Hyperspectral photon-counting optical time domain reflectometry

Anouar Rahmouni*[a], Samprity Saha[b], Oliver Slattery[a], Thomas Gerrits[a]

[a]National Institute of Standards and Technology, 100 Bureau Dr, Gaithersburg, MD 20899, USA

[b]Virginia Commonwealth University, 912 West Grace St, Richmond, VA, USA

1. ABSTRACT

Optical time-domain reflectometry (OTDR) is one of the most used techniques for characterization of optical-fiber link loss. Although conventional OTDR exhibits good performance in classical network applications, photon-counting OTDR (ν-OTDR) offers a promising way for in-situ optical channel characterization of quantum-network fibers where single-photon detectors are present. ν-OTDR has been demonstrated at the telecommunication wavelengths of 1310 and 1550 nm. Here, we present our hyperspectral ν-OTDR measurement covering a wavelength range from 1150 nm to 1800 nm. The results show a low attenuation in SMF-28 fiber between 1150 nm and 1700 nm of less than 0.5 dB/km. However, we show that connector loss can worsen significantly for wavelengths greater than 1550 nm.

1. INTRODUCTION

A future quantum network will distribute entanglement using telecom-band photons due to their low-loss transmission in optical fibers and the high performance of standard telecom components to enable relatively long-distance quantum links between nodes [1,2]. To date, the lowest loss of standard commercial single-mode fiber - the most widely used in long-distance communications - is 0.18 dB/km at near 1550 nm. A recent record-low attenuation of 0.146 dB/km was achieved in a silica-core fiber with an ultra-large effective area [3]. Further, additional loss is typically due to imperfect connectors as well as splicing or manufacturing defects in the fiber. For fiber connectors, the standard polishing methods of ferrule end faces are physical contact (PC), ultra-physical contact (UPC) and angled physical contact (APC) which typically have insertion losses of less than 0.5 dB for 1550 nm and 1310 nm [4,5].

A stationary qubit in a future quantum network can be based on a variety of technology platforms, ranging from ion or atom-based systems to engineered defects in solid-state devices, any of which may emit photons or have photons converted to a network operating wavelength of around 1550 nm in telecom band. Thus, the fibers and fiber connectors will require efficient characterization of losses over the telecom band to validate the link's performance, preferably as a function of wavelength.

Conventional optical time-domain reflectometry OTDR is one of the most common and widely used techniques for nondestructive characterization of optical fiber links [6]. Photon-counting optical OTDR (ν-OTDR) using single-photon detectors has been demonstrated at the telecommunication wavelengths of 1310 and 1550 nm [7,8]. The basic components to establish such ν-OTDR measurements will already be present in a quantum-network setting, and particularly the single-photon detectors. The ν-OTDR offers a promising way for in-situ optical channel characterization of quantum-network fibers that is compatible with quantum networking systems and components.

Here we employ a pulsed supercontinuum tunable laser and a superconducting nanowire single-photon detector (SNSPD) to characterize the loss of two spools of telecom fiber with one fiber connector between them over the wavelength range of 1150 to 1700 nm. The results show the attenuation of SMF-28 fiber between 1150 nm and 1700 nm to be less than 0.5 dB/km. However, the connector loss can worsen significantly for wavelengths greater than 1550 nm and this may impact the quantum network implementation of quantum devices that operate at these wavelengths, such as the sources used for the generation of Ion-Photon Entanglement in 171Yb+ ion [9].

* anouar.rahmouni@nist.gov; https://www.nist.gov

2. EXPERIMENTAL SETUP

The ν-OTDR technique operates by sending a series of optical pulses into the fiber-under-test and by measuring the time-of-flight of the single-photon signals. The time-of-flight is the total round trip time between the fiber launch point and the point where Rayleigh or other backscattering occurs. This measurement allows the spatial reconstruction of the losses along the fiber-under-test. By analyzing the measured signal characteristics, losses due to the reflection, cracks, bad connections, or fiber bending can be detected and characterized.

In this work, we used our quantum network testbed tools to build a basic ν-OTDR setup [10,11]. We then performed a spectral ν-OTDR measurement of two standard telecom fibers of lengths 25.2 km and 12.6 km, respectively, that are connected using a UPC connector, as shown in figure 1. A supercontinuum laser is used to emit pulses with a repetition rate of 1 kHz, allowing measurement ranges of up to 100 km. A tunable band-pass filter is used to select the wavelength covering the range from 1150 nm to 1800 nm. We used a variable attenuator to adjust the input laser pulse energy such that the backscattered photon rate was below the saturation level of the detector. The weak laser pulses are then launched into the fiber-under-test via a circulator. The backscattered light from the fiber exits port 3 of the circulator and is detected by the SNSPD. The arrival time of the SNSPD's electrical output signal is detected by time tagging electronics. The trigger signal from the laser is used as a reference.

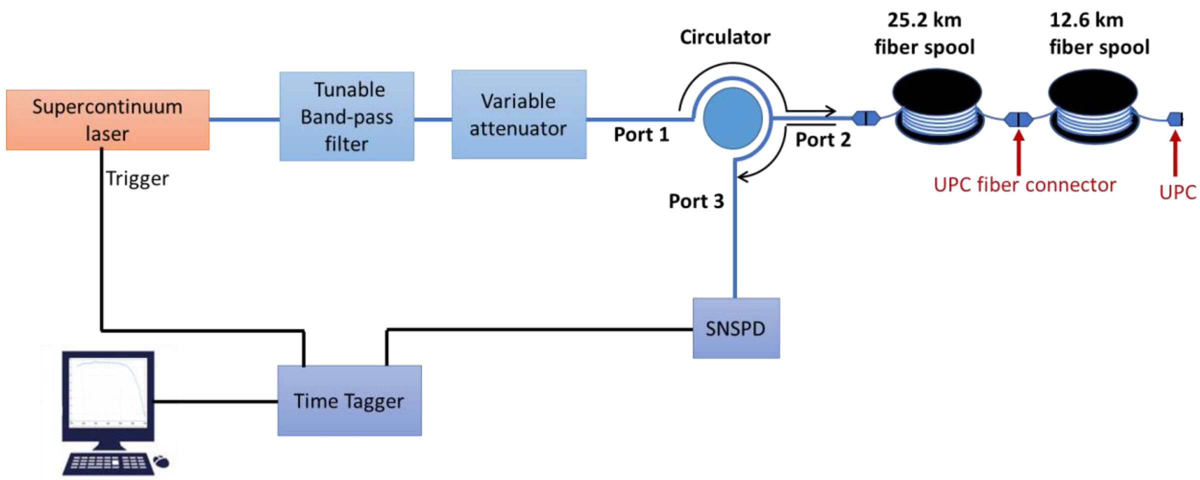

Figure 1: ν-OTDR optical setup: A supercontinuum laser is used to emit pulses with a repetition rate of 1 kHz. A tunable band pass filter is used to select the wavelength. A variable attenuator is used to ensure that we do not saturate the detector with the backscatter from the beginning of the fiber. A fiber optical circulator is used to divert backscattered light to port3, which is connected to the SNSPD. The trigger signal from the laser is used as a reference.

The SNSPD used here has a detection efficiency (DE) of around 95 % at 1550 nm and a maximum count rate of around 500k counts per second, with a dark count rate of less than 500 counts per second.

3. EXPERIMENTAL RESULTS

Because the SNSPD has a recovery time, which is the sum of the dead time when no photons can be detected and the reset time when the detector is returning to its steady-state value [12], the ν-OTDR trace will have to be corrected to show the true loss values. The ν-OTDR trace is corrected by estimating the count rate in the fraction of time when the detector is unable to detect photons, which can be expressed by $R_{meas}\tau_{hold}$, where R_{meas} is the measured count rate and τ_{hold} is the user-selected hold-off time set by our time tagging electronics. Thus, the fraction of time when the detector is active can be expressed by $1 - R_{meas}\tau_{hold}$. Therefore, the photon rate measured by the SNSPD is related to the inferred photon arrival rate, R_{inf}, at the detector and the detection efficiency, η, by [13]:

$$R_{meas} = R_{inf}\eta(1 - R_{meas}\tau_{hold}) \quad (1)$$

The round-trip loss in the fiber is given by $10\,log\left(\frac{R_{inf(L)}}{R_{inf}(0)}\right)$, where R_{inf}(L) are the inferred count rates of the backscattered photons as a function of the length of optical fiber to the backscattering feature which corresponds to the time-of-flight. $R_{inf}(0)$ is the count at the launch point of the fiber. Thus, the single-pass loss through the fiber, as it is common in OTDR experiments, is expressed by:

$$loss(L) = 5\,log\left(\frac{R_{inf(L)}}{R_{inf}(0)}\right) \tag{2}$$

Figure 2 shows an example of a ν-OTDR trace of raw data and corrected data applying equation (2) measured on a sample consisting of two connected fibers spools of length 25.2 km and 2.5 km, respectively

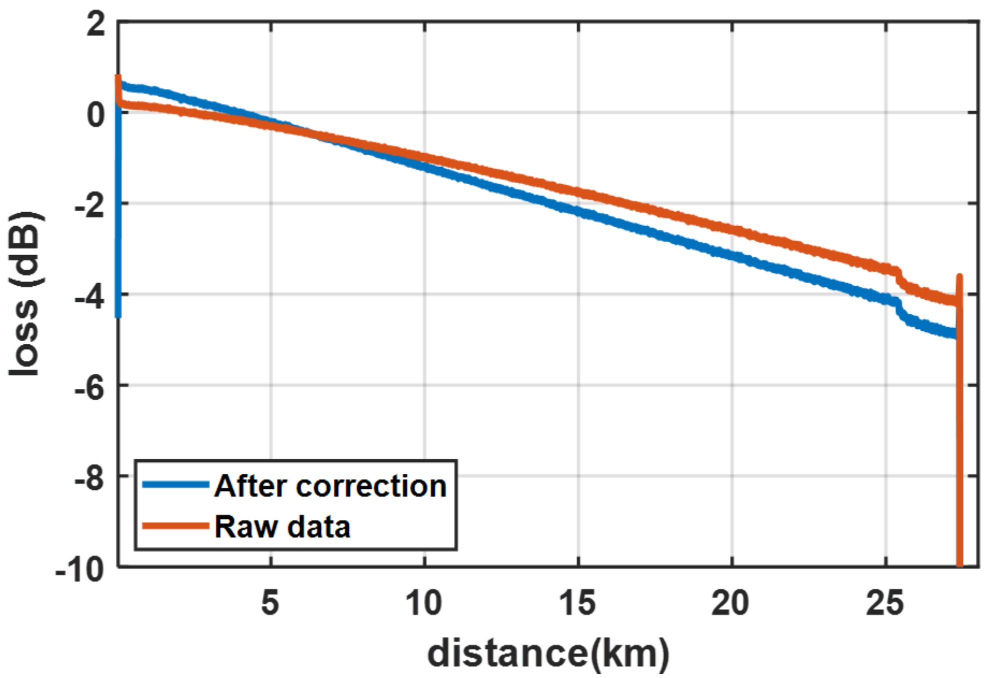

Figure 2: ν-OTDR traces calculated from Eq (2) using raw data and corrected data.

Figure 3 shows the ν-OTDR traces for two standard telecom fibers of lengths 25.2 km and 12.6 km, respectively, that are connected using a UPC connector. The scan covers the wavelength range from 1150 nm to 1800 nm. The dynamic range (dynR) of the ν-OTDR system from the initial point of the trace to the noise floor is approximately 20 dB. The dynR was limited by the maximum count rate of the SNSPD used here. However, using a SNPSD with a high maximum count rate and low dark count rate may increase the dynR to be higher than 60 dB. The time-bin width used for this measurement was set to 20 ns, resulting in a spatial resolution of $\Delta L = \Delta t\, *\, v_g = 4$ m. From figure 3, we can clearly see the loss associated with the connector at 25.2 km. It should be noted that we observed a loss at approximately 35 km indicating a manufacturing defect in the fiber at that location. Importantly, the spectral ν-OTDR traces show that the losses at the connector and the defect are more dependent on the wavelengths than the loss in the fiber generally. For instance, the fiber loss for both 1450 nm and 1650 nm are similar, but the connector loss varies by more than 3 dB between both wavelengths.

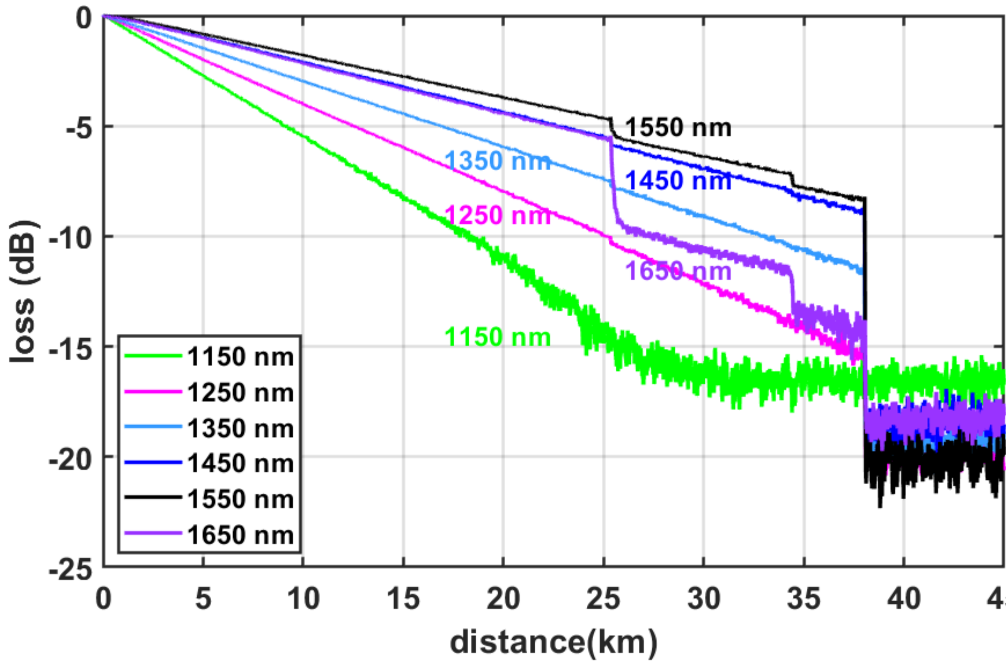

Figure 3: Spectral ν-OTDR traces for two standard telecom fibers (of lengths 25.2 km and 12.6 km) connected by UPC-connectors at 25.2 km and a fiber defect located at ~35 km. The scan covers the wavelength range from 1150 nm to 1700 nm.

The measured connector and fiber losses for different wavelengths ranging from 1150 nm to 1700 nm are plotted in figure 4. The data show a nearly flat fiber transmission curve for the SMF-28 fiber between 1150 m and 1700 nm of less than 0.5 dB/km. However, the connector loss increases significantly for wavelengths greater than 1550 nm. For example, at 1650 nm, the connector loss is greater by 3.5 dB.

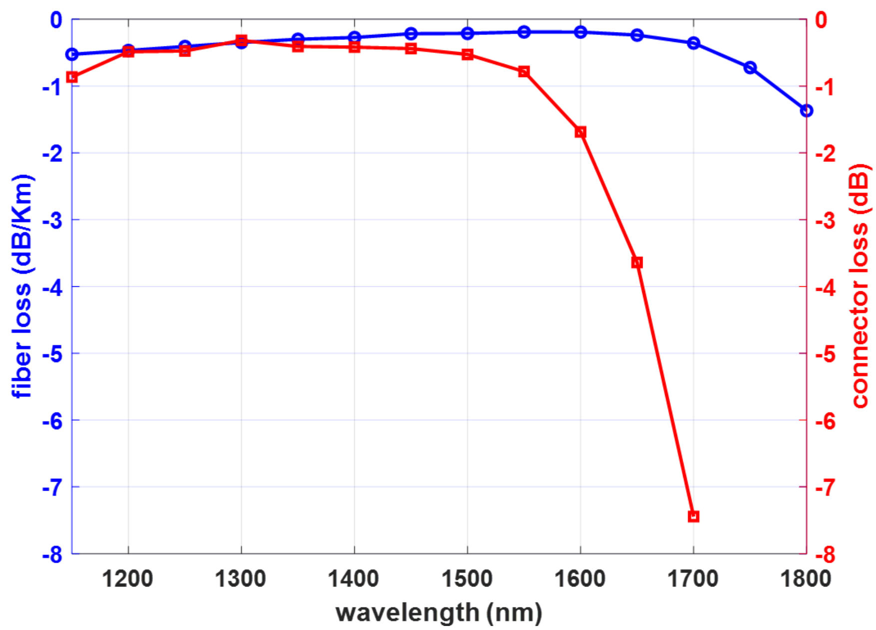

Figure 4: Connector loss and fiber loss per kilometer as a function of wavelength.

4. CONCLUSION

We have implemented a hyperspectral photon-counting OTDR measurement of two standard telecom fibers of lengths 25.2 km and 12.6 km, respectively connected with a single UPC connector, using an SNSPD and a pulsed supercontinuum tunable laser. The spectral ν-OTDR traces for a wavelength range between 1150 nm to 1700 nm show a low attenuation in SMF-28 fiber of less than 0.5 dB/km . Importantly, the UPC connector presented a high loss for wavelengths greater than 1550 nm, which may affect how quantum network devices operate at these wavelengths. We speculate that for longer wavelengths the mode extends further into the fiber cladding and therefore would have a greater sensitivity to the optical fiber connector alignment. The ν-OTDR offers a promising way for in-situ optical channel characterization of quantum-network fibers that is compatible with quantum networking systems and components. In the future, we will evaluate multiple other fiber connector types and combinations and we will use simulation tools to verify our assumptions.

5. DISCLAIMER

Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

6. REFERENCE

[1]: Slattery, Oliver, et al. "The Quantum Communications and Networking Project at the Information Technology Laboratory of NIST." 2021 IEEE Conference on Communications and Network Security (CNS). IEEE, 2021.

[2]:]: Tittel, Wolfgang, and Gregor Weihs. "Photonic entanglement for fundamental tests and quantum communication." arXiv preprint quant-ph/0107156 (2001).

[3]: Makovejs, S., Roberts, C. C., Palacios, F., Matthews, H. B., Lewis, D. A., Smith, D. T., ... & Ten, S. Y. (2015, March). Record-low (0.1460 dB/km) attenuation ultra-large Aeff optical fiber for submarine applications. In Optical Fiber Communication Conference (pp. Th5A-2). Optical Society of America.

[4]: Guide, Product Ordering, and Machine Vision Guide. "OPTICAL SPECIFICATION."

[5]: O'Byrne, V., Kokkinos, D., Meis, D., Piehler, D., Coppinger, F., & Pender, L. (2005, March). UPC vs. APC connector performance in passive optical networks. In National Fiber Optic Engineers Conference (p. NTuF3). Optical Society of America.

[6]: Tateda, M., & Horiguchi, T. (1989). Advances in optical time domain reflectometry. Journal of lightwave technology, 7(8), 1217-1224.

[7]: Ribordy, Grégoire, et al. "Photon counting at telecom wavelengths with commercial InGaAs/InP avalanche photodiodes: current performance." Journal of modern optics 51.9-10 (2004): 1381-1398.

[8]: Zhao, Q., Xia, L., Wan, C., Hu, J., Jia, T., Gu, M., ... & Wu, P. (2015). Long-haul and high-resolution optical time domain reflectometry using superconducting nanowire single-photon detectors. Scientific reports, 5(1), 1-8.

[9]: Wang, W., Goham, C., Laugharn, A., & Britton, J. W. (2020, September). On the Direct Generation of Ion-Photon Entanglement at Telecom Wavelengths in 171Yb+. In Quantum 2.0 (pp. QW6A-12). Optica Publishing Group.

[10]: Rahmouni, A., Gerrits, T., & Slattery, O. (2022, June). Progress towards a portable polarization-entangled photon source & receiver toolset for quantum network metrology. In Quantum 2.0 (pp. QTh3C-3). Optica Publishing Group.

[11]: Rahmouni, A., Gerrits, T., Migdall, A., Slattery, O., Shaw, P. S., & Rice, J. P. (2022, May). A self-validated detector for characterization of quantum network components. In CLEO: Applications and Technology (pp. AW5P-6). Optica Publishing Group.

[12]: Chunnilall, C. J., Degiovanni, I. P., Kück, S., Müller, I., & Sinclair, A. G. (2014). Metrology of single-photon sources and detectors: a review. Optical Engineering, 53(8), 081910.

[13]: Rosenberg, D., Kerman, A. J., Molnar, R. J., & Dauler, E. A. (2013). High-speed and high-efficiency superconducting nanowire single photon detector array. Optics express, 21(2), 1440-1447.