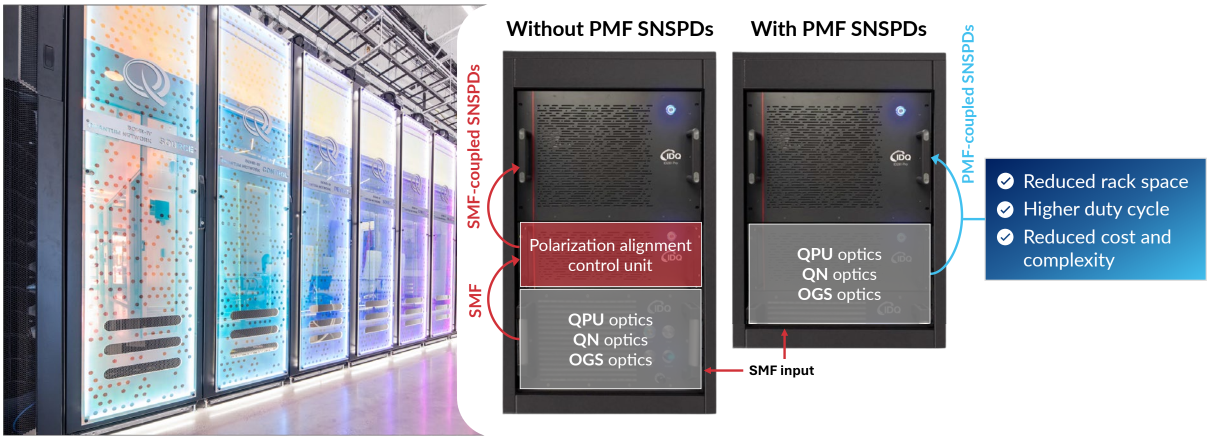
APPLICATION NOTE

Simplifying polarization control for SNSPDs operating in Quantum Data Centers using PMF coupling

Applications:	Quantum Networking, Quantum Computing, Optical Ground Stations, Polarization Sensitive Experiments
Products:	ID281, ID281 Pro



SUMMARY

Detecting a single photon and converting it into a machine-readable signal is possible with technologies like photomultiplier tubes (PMTs) and single-photon avalanche diodes (SPADs). When it comes to ***Frontier Quantum Science****, Superconducting Nanowire Single-Photon Detectors (****SNSPDs****) offer unmatched efficiency (> 90%), ultra-low jitter (< 20 ps), minimal dark counts (< 1 cps) and high detection rates (> Gcps). However, their top-tier efficiency is generally dependent on the polarization of the incoming light.*

In applications such as ***Quantum Networking*** *and* ***Photonic Quantum Computing****, maintaining the polarization state from transmission to detection is essential and can become a limiting factor if left unmanaged. Indeed, environmental influences such as temperature shifts or fiber bending can cause polarization drift, compromising system reliability over time. This can, for instance, happen over short fiber distances (few meters) that one finds in rack-mounted systems which are used to house Quantum Processing Units (QPU) and Quantum Networking (QN) or Optical Ground Stations (OGS).*

*To address this challenge, ID Quantique has developed polarization-maintaining fiber-coupled SNSPDs (****PMF SNSPDs****), a solution that merges high-performance detection with robust polarization control. This simplifies system integration, especially where long-term stability paired with hands-off operation is a requirement.* ***With PMF SNSPDs, there is no need to worry about polarization perturbation in the last fiber stretch.***

Introduction

The present-day golden standard for single-photon detection (SPD) is the Superconducting Nanowire Single-Photon Detectors (SNSPD). These devices are made of a single meandering line of superconducting material which is held close to its superconducting threshold, as can be seen in **Figure 1**. The absorption of a single photon will create a localized but measurable resistance spike in the nanowire. Today, ID Quantique (IDQ) sells SNSPDs that reach high efficiency (> 90%), ultra-low jitter (< 20 ps), minimal dark counts (< 1 cps) and high detection rates (> Gcps). This allows the use of SNSPDs for a much wider range of photonic experiments and industrial applications than their Single-Photon Avalanche Diode (SPAD) or Photomultiplier tubes (PMT) counterparts. The exceptional detection efficiencies of SNSPDs typically come with one drawback: the meandering pattern direction of the detector offers a preferential photon absorption direction, thus limiting the maximum achievable detection efficiency to a specific polarization.

Motivation: Why does polarization matter?

SNSPD performance depends on polarization

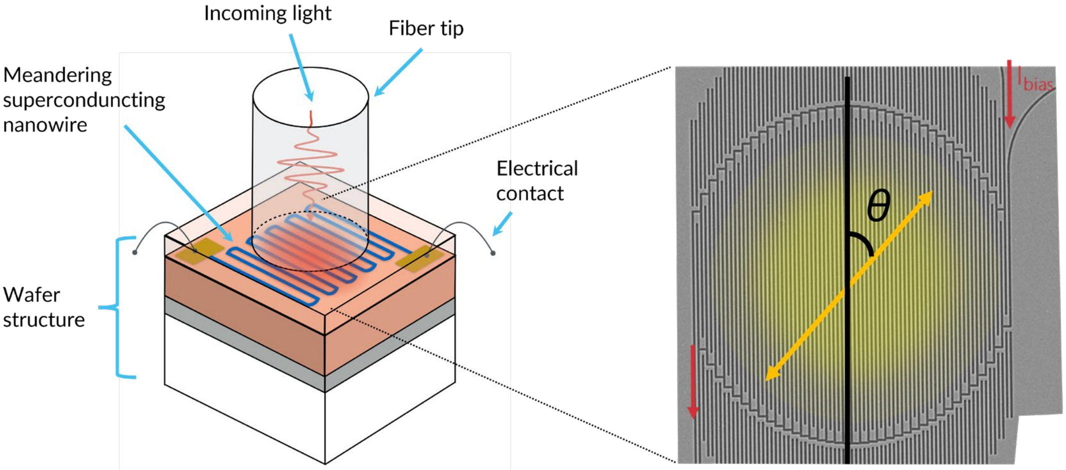


Figure 1

Sketch of a typical SNSPD detector and its architecture and showing the fiber tip just above the detector active area, which guides the incoming light. Adapted from [1].

The inset is a SEM image of a typical SNSPD detector. A current biased superconducting nanowire (I_{bias}) is meandering with a preferential direction (marked as a black *vertical line), which is the basis of their polarization dependent efficiency. Maximal absorption of the photons (hence best detector efficiency) is obtained when the photon polarization is parallel to the meandering pattern, i.e. $\theta = 0^{\circ}$.*

When the input light linear polarization is tilted by an angle $\theta \neq 0^{\circ}$, as depicted in the inset of **Figure 1**, the efficiency of the SNSPD decreases. Indeed, the meandering pattern of the nanowire offers a preferential detection direction and only when the light polarization is **parallel** to this preferred direction can one expect the **full detection efficiency** [2]. This dependency is not just a mere possibility since the input polarization can change for various reasons, for example: bending, twisting and/or temperature fluctuations of the input fiber link. These perturbations are usually the cause of polarization changes while the light is propagating through said fiber, ultimately hurting detection capabilities. The traditional way to deal with this dependency is to correct these polarization perturbations by adding a polarization controller just before injecting the light into the detector. This is often sufficient in a laboratory environment. Another solution is to employ IDQ's polarization-insensitive SNSPD, with spiral meandering architectures, which typically leads to slightly lower efficiencies.

Examples of polarization sensitive application

Examples of polarization sensitive application are for instance polarization-state quantum memory [3] and quantum communication in a metropolitan area [4] (where one needs to ensure the right polarization measurement basis), or Polarization Sensitive Optical Coherence Tomography (PS OCT) [5].

But other applications, as depicted in in **Figure 2**, would be susceptible to polarization sensitivity:

- **Optical Ground Station (OGS)** for **space-to-ground Quantum key distribution (QKD)**, as depicted,
- **A quantum-enabled Data Center room hosting quantum networking equipment**
- **Restricted-access quantum computing facility**.

Any unwanted polarization drifts in the fiber optics network of these remote and inaccessible environments could degrade the whole detection schema.

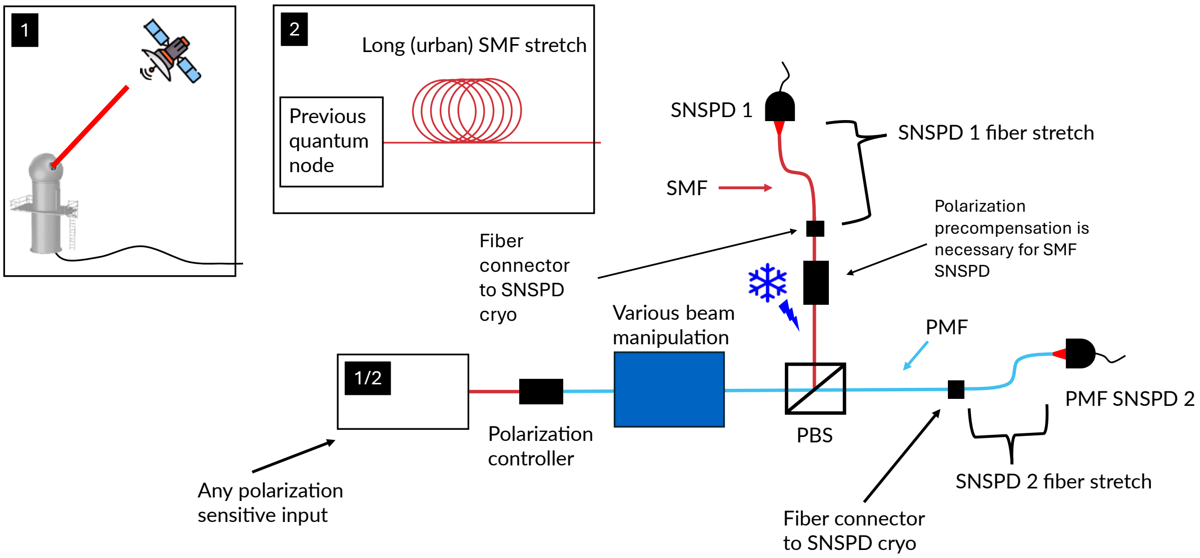


Figure 2

*Typical Space QKD scheme or a node in a Quantum Network. The harsh environment of applications like (1) Space-to-ground QKD or (2) a node in a quantum network requires the last fiber stretch to also be made from PMF to avoid polarization drift just before the detector like in the **horizontal arm**. Indeed, polarization drifts due to the thermally unstable environment are normal, requiring a polarization controller at the entrance and the subsequent use of PMF. This allows, for instance, the right measurement basis for QKD applications, ensuring low Quantum Bit Error Rate (QBER). For Quantum Networking applications, the use of PMF-SNSPD avoids adding unnecessary complexity to the system as if one employed a standard SNSPD, a supplementary polarization controlling step in the last fiber stretch would be required, like the **vertical arm** after the last PBS. Using a **PMF-coupled SNSPD simplifies the system**. The use of PMF SNSPD, like in the **horizontal arm**, is therefore **highly beneficial** in these applications.*

Solution

Polarization-maintaining fibers (PMF)

Polarization maintaining fibers (PMF) are a special type of optical fiber designed to preserve the two specific polarization states of light, orthogonal to each other, as it travels through the fiber. Unlike standard single-mode fibers (SMF), which allow all input polarization to drift along propagation due to environmental factors like stress or temperature changes, PMF relies on high birefringence to preserve the two specific polarization state of light.

Birefringence is introduced by structural asymmetries, typically through stress-applying parts embedded alongside the fiber core (stress rods), as sketched in **Figure 3**. This causes two orthogonal polarization modes (commonly referred to as the **fast axis** and **slow axis**) to propagate at different phase velocities.

As generally the polarization state at the PMF exit might generally still be slightly elliptical, the key parameter characterizing PMF is the **extinction ratio** V, defined as [6]:

$$V = \frac{P_\mathrm{p}}{P_\mathrm{s}} = \cot^2(\eta),$$

Where P_p is the fraction of linearly polarized light being transmitted when analyzing the output light through a linear polarizer, P_s is the fraction of the blocked light in the same analysis and η is the ellipticity of the output light. Hence, when light is launched aligned with one of the principal axes, it remains in that polarization state throughout propagation, with a quality given by the extinction ratio V. However, if the input polarization is misaligned, the light can couple into both axes, leading to polarization drift. Therefore, precise alignment of the polarization at the input is crucial for optimal guiding performance along the PMF.

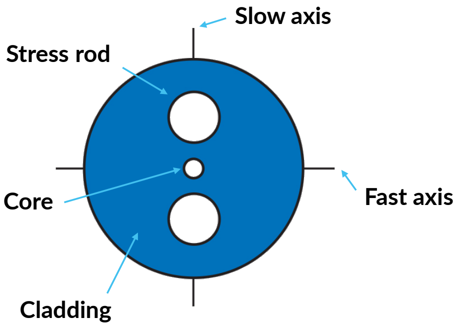


Figure 3
Cross-sectional sketch of a PANDA-type PMF, showing stress rods, cladding and core alignment for achieving the right birefringence. Adapted from [7].

Maintaining polarization throughout detection with PMF SNSPD

To cater for sensitive polarization sensitive experiments, ID Quantique proposes for its SNSPDs (housed in the **ID281** and **ID281 Pro** systems) the possibility to have **polarization-maintaining fiber-coupled SNSPD (PMF SNSPD)**. This can ensure that the polarization state is maintained from the output of the optical circuit all the way to detector chip itself.

With this scheme it is now possible to achieve peak efficiency with no need for supplementary polarization control for the detectors and fill an entire system with PMF SNSPDs. This allows stability, it simplifies the overall system and its field-bound operation all at once. There is no need to worry about polarization drifts in the last fiber stretch. Furthermore, this is achieved while maintaining IDQ's SNSPD's **low dark count rate** and with the same trusted performance on **jitter**, **efficiency** and **recovery time**. This allows users to unlock operational simplicity with no performance compromises in various polarization sensitive experiments like space-to-ground QKD, entanglement distribution in quantum networks, and photonic quantum computing.

Typical use case: The EPB Quantum Network

The EPB Quantum Network **[8]** is a commercially managed quantum network in the United States. It is based in Chattanooga, Tennessee, and is designed to support the development, testing, and commercialization of quantum technologies in real-world conditions. It provides access for industry, academia, and national laboratories developing next-generation quantum technologies. This software-defined quantum network includes ten user nodes linked through two quantum data centers allowing users to design and configure network operations for their specific applications, such as quantum communication, computing, or even sensing applications.

Quantum networks like the EPB Quantum Network exemplify the **benefits** of using a PMF SNSPD solution. Indeed, the long urban SMF fiber stretch link between quantum data centers sees polarization drifts. This requires polarization control at the entrance of the optics, and a polarization control before the SNSPD. On the contrary, a PMF SNSPD solution can directly output the light from the optics to the SNSPD without required polarization control, as depicted in **Figure 4**. Hence, the PMF SNSPD solution can **reduce the necessary rack space**, **increase duty cycle**, and overall, **reduce costs and operational complexity**.

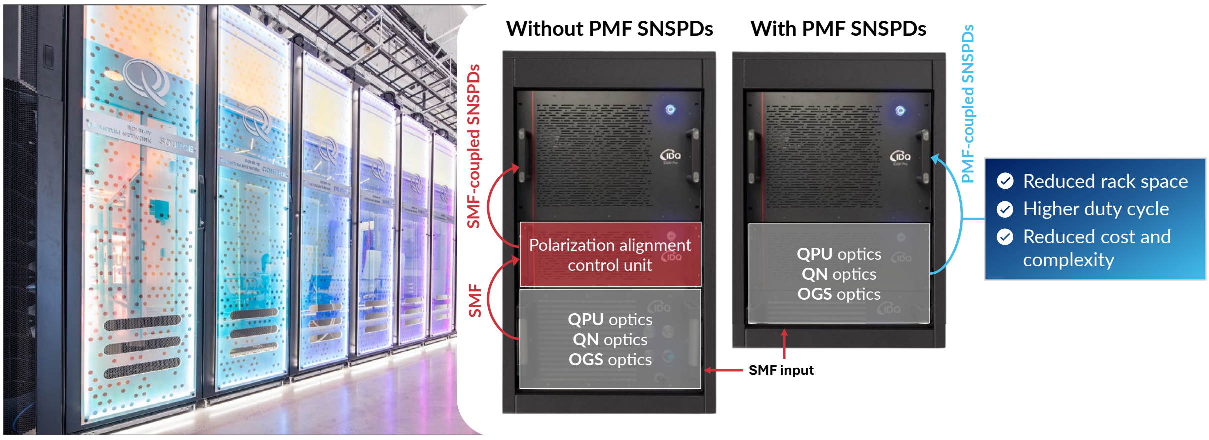


Figure 4

(Left) Image of an EPB quantum node. Photo courtesy of EPB Quantum Network, used with permission.

(Right) Typically, a polarization sensitive application, such as a Quantum Processing Unit (QPU), a Quantum Networking (QN) node or an Optical Ground Station (OGS), requires a Polarization Alignment Control unit before feeding the photons to the SPD. The use of ***PMF SNSPDs*** *allows* ***reduced complexity*** *and rack space, which allows* ***reduced costs*** *and* ***higher duty cycles****.*

Conclusion

The introduction of **PMF SNSPDs** marks a significant advancement in single-photon detection technology. With this solution, users **no longer need to worry** about **polarization alignment in the last fiber stretch** before the detector input, enabling peak system efficiency right out of the box and over any period. This innovation allows for the integration of many of such detectors in a single cryostat, **streamlining system architecture** and **simplifying deployment** in both laboratory and field environments. The detectors continue to deliver the trusted performance that ID Quantique is known for, including extremely low dark count rates, high detection efficiency, minimal timing jitter, and rapid recovery times.

By using PM fiber the efficiency is stabilized and this is particularly valuable when space is limited or environmental conditions are variable. This makes SNSPD more compatible with demanding applications such as space-to-ground quantum key distribution, entanglement-based quantum networks, and photonic quantum computing platforms. The successful implementation of this approach confirms its readiness for real-world deployment and highlights its potential to redefine operational simplicity using SNSPD technology.

References

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