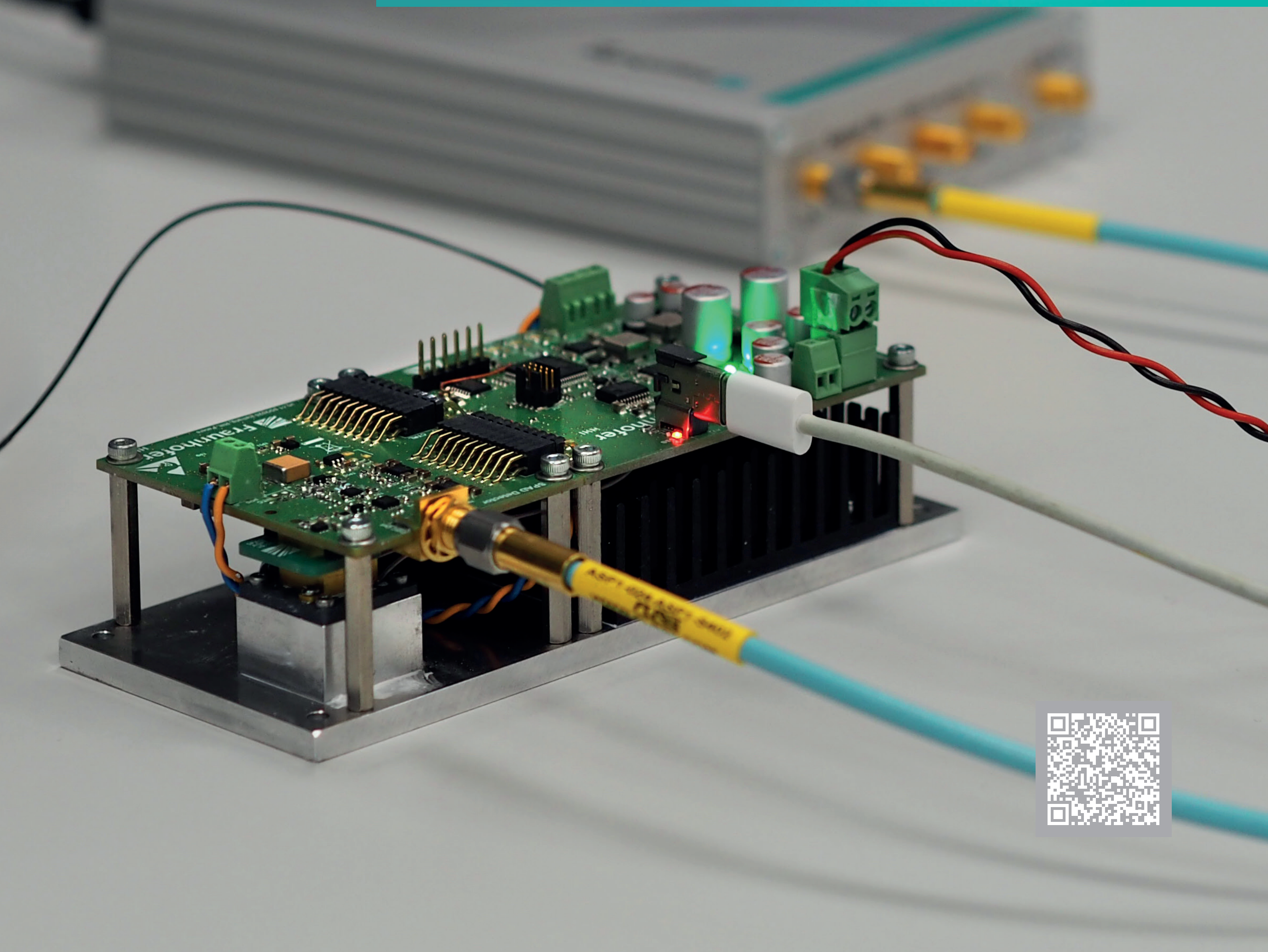
Fraunhofer HHI

APPLICATION NOTE

Quantum Ready

Single Photon Detection Module

High-Precision and Low-Noise Photon Detection



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SPAD Module

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1 Introduction

The Single Photon Detection Module (SPAD) developed by the Fraunhofer Heinrich Hertz Institute offers a compact, high-sensitivity, and cost-efficient solution for the precise detection of individual photons in the optical C-band and O-band. It is designed to meet the requirements of quantum communication, quantum computing, and photon-based sensing, providing low dark count rates, sub-nanosecond timing resolution, and flexible configuration options for diverse system environments.

As quantum technologies advance, the ability to detect single photons with high precision and stability becomes increasingly essential for both research and commercial applications.

The SPAD Module addresses these needs through its optimized detection performance, temperature-stabilized operation, and software-based configurability, enabling straightforward integration into existing optical and quantum systems.

This Application Note provides an overview of the SPAD Module's design, configuration, and key performance characteristics. It further illustrates versatile integration examples across representative use cases such as next-generation photonic and quantum networks, Quantum Key Distribution (QKD), Single-photon based LiDAR (Light Detection and Ranging), and fluorescence lifetime imaging (FLIM).

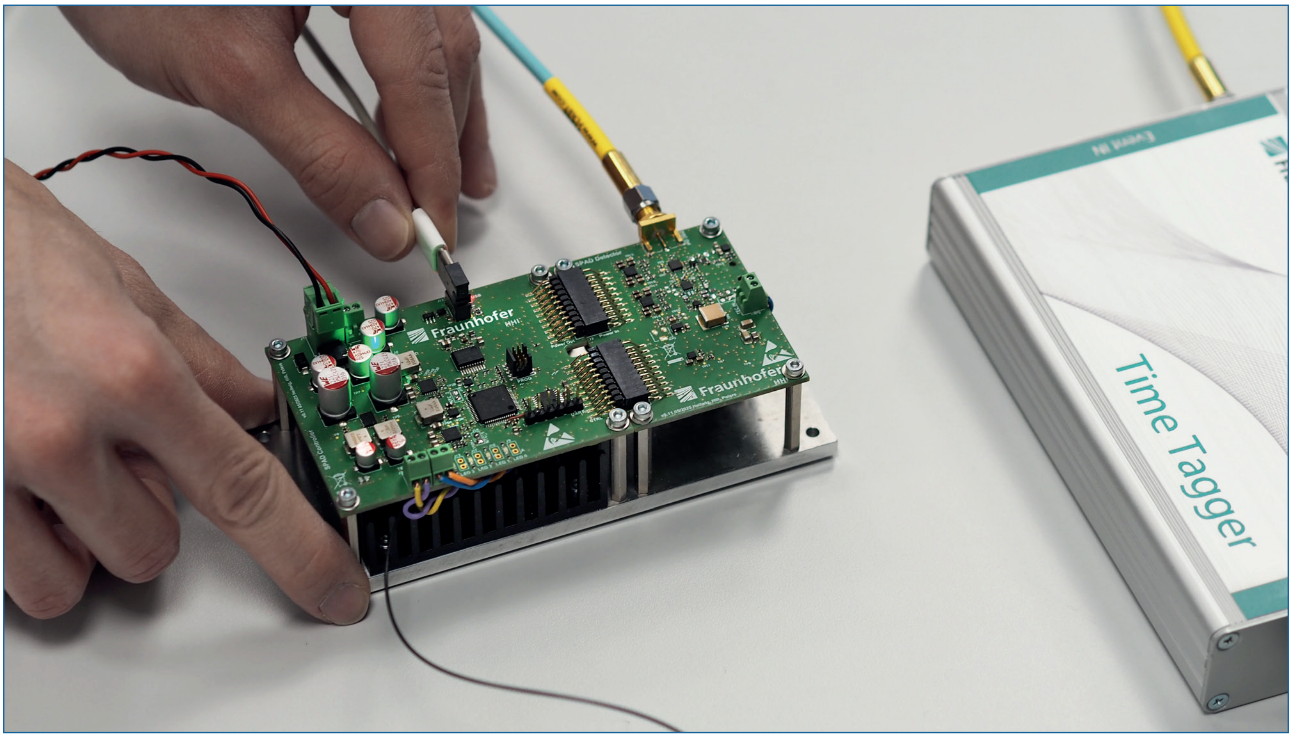

Figure 1: SPAD Module – the compact single photon detection system with an optical single mode fiber input and an electrical CML detection output

2 Overview of the Single Photon Detection Module

The Single Photon Detection Module is designed for precise single-photon detection in the wavelength range between 1060 nm and 1570 nm, covering both the optical C-band and O-band.

The module offers:

- Compact form factor and competitive cost-efficiency
- Operation in continuous free-running mode
- Adjustable configuration parameters (bias voltage, dead-time, temperature, and threshold voltage)
- Fiber-coupled optical input (FC/PC connector)
- 50 Ω CML logic compatible detection signal output
- USB-based control interface for convenient integration

The detector is available both as a stand-alone single-photon-detector module and as an OEM version. This flexibility allows integration into diverse optical systems, including laboratory setups, quantum key distribution (QKD) receivers, and sensing systems.

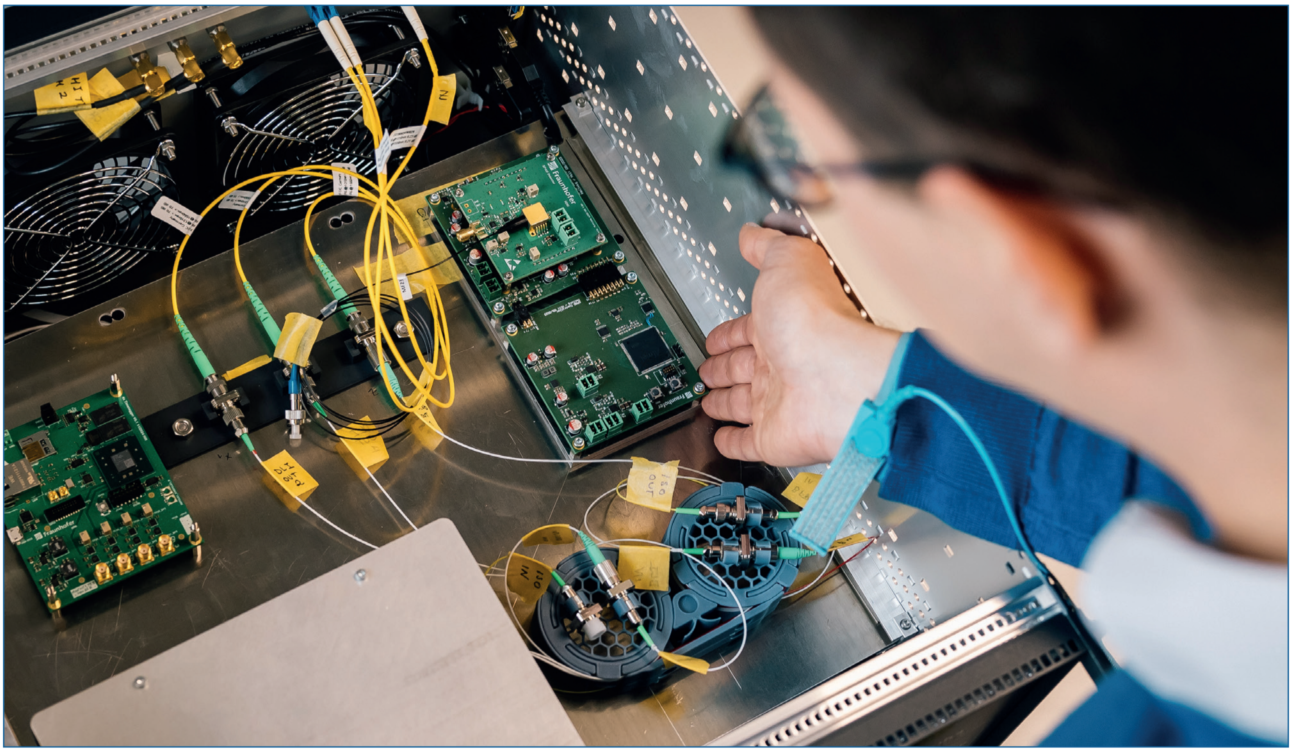

Figure 2: SPAD Module integrated in Quantum Key Distribution setup

3 Setting Up the SPAD Module

The SPAD Module can be set up in a few straightforward steps:

- Supply power (12 V DC, max. 8 W) via the power connector.
- Connect the USB interface to a control computer for configuration and monitoring.
- Connect the DSP or Timetagger to the detection output (50 Ω CML logic compatible).
- Connect the fiber to the FC/PC connector of the module.

The module's internal Thermo-Electric Cooler (TEC) stabilizes the detector temperature ensuring stable performance across a wide range of conditions.

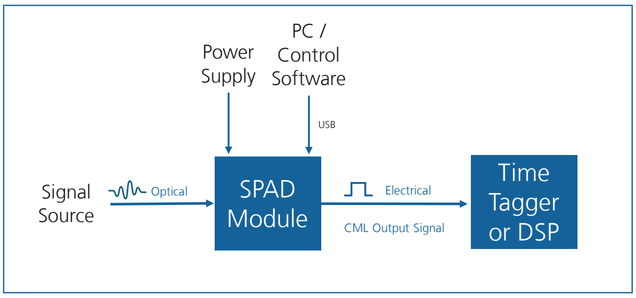

Figure 3: Example setup showing fiber connection, power, and USB control interface

4 Readout and Signal Processing

The module outputs a single-ended CML signal (1.0–1.5 V amplitude) representing detection events with low timing jitter. These events can be processed by external timing electronics such as time taggers or counting devices.

Each photon detection event corresponds to a distinct electrical pulse. Depending on the system design, these pulses can be used directly for counting statistics or further processed for timing and correlation analyses (e.g., in Time-Correlated Single Photon Counting systems).

5 Configuring the SPAD Module

The module's configuration can be performed via the USB interface using standard commands (SCPI-compatible). The USB interface allows users to monitor detector status and adjust operating parameters in real-time.

The module operates fully autonomously once configured, making it ideal for integration into long-term experiments or deployed quantum network systems. The following parameters can be adjusted individually for the detector channel:

5.1 Bias and Excess Voltage

- Bias Voltage adjustable between 0 V and 90 V
- Excess voltage range 0 - 5 V for optimizing detection efficiency (PDE) and signal-to-noise ratio

5.2 Temperature Control

- Settable between +30 °C and -40 °C
- Internal TEC controller with typical current consumption of 250 mA at 3.3 V
- Allows optimizing the trade-off between dark count rate and afterpulsing / minimum deadtime

5.3 Deadtime

- Adjustable range from 50 ns to 1 s
- Used to suppress afterpulsing

5.4 Threshold Voltage

- Configurable between -100 mV and +100 mV to adapt to varying signal amplitudes

5.5 Auxiliary Functions

- FAN control and temperature monitoring
- TEC, thermistor and system parameter readout

6 SPAD Controller Tools – Graphical User Interface

The SPAD Controller Tools are graphical user interfaces designed to configure and monitor SPAD modules. They provide full access to all relevant module parameters and display them in real time, allowing users to immediately observe operating conditions and any changes.

Each interface is divided into clearly structured sections covering detector settings, high-voltage supply, temperature control (TEC), and test-signal generation. All values are shown live to ensure precise and transparent monitoring.

In the Basic View (top-left tab), the tools also offer a simplified overview of essential parameters – such as detection rate, bias voltage, and temperature – across multiple connected detectors. This enables quick comparison and efficient oversight in multi-detector setups.

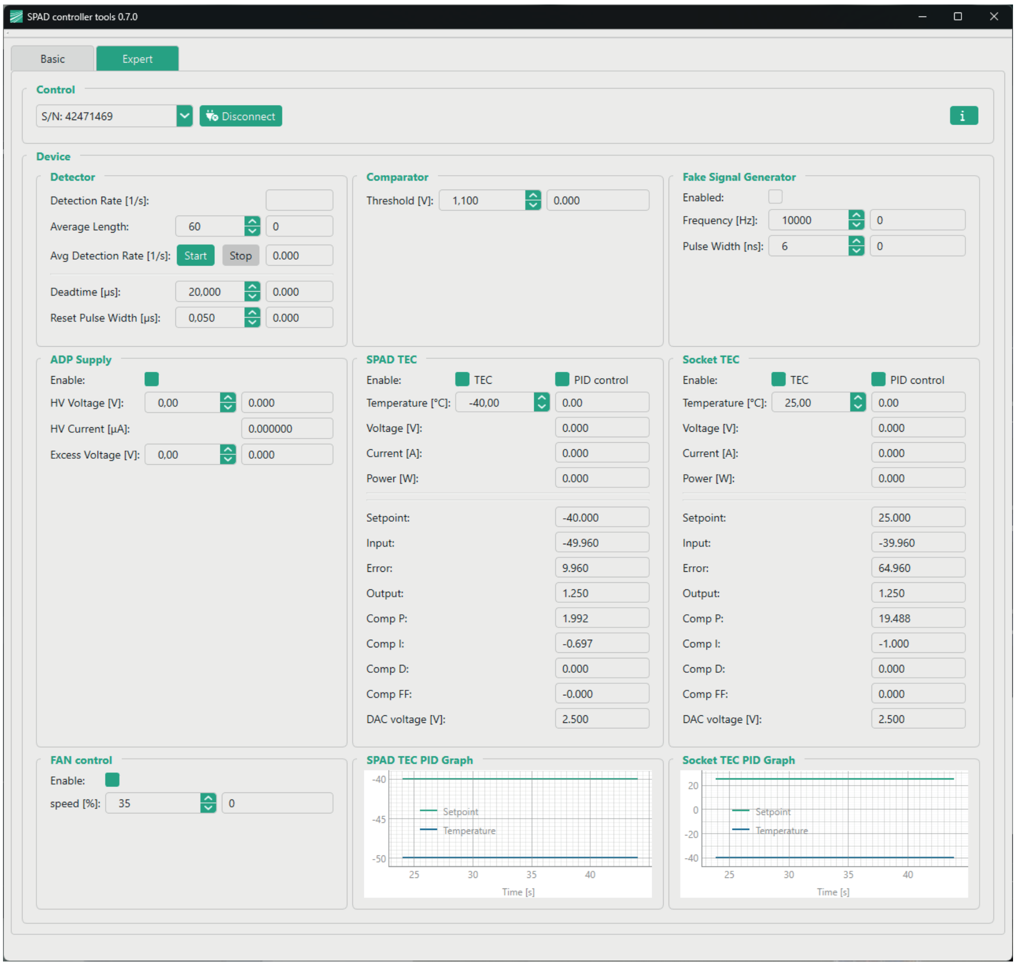

Figure 4: SPAD Controller Tools – graphical user interface for configuring and monitoring the SPAD module

7 Performance Characteristics

The electro-optical specifications of the SPAD Module are summarized as follows:

Parameter	Parameter Value / Range	Note
Wavelength range	1000 nm to 1600 nm	typ. λ = 1550 nm
Efficiency	10 - 25 %	@ λ = 1550 nm
Dark count rate	10 %: 1.3 kHz (typ. 800 Hz) 15 %: 2.7 kHz (typ. 2.5 kHz) 20 %: 5.1 kHz (typ. 3 kHz) 25 %: 10 kHz (typ. 5.1 kHz)	
Timing jitter	~200 ps @ 10 % ~150 ps @ 15 % ~120 ps @ 20 % ~100 ps @ 25 %	@ 25% efficiency
Deadtime range	~100 ns to 80 µs	in 100 ns steps
Optical coupling	SMF-28 optical single-mode fibre Pigtail L = 100 cm	
Output signal format	1.0 V low, 1.5 V high	into 50 Ω single ended (CML)
Output connector	SMA	
Dimensions (W × H × L)	140 mm * 60 mm (OEM Version)	

Preliminary specifications

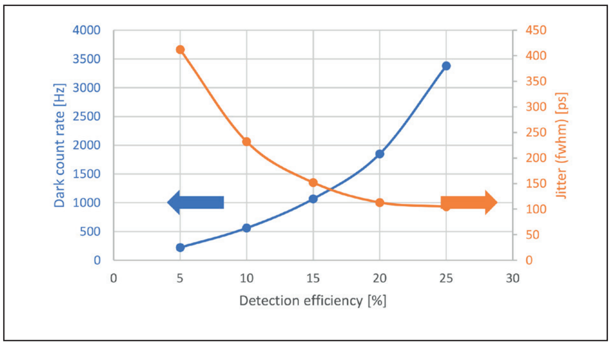

Figure 5: Dark count rate and timing jitter as a function of detection efficiency

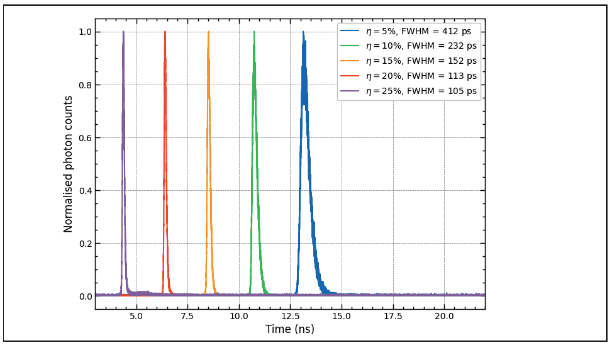

Figure 6: Decrease in timing jitter for increasing detection efficiency

8 Application Examples

8.1 Quantum Key Distribution (QKD) and Quantum Networks

The Single Photon Detection Module enables high-precision photon detection in quantum key distribution (QKD) systems operating over fiber and free-space channels. Its low dark count rate and timing jitter below 170 ps ensure stable key generation even under high-loss or dynamically routed conditions.

The module has been successfully employed in clock-channel-free QKD field trials. The system demonstrated the autonomous synchronization and seamless continuation of secure key exchange after optical path rerouting or link interruptions of several minutes.

This robustness makes it ideally suited for future software-defined quantum networks and scalable deployment of quantum key distribution.

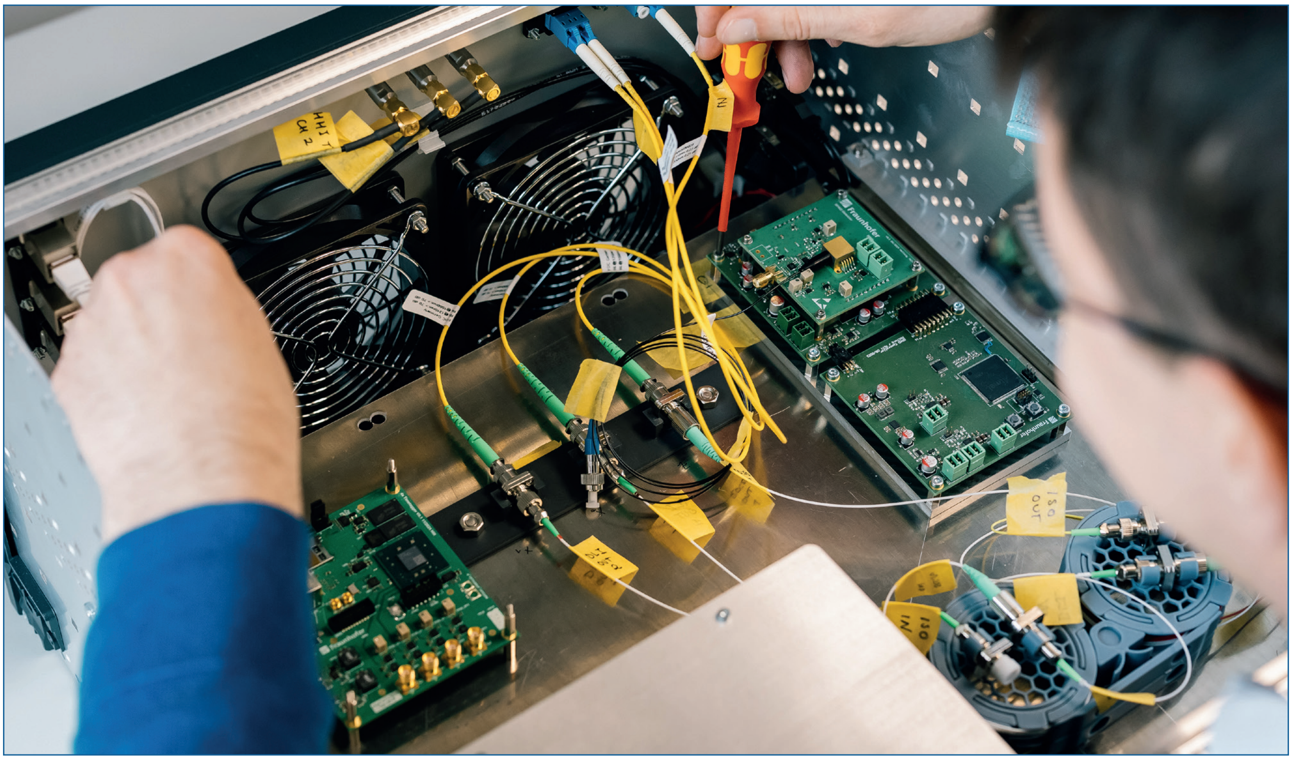

Figure 7: SPAD Module integrated in Quantum Key Distribution setup

8.2 Quantum Communication and Computing

In quantum communication and computing experiments, the SPAD Module provides low-jitter coincidence detection and stable free-running operation for photon correlation, entanglement analysis, and Bell-state measurements.

In multi-channel setups, the Single Photon Detection Module enables scalable coincidence setups for entanglement-based QKD and photon-source characterization in laboratory and field environments.

8.3 Optical Time Domain Reflectometry (OTDR) and LiDAR

For photon-counting distance measurements, the SPAD Module offers sub-nanosecond time resolution and a high dynamic range.

These characteristics enable precise time-of-flight analysis for LiDAR and distributed optical sensing applications, such as structural health monitoring or fiber fault detection.
The module's temperature-stabilized operation ensures repeatable measurements even under varying environmental conditions.

8.4 Fluorescence Lifetime and Biomedical Imaging

The SPAD Module is fully compatible with time-correlated single-photon counting (TCSPC) systems used in fluorescence lifetime imaging (FLIM) and Förster resonance energy transfer (FRET).

Its adjustable deadtime and threshold parameters allows optimizing count stability and minimize afterpulsing, providing reliable lifetime analysis across a broad spectral range.

Applications include biomedical diagnostics, singlet oxygen detection, and integrated circuit (IC) inspection, benefiting from the module's compact form factor and software-configurable operation.

9 Further Information and Resources

https://www.hhi.fraunhofer.de/en/pn-hardware/single-photon-detection-module.html

https://www.hhi.fraunhofer.de/en/qkd.html

https://www.hhi.fraunhofer.de/fileadmin/PDF/PN/FSO/2025_Single_Photon_Detector_web.pdf

https://www.hhi.fraunhofer.de/en/time-tagger.html