because the timing resolution is fundamental to have an accurate retrieval of the physiological parameters to extract.

More in detail, Figure 1 depicts the measured detection efficiency and dark count rate for one detector from each category in the Table 1. For single-mode SNSPDs the presence of a saturation plateau allows us to choose the operating current to reduce the dark count to negligible values ( $<10$  cps). Note that in this case we tested the efficiency using linearly polarized light parallel to the nanowires in the SNSPD, maximizing the detection efficiency.

In the case of multi-mode SNSPDs, the dark counts are significantly higher due to the bigger size of the detector. In this case we used unpolarized light, leading to a lower detection efficiency due to the preferred absorption along the nanowire of the SNSPD.

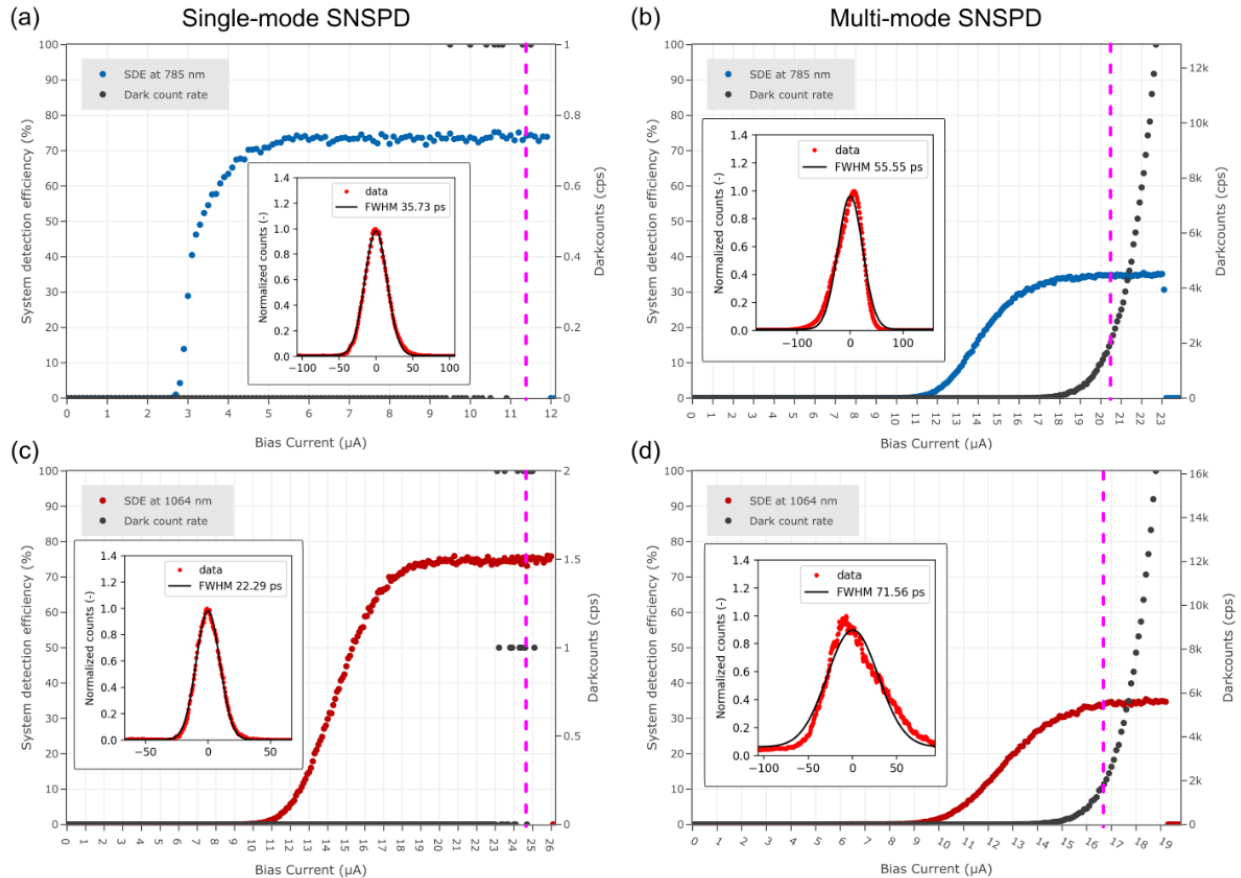


Figure 1: SNSPD system characterization: detection efficiency and dark count rate for different bias currents. (a) SNSPD optimized for 785 nm and Single-mode fibre. (b) SNSPD optimized for 785 nm with a multi-mode fibre. (c) SNSPD optimized for 1064 nm for single-mode fibre. (d) SNSPD optimized for 1064 nm for multi-mode fibre. The vertical dashed magenta line depicts the operating current at which the jitter is measured. The working wavelength is mentioned in the legend. The inset plots depict the measured jitter curve.

### 3. Diffuse optics experiments: TD-DCS and TD-NIRS

To show the suitability of the proposed detector for TD-NIRS, we performed the spectral (from 600 to 1100 nm at step of 10 nm) measurement of a tissue mimicking liquid phantoms (made of a mixture of water and intralipid with a nominal scattering of  $12 \text{ cm}^{-1}$  at 700 nm). The setup was based on a supercontinuum laser coupled to a prism for wavelength selection and implemented a non-contact (NC) geometry (distance from the sample: 7 cm; source-detector distance of 0.5 mm). Indeed, exploiting the high dynamic range of the SNSPDs (4 decades) it was possible to cope with the high number of early (i.e., scarcely diffused) photons thus detecting also those from later times without getting hindered by detector tails or background noise.

Figure 2 reports the recovered absorption (left) and reduced scattering spectra (right) in blue and the values are compared to the expected values (literature or Mie law respectively, dotted lines). Generally speaking, there is a fairly good agreement in the retrieval of the optical properties even if for absorption not-negligible errors can be found in the region 600-800 nm due to the low absolute value of absorption while for wavelength larger than 1064 nm the discrepancy has to be ascribed to the noise of the laser pump.

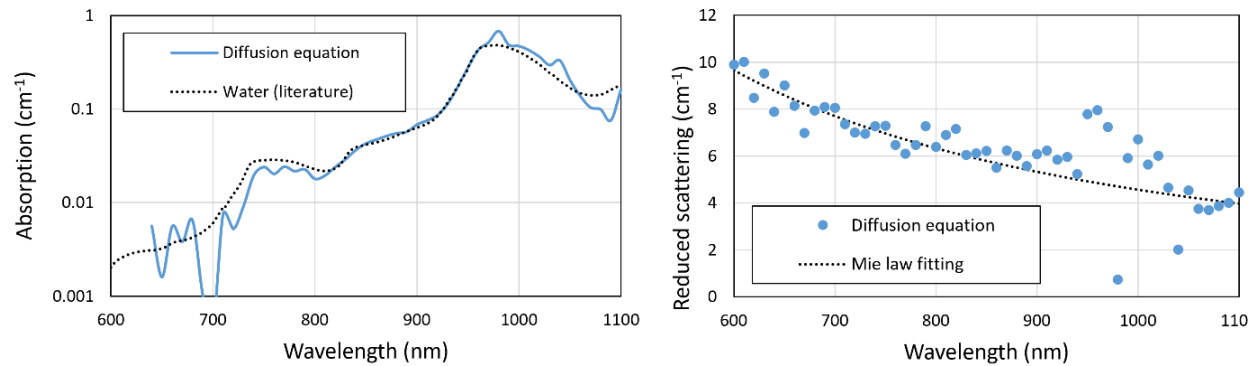


Figure 2: On the left side, the recovered spectrum of liquid phantom (blue line) compared to the literature one; on the right side, the reduced scattering recovered compared to the expected theoretical one (i.e., using the Mie law for fitting).

With the presented SNSPD detector system we also performed in-vivo TD-DCS measurements in a healthy volunteer. An inflatable arm cuff was placed on the upper arm, and the measurement probe consisting of a source (1050 nm, pulse full-width half-maximum 240 ps) and single-mode detector fibre was placed on the forearm. The detector fibre was coupled to one of the single-mode 1064 nm detector channels. The distance between source and detector fibre was 1.5 cm. After a three minute baseline period when the cuff pressure was 0 mmHg, the pressure was increased to 180 mmHg blocking blood flow to the forearm. After three minutes of occlusion, the arm cuff was released (0 mmHg) reintroducing blood flow. We note that although the detector channel specifies 1064 nm, the experiments were run at 1050 nm due to higher laser stability at this wavelength. This translate into a 1 or 2% decrease in detection efficiency due to the mentioned spectral shift.

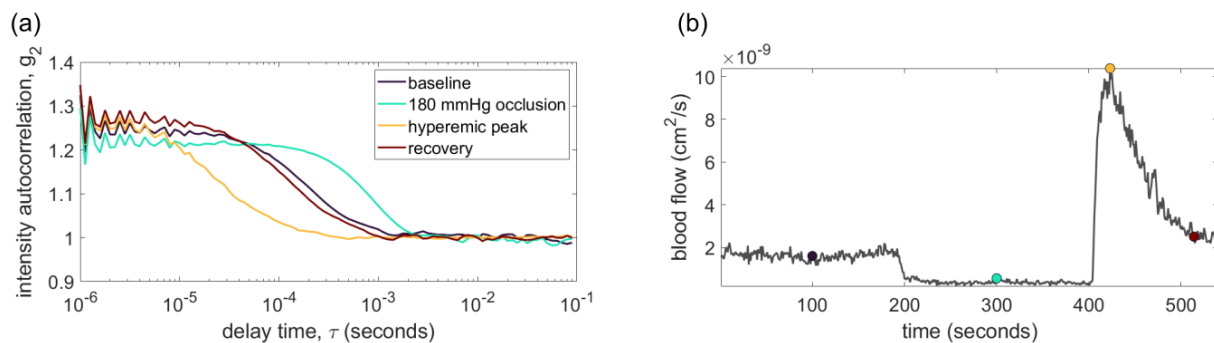


Figure 3: TD-DCS in vivo results using SNSPDs as detectors. (a) Intensity autocorrelation functions for the four stages of the experiment, where one can clearly distinguish the different characteristic time in each stage. (b) Recovered blood flow as a function of time. The dots indicate the points in time at which the autocorrelation curves from (a) correspond.

Figure 3 depicts the results of a simple occlusion experiment. The intensity autocorrelation function was computed in post-processing using an integration time of 1 second and then fit to the solution of the correlation diffusion equation for a semi-infinite homogeneous medium [3] to extract blood flow as a function of time. As seen in Figure 3, intensity autocorrelations could be properly detected with sufficient signal quality to clearly distinguish changes in the decay rate of the intensity autocorrelation (Figure 3 (a)) which directly corresponds to a detection in change in blood flow (Figure 3 (b)).

In summary, we presented a superconducting nanowire single-photon detector system for TD-DCS and TD-NIRS and we show in-vivo and in-vitro measurements that show the relevance of this detector technology for these applications.

#### 4. Acknowledgements

The fastMOT project (<https://fastmot.eu>) is funded by the EU's HORIZON EUROPE program under grant agreement number 101099291 and by the UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee (grant number 10063660).

#### 5. References

- [1] A. Pifferi et al., "New frontiers in time-domain diffuse optics, a review," *Biomed. Opt.* 21, 091310 (2016).
- [2] J. Sutin et al., "Time-domain diffuse correlation spectroscopy," *Optica* 3, 1006-1013 (2016)
- [3] L. Di. Sieno et al., "Oxyhemoglobin Measurements Using 1064 nm Light," *IEEE Journal of Selected Topics in Quantum Electronics*, 31(4), (2025)
- [4] T. Durduran and A.G. Yodh. "Diffuse correlation spectroscopy for non-invasive, micro-vascular cerebral blood flow measurement." *Neuroimage* 85 (2014)