Implementing QKD over Multi-Fiber Ribbon Cables: How Dark is the "Dark Fiber"?

Florian Honz[(1)], Vana Pezelj[(1)], Theodor Strobl[(1)], Florian Kutschera[(1)], Valeria Saggio[(1)], Philip Walther[(2)], Hannes Hübel[(1)], and Bernhard Schrenk[(1)]

[(1)]AIT Austrian Institute of Technology, Center for Digital Safety & Security / Security & Communication Technologies, 1210 Vienna, Austria.

[(2)]University of Vienna, Faculty of Physics, Vienna Center for Quantum Science and Technology (VCQ), 1090 Vienna, Austria.

Author e-mail address: florian.honz@ait.ac.at

Abstract: We identify inter-lane crosstalk as main cause for QKD degradation in 1×12 bend-loss insensitive fiber ribbon cables. Despite allocating QKD to unused fiber lanes, neighboring classical signals can lead to total saturation of single-photon detectors.

1. Introduction

The bundling of light-carrying fibers into ribbon cables for a parallel high-density transmission of independent optical signals has found widespread applications, with cables reaching a massive count of up to 6912 fibers [1] to adhere to the ever-increasing need for transmission capacity and space constraints in deployed optical networks. Applications for these high-density cables include multi-lane datacenter links, where low-cost grey or uncooled (i.e. wavelength-drifting) optics can be applied [2], trunk segments of in-house signal distribution networks [3], or the arrayed signal coupling to and from photonic integrated circuits [4]. With quantum communication now enriching the heterogeneity of optical communication networks, classical/quantum co-existence becomes an important aspect to lower the operating expenditures. Novel hollow-core designs or multi-core fibers that share the same cladding can address this challenge [5, 6]. However, these fibers are hardly commercialized, making the standard single-mode ribbon fiber (such as captured through the bending-loss insensitive ITU-T G.657 specification) the prime choice for deployments as it provides a cost-effective solution to provide a dark fiber core that is employed exclusively for quantum applications.

As we will prove in this work, the individual fibers of such a ribbon cannot be treated as a well-isolated dark fiber to ensure classical/quantum co-existence through space division multiplexing (SDM). We show that a single classical data channel on neighboring fibers of 12- and 24-lane ribbon cables prevents secure-key generation through crosstalk induced upon fiber bends, highlighting the need for a careful spatial channel allocation when implementing practical SDM schemes that involve a large power difference of ~80 dB between a carrier-grade data signal and a QKD channel.

2. Bend-Induced Crosstalk in Multi-Fiber Ribbon Cables

Figure 1a introduces the layout of a multi-fiber ribbon cable, typically encapsulating up to n = 8-12 individual single-mode cores, each with their own individual 125 µm thick cladding that results in a lane spacing of Δ > 125 µm, for which little coupling can be expected among neighboring lanes. All n fibers are then bundled to a flat ribbon cable using an acrylate resin and covered by a single jacket with a special multi-fiber push-on (MPO) connector. Figure 1b shows such a ribbon cable consisting of n = 12 individual fibers with and without jacket. Even though ribbon fibers are often rated as bend-loss insensitive fibers to enable their flexible deployment, this does not guarantee crosstalk-free operation when introducing fiber bends. With the emergence of highly sensitive superconducting nanowire single-photon detectors (SNSPD), quantum engineers are offered a tool that detects optical signals at the single-photon level by featuring an unprecedented efficiency of ~90% at low dark-count rates of ~10 Hz. Translated into optical power, this means a 10^{15}-fold (150 dB) difference in signal level between classical channel and SNSPD darks level, rendering any QKD channel highly sensitive even to faint coupling among adjacent lanes of a fiber ribbon cable. Depending on the crosstalk arising from various classical signals transmitted through numerous cores of the ribbon cable, the requirement for dark guard fibers (Fig. 1a) between the quantum and the classical channels might arise.

To investigate this potential crosstalk, a C-band laser diode (LD) operated at λ_C = 1550 nm and 0 dBm was fed to one of the cores of a 1-m long ribbon cable (Fig. 1c). This ribbon cable was bent once around cylinders with different diameters to emulate bend radii ρ. At the output of the ribbon cable a NbTiN-based

SNSPD (η = 93%, τ_{dead} = 33 ns, DCR ~15 Hz) was employed to monitor crosstalk. Manual polarization control was employed to guarantee optimum detection efficiency of the SNSPD, thus acquiring the worst-case condition in terms of crosstalk. Figures 2a and 2b present the measured crosstalk at two specific (quantum) channels under test (CUT) due to the coupling of photons from various lanes into which the classical signal has been launched. Results are presented for bend radii ρ reaching from 50 mm down to 9.5 mm, while the CUT was centric to the ribbon (lane 6) and at its outermost lane (12). As can be expected, the coupling of noise photons increases with a reduced distance between the CUT and the lane into which the classical signal is injected. While the crosstalk remains below 400 cts/s for ρ > 20 mm and is mainly noticeable for injection into adjacent lanes, a smaller ρ leads to a significant increase up to 120 kcts/s for ρ = 12.3 mm and detector saturation for ρ = 9.5 mm. This clearly illustrates potential limitations concerning classical/quantum co-existence.

We further tested a jacketed 1-m ribbon fiber, which showed reduced coupling (Fig. 2c,d). Here, the crosstalk remains below 650 cts/s, even for the smallest bend radius. While this would be in principle compatible with QKD, a deployed fiber is likely to feature multiple bends of different radii. Furthermore, while the crosstalk increases linearly with the spacing to the CUT for the ribbon cable without jacket, the distribution of the crosstalk is more irregular for the jacketed ribbon, which is attributed to the different mechanical arrangement of the fiber lanes. This effect can be nicely seen in Fig. 2c for ρ = 9.5 mm, where the highest coupling to lane 6 arises from a classical signal launched into lanes 1, 5 and 7. Similarly, 8 lanes couple nearly equally to the CUT at the outermost lane (Fig. 2d). This complicates the potential allocation of dark guard fibers. An increase in the number of fibers to 24 (Fig. 2e) shows an increase in crosstalk even for ρ = 50 mm. This is attributed to the higher fiber density and mechanical stress on the individual fiber lanes due to the higher fill-factor within the 3-mm cable jacket. Figure 2f summarizes the coupling of noise photons to the CUT as a function of the number of guard fibers, where a value of 0 corresponds to a classical channel next to the CUT at lane 12. The crosstalk reduces exponentially with increasing bend radius ρ and at least one guard fiber should be employed to minimize the coupling of noise photons to the quantum channel.

3. Noise-Robust Classical/Quantum Co-Existence in Ribbon Cables: Is there a Need for Optical Filtering?

High power classical signals transmitted through optical fibers generate far-reaching Raman noise photons [6]. Therefore, two mitigation strategies exist to enable the co-existence in single-mode fibers (SMF): First, the use of remote wavebands, such as the O- / C-bands for the quantum / classical channels, and second, the narrow optical filtering of the quantum channel to reduce the impact of in-band noise photons. In order to investigate the origin of the crosstalk, a wideband classical lane (WB) consisting of 72 channels spanning from the O- to the L-band with an aggregate power of 14 dBm was generated (Fig. 3a) and transmitted through a 461-m long ribbon fiber that is installed throughout our building and roof-top. This link is characterized by 6 MPO inter-connects and an end-to-end loss of 5.3 dB. The crosstalk on the neighboring fiber core was then measured with a single-photon resolving optical spectrum analyzer. Figure 3a shows that noise mainly arises due to the coupling of photons from a few high-power classical channels rather than Raman contributions. This indicates a need for narrow filtering centric to the quantum channel. However, as the exemplary filter transmission spectra for fiber-based thin-film filters with bandwidths of 16 nm (CWDM), 1.6 nm (DWDM-1,-2) and an O/C waveband splitter of Fig. 3b show, most of the telecom-centric filters show unpredictable transmission windows rather than high suppression below 1400 nm.

The influence of inter-lane crosstalk was then investigated for a commercial QKD system (ThinkQuantum QUKY). The utilized system can tolerate up to 24 dB of link loss and employs a polarization-based BB84 protocol. It has an internal 1-nm wide optical filter centered at 1550.12 nm and employs InGaAs single-photon avalanche detectors (SPAD). It was first tested with a fixed attenuation of 15 dB, followed by the 1-m long jacketed ribbon fiber to emulate co-propagation along a server rack. The quantum and a classical channel were placed on neighboring lanes. Without classical signal, a secure-key rate (SKR) of 4 kb/s is obtained for ρ = 9.5 mm (Fig. 4a). Once the LD, emulating a classical channel at the same wavelength of 1550.12 nm, yet on a different lane is activated, no key can be generated for ρ = 9.5 mm as well as 12.3 mm, for classical optical levels of 5.6 dBm and 13.1 dBm, respectively. For ρ = 16 mm the QKD system operates without penalty, clearly highlighting that bend-induced crosstalk can be detrimental. In a next step, a test over the 461-m installed ribbon fiber was conducted, for which a background of 500 cts/s was measured with the SNSPD. As suspected from the crosstalk spectrum and due to the internal filter, the system is not affected by the WB channels (Fig. 4b). It is important to note the absence of a channel at 1550.12 ± 0.8 nm in the WB channel spectrum. This channel was emulated separately by a LD operated at 4.8 dBm and at 16.5 dBm (via a booster EDFA). Depending on the exact optical power, crosstalk significantly reduces the SKR.

Finally, we subjected a time-bin BB84 QKD system [7] that employs SNSPDs to the installed ribbon-fiber link. In order to multiplex the quantum channel at 1550.12 nm and its synchronization channel at 1310 nm, the O/C waveband splitter shown in Fig. 3b was employed. No performance degradation was found for co-propagating the WB channels (Fig. 4c). However, once a LD with a launch power of 13.1 dBm is activated at the wavelength of the quantum channel, while co-propagating at the neighboring fiber lane, the SKR drops to zero due to excessive background photons, even if a 16-nm wide CWDM filter is employed. With a 1.6-nm wide DWDM-filter, key-generation becomes possible at 1.9 kb/s, while narrow 0.8-nm filtering enables a SKR of 23.9 kb/s. This improvement in the SKR between the two narrowest filters is attributed to the removal of the spontaneous emission tails of the LD. Nonetheless, a significant 5.2-fold degradation in SKR remains due to the coupling between neighboring fiber lanes.

4. Conclusion

We investigated the crosstalk between classical and quantum channels propagating on different fiber lanes of a multi-fiber ribbon cable, revealing that a notable crosstalk between the individual lanes can occur when the ribbon transports carrier-grade classical signals – up to a total saturation of single-photon detectors. Furthermore, a significant degradation of the QKD performance was noticed if a classical channel is operated at the same wavelength as the QKD channel. As a result, either dark guard fibers need to be employed, or no classical channels should be operated at the quantum wavelength if the QKD system hosts a narrowband optical filter with far-reaching suppression profile.

5. References

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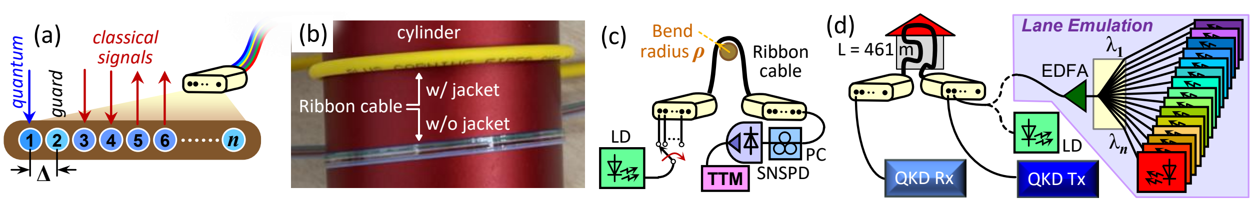

Fig. 1. (a) Fiber ribbon layout and (b) coiled ribbon cables. (c) Setup for investigating crosstalk among lanes and (d) for intra-building QKD.

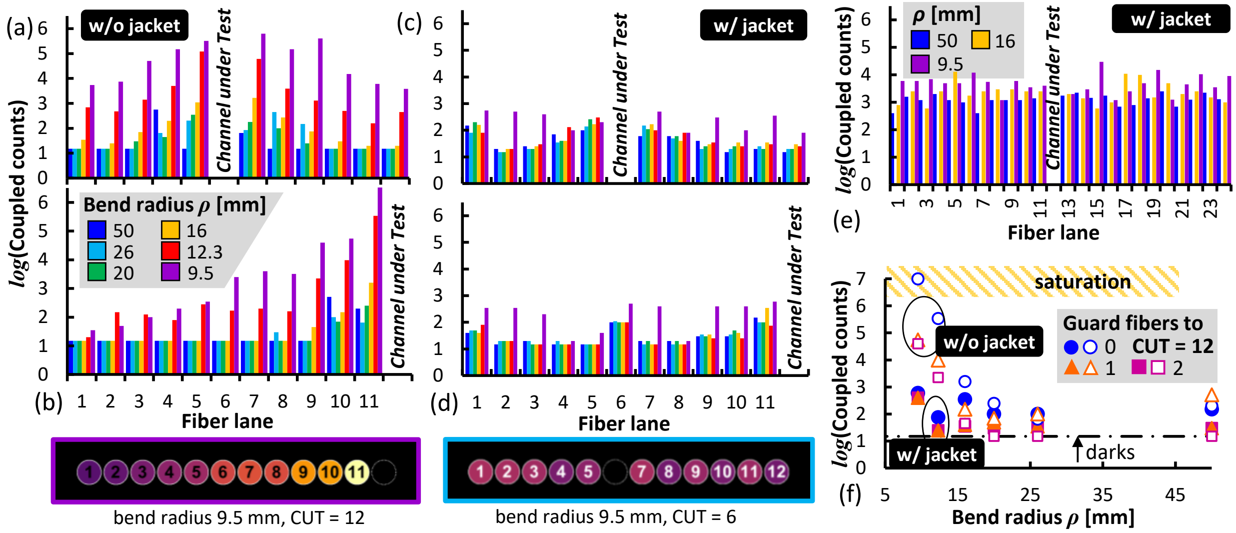

Fig. 2. Classical light coupling for a ribbon fiber without jacket for (a) CUT = 6 and (b) CUT = 12, as well as for a jacketed ribbon for (c) CUT = 6 and (d) CUT = 12. (e) Dependence of the coupling on bend radius ρ and number of guard fibers between the CUT and the classical channel.

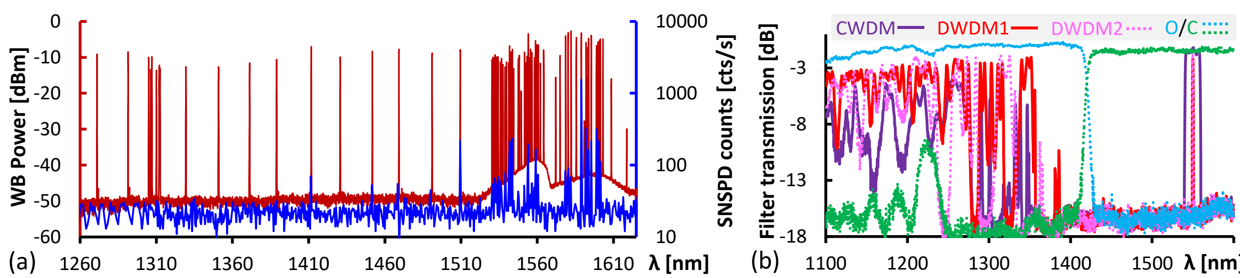

Fig. 3. (a) Classical lanes and spectrally resolved crosstalk to the CUT for a 461-m long ribbon link. (b) Transmission filters for QKD channels.

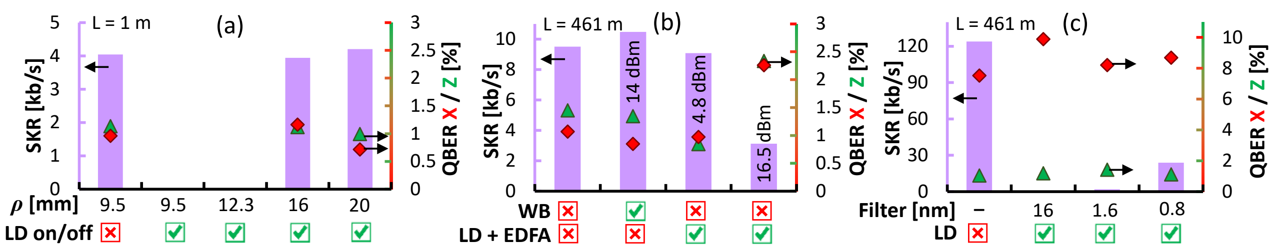

Fig. 4. QKD performance (ThinkQuantum QUKY) over (a) 1-m long ribbon fiber, co-propagated with a LD on the adjacent lane, and (b) 461-m long ribbon fiber link with either WB or an EDFA-boosted LD. (c) QKD performance for an SNSPD-assisted QKD system, using various filters.