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S. Virzì [a], A. Meda *[a], C. Clivati [a], S. Donadello [a], C. Liorni[b], G. Bertaina [a], M. Gramegna [a], I. P. Degiovanni [a], M. Dispenza[b] , M. Genovese [a] and D. Calonico [a]

[a]Istituto Nazionale di Ricerca Metrologica, Strada delle Cacce 91, I-10135 Torino, Italy
[b]Leonardo Labs, Quantum Technologies Lab, Via Tiburtina, km 12,400 – Rome – 00131 – Italy

**ABSTRACT**

Quantum key distribution (QKD) allows the sharing of secret cryptographic keys between two distant users, whose intrinsic security is guaranteed by the laws of nature. Nowadays, the most promising technique for the integration of QKD in already deployed long-haul telecommunication fiber networks is the Twin-field QKD (TF-QKD) protocol, but it requires that the communication channel is stable in terms of phase oscillations and it is free from background light, that reduces the transmission key-rate. Recently, we presented a solution [1] to the phase stabilization problem, derived from atomic clocks comparison technology, demonstrating advantages in performances of real word TF-QKD. Here we quantify and characterize the background photons, analyzing in details their effects on the transmission and the practicalities to reduce their contribution to a negligible level.

**Keywords:** Quantum Key Distribution, single photons, Twin-Field QKD

## 1. INTRODUCTION

Quantum key distribution (QKD) is a quantum communication protocol that ensures the sharing of secret cryptographic keys between two distant users (Alice and Bob) with an intrinsic level of security guaranteed by the laws of nature [2]. QKD is a mature technology and several QKD networks are already under deployment worldwide; the challenge is the integration of different QKD solutions in already deployed telecommunication fiber networks, in particular, in long haul segments that connects distant cities [3]. At present, a feasible solution to cover long distances is the adoption of intermediate nodes. However, such nodes must be “trusted” to guarantee, at least in principle, the same level of security [4].

The Twin-field QKD (TF-QKD) protocol [5] represents an innovative approach that limits the need for trusted nodes, whose security is still an open point. TF-QKD presents a weaker dependence on channel losses, allowing one to double the communication distance with respect to the conventional prepare-and-measure solutions.

In TF-QKD photons are sent by both Alice and Bob to a central node Charlie, that might also be untrusted. Nevertheless, a strong requirement of TF-QKD is that the optical pulses are phase-coherent in Alice and Bob. In addition, their coherence must be preserved throughout both the paths to Charlie. This situation can be easily reproduced in laboratory, but in deployed fibers, in particular in metropolitan networks, uncorrelated phase changes take place due to the length and refractive index variations. Such a coherence degradation reduces the visibility of the interference measurement, then the performance of the protocol.

Recently, we presented a solution [1] to the phase stabilization problem, derived from atomic clocks comparison technology [6], demonstrating advantages in performances of real world TF- QKD. We exploited ultrastable lasers and the active cancellation of the phase noise introduced by connecting fibers to minimize the phase fluctuations of both the lasers and the fiber channels. We implemented a measuring apparatus suitable for TF-QKD and tested it on an in-field network that connects two Italian cities, Bardonecchia and Santhià (Alice and Bob) to INRIM laboratories, in Turin, where we located Charlie. The overall distance between Alice and Bob is 206 km, with a connection with standard optical fibers that induce a net loss as high as 65 dB.

In metropolitan environments, fibers are usually employed for the transmission of different optical signals such as telecom signals, internet data, etc. However, the low light level required by QKD usually imposes that the signals are transmitted through dedicated dark fibers, since the absence of additional signals avoids that the photon where the key is encoded are lost in the noise. As a matter of fact, an increase in the background photon counts on the QKD detectors deteriorates the the key transmission, increasing the quantum bit error rate (QBER) beyond the tolerable limit. Hence, the ultimate limit to the transmission distance is set by the noise of the single-photon detectors employed to measure the signal photons.

In our approach, the stabilization of the fiber is obtained by transmitting an additional “sensing” laser in the whole TF-QKD interferometer, even in the dark fiber. The solution that we adopted to separate the photons of the key from the photons of the stabilization laser is the wavelength-division multiplexing (WDM) architecture. In this paper, we present more in details the technological challenges to achieve the multiplexed solution and to minimize the number of background photons observed by the single-photon detector in the dark fiber, carefully analyzing their sources.

## 2. CHARACTERIZATION OF BACKGROUND PHOTONS

### 2.1 Sources of background photons

The advantage of the adoption of a TF-QKD protocol in terms of both transmission rate and distance has been largely demonstrated [7-13]. Nevertheless, such results were achieved either in laboratory [7-12], in a very controlled environment, or in dedicated metropolitan networks [13], with ultra-low loss optical fibers and a dark channel used for QKD transmission only. For these reasons, it was sufficient a synchronization performed in a channel different from the quantum one.

In a metropolitan environment, there is an increasing demand for multiplexing of QKD signals with classical optical communications, in order to avoid an increase of costs for QKD networks deployment. Moreover, as we demonstrated in our paper, one can reach a high level of phase stabilization only by injecting the sensing laser multiplexed with the quantum signal in the same fiber. Nevertheless, even if it is possible to filter out unwanted photons, a small percentage of unfiltered photons can survive and mix with the QKD signal, increasing the experimental errors of quantum key transmissions and, thus, limiting the advantage of the TF-QKD protocol in terms of distance and rate. Unwanted photons, in real-field experiments, could also came from adjacent fibers where data traffic at the same wavelengths of the QKD signal may travel and enter in the fiber due to evanescent coupling, making useless the adoption of multiplexed architectures. In addition, stray photons could be increased by Rayleigh backscattering, due to connections in the transmission line that may cause a broadband presence of detected background photons. In laboratory, the adoption of a complete dark fiber dedicated to QKD transmission is quite an easy task. This way, spurious counts are mainly due to detector dark counts in absence of QKD signal, whereas in metropolitan network the identification and elimination of unwanted photons requires a systematic analysis of all the possible sources and the evaluation of the possibility to suppress them.

To understand and minimize the sources of background photons in our metropolitan network, we acted on the different optical sources exploited for the stabilization of the testbed length, and we measured background photons with a single-photon detector on the quantum fiber.

### 2.2 The testbed

We tested the presence of background photons on a part of the Italian Quantum Backbone (IQB) depicted in Figure 1: a commercial optical-fiber infrastructure used for the dissemination of both time and frequency signals with the best accuracy. In particular, we used two segments of the IQB. The first one is the Alice – Charlie (AC) segment, an optical fiber used both for internet connection in Valsusa and for frequency distribution between INRIM and other National Metrological Institutes in Europe. The fiber is provided by the TOP-IX consortium, involving two fiber spans that connect the cities of Turin and Bardonecchia for a total length of 114 km and 35 dB of attenuation. The other optical fiber is the Bob – Charlie (BC) segment, a part of IQB of 92 km of length and 30 dB of attenuation connecting Turin with the city of Santhià. Such a fiber is part of the INRIM infrastructure for the time and frequency signals dissemination in Italy.

The backbone will represent the foundation of the Quantum Communication Infrastructure (QCI) deployment in Italy, an initiative for implementing systems and networks on the national territory able to test quantum communication technologies.

We measured background photons exploiting the apparatus suitable for TF-QKD (Figure 2). The highest level of stabilization is obtained if the stabilization laser and the lasers used for QKD transmission share the same optical path. To minimize the background photons due to Rayleigh scattering, we adopt a multiplexed solution,


Figure 1. The Italian Quantum Backbone. The backbone is used to start the deployment of the Quantum Communication Infrastructure (QCI) in Italy.

where QKD lasers and the sensing laser coexist in the same fiber (see Figure 2). Moreover, QKD lasers are locked by means of a “reference” laser that emits at the same wavelength and sets a reference for the phase of the lasers in Alice and Bob. This solution is inspired by the transmission of coherent laser radiation over thousands of kilometers used to compare distant atomic clocks, where ultra-stable lasers and appropriate techniques for phase stabilizing optical fiber are adopted.

The reference laser (and QKD lasers) emits at 1542.14 nm (channel 44 of the 100 GHz-DWDM grid), and it is addressed, together with bidirectional data signals, to Alice and Bob terminals through a service fiber. It is multiplexed with the sensing laser that emits at 1543.33 nm (in the middle between the channels 42 and 43 of the 100 GHz-DWDM grid) and it is offset phase locked to the reference laser using an optical frequency comb. The sensing laser detects the noise of the fibers along the total path to Alice and Bob on the service fiber, and to the central node Charlie on the quantum fiber.

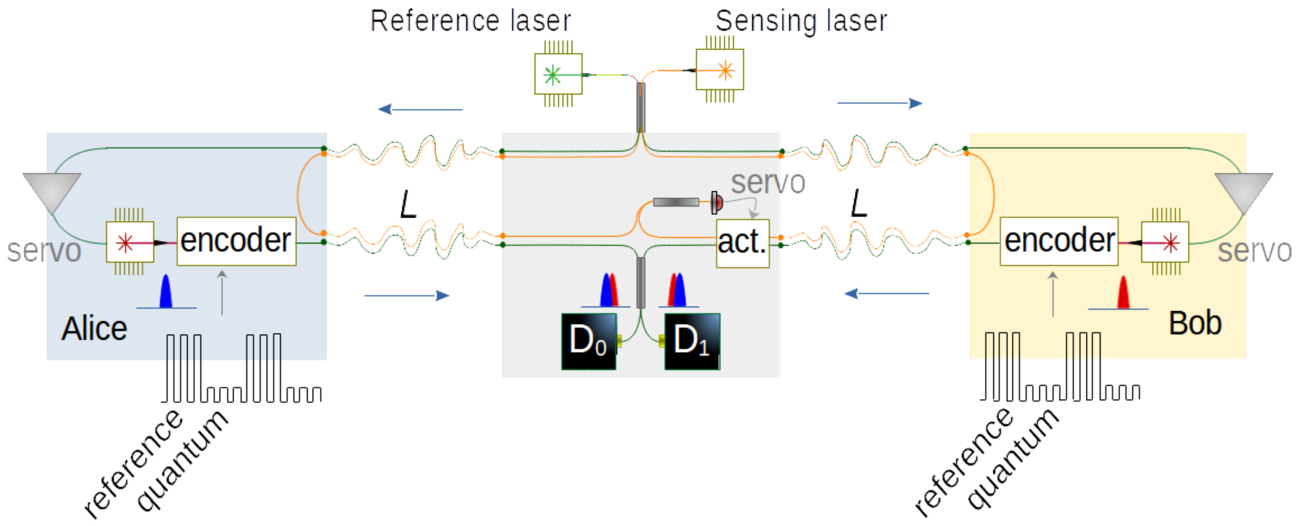


Figure 2. The experimental setup: laser1 (orange) is the sensing laser, for detecting the noise of the fiber in the common path with QKD lasers (RIO 1 and RIO 2); laser 2 (green) is the reference laser that phase lock the QKD lasers in Alice and Bob; it is used for stabilizing the whole interferometer.

## 3. PRACTICALITIES ON BACKGROUND PHOTONS REDUCTION

Here, we carefully analyzed the trade-off between the presence of background photons and performance of the setup in terms of phase stabilization.

The coexistence of the QKD and the sensing signals in the same fiber presents the first issue to be addressed; a fundamental aspect is the proper filtering of the sensing signal on the single-photon detectors. The two signals must be separated using DWDM filters, but it could not be sufficient.

Then, we employed two cascaded 100 GHz-DWDM filters, with a total nominal rejection of 120 dB and we measured the residual optical power. As shown in Figure 3, after filtering the residual power was not so negligible (30nW) for a single-photon working regime. This was due to the not ideal behavior of filters before 1300 nm and to the huge amount of photons present in the quantum fiber below that wavelength. The reason is the noise due to Amplified Spontaneous Emission (ASE) of QKD lasers that extends to a wavelength of 1200 nm. To minimize the impact of ASE photons we added two free-space optical filters, with nominal 50 dB rejection over the visible and near-IR band and 84% of transmissivity at 1550 nm, in front of the single-photon detectors. The filters were coupled with proper coupling optics to realize the fiber-air interface (and vice versa), and they were embedded in a black box to avoid background photons increasing due to environment light, eliminating the ASE photons.

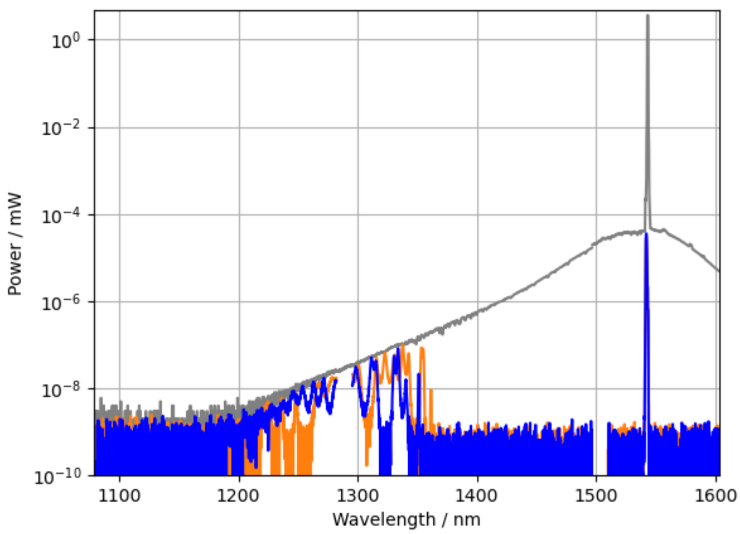


Figure 3. Orange and blue: spectra of the same laser, passed through two different band-pass filter models centered at 1542 nm, showing adjacent channel rejection of the carrier by about 50 dB, and limited performances outside the C-band. Below 1350 nm the filter losses efficiency, and the residual diode laser ASE noise power amounts to about 30 nW

Nevertheless, the presence of the sensing laser in the quantum fiber contributes to background photons, even after its filtering, due to secondary effects. Its Raman scattering, at the same wavelength of the QKD signal, cannot be filtered out. To understand the impact of such an effect, we measured Raman contribution as a function of the sensing laser optical power after different lengths of standard optical fibers. Considering that the length of the fiber segment where the sensing and the QKD lasers coexist is 20km, we estimated that, to maintain Raman contribution below an acceptable level, the power of the laser must be lower than 1 μW when injected in the quantum fiber. In our setup, this condition is naturally achieved by the attenuation of the laser in the service fiber.

Another source of background noise could be the internet data traffic. A straightforward consideration is that it is mandatory that data traffic, if present in the quantum fiber, must migrate on the service fiber. Even in this case, data traffic could enter in the quantum fiber for evanescent coupling.

Another possible source of background photons are optical amplifiers (as EDFAs) present in the service fiber. Since both the sensing and reference lasers are classical signals, their detection requires that they arrive on their detectors with an acceptable signal-to-noise ratio (SNR) for a stable phase lock in Alice and Bob. For this reason, EDFAs should be necessary on the path, but Rayleigh-scattered photons propagating backward into the service fiber may fall into the QKD fiber due to evanescent coupling. Then, the positioning of EDFAs in the optical path requires a careful analysis to find the best trade-off between the presence of background photons and SNR of the classical signals.

Finally, Rayleigh scattering of the reference laser may occur in the service fiber, and photons can fall in the quantum fiber. Their contribution can be minimized by reducing the launched power of the reference laser in the service fiber. In our case, the maximum allowed power was 20 μW.

### 3.1 Single photon detectors

A careful evaluation of background photons requires that the exploited detectors present a very low intrinsic level of dark counts.

The dark counts rate depends on the kind of single-photon detector used and on the operating conditions. The most exploited solutions around 1550 nm are InGaAs/InP Single-Photon Avalanche Diodes (SPADs), since they operate at room temperature, typically with 1000 cps of dark count rate with a quantum efficiency of 20% and 25 μs of dead time. This does not represent the best choice in terms of dark counts and efficiency. On the contrary, Superconductive

Nanowire Single-Photon Detector (SNSPD)s can reach unprecedented performances, with dark count rate below 0.01 cps, high photon detection efficiency above 90%, few ps timing jitter and dead time below 1 ns. Nevertheless, such benefits come at the cost of cryogenic operation, a solution that limits the use of such detectors in real word applications.

To find a good compromise between cost and performances, we exploited a commercial fiber-coupled InGaAs/InP avalanche detector (Id Quantique ID230), but mounted with a Stirling cooler that cools down to −90 °C the sensor for minimizing the intrinsic dark count rate to (4.5 ± 0.03) cps. Its free-running mode operation enables asynchronous photon detection with 150 ps timing resolution, in a spectral bandwidth ranging from 900 nm to 1700 nm. We measured background photons with a detection efficiency of 10%, meaning that the effective number of background photons present in the quantum fiber is ten times higher.

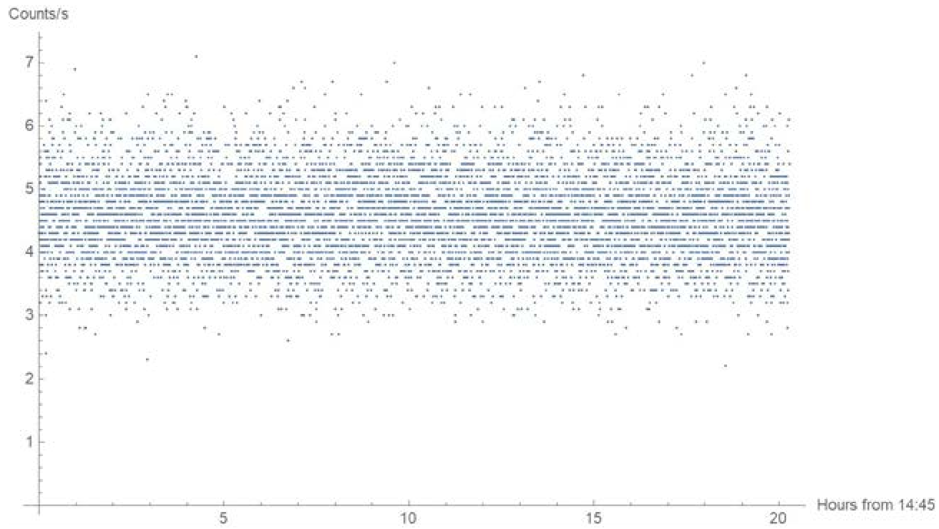


Figure 4. A 24 h acquisition of background photons. Each point represents an acquisition averaged over 10 s. The background is stable, meaning that no fluctuation due to environment light or data traffic is present in the testbed

Figure 4 reports the residual photon rate and its stability in time; it is important to evaluate background photons at different times during the day, since data traffic may change. We measured an average of (5.09 ± 0.01) cps, slightly above the dark count rate of the detector. Background with both the sensing and the reference lasers off, i.e. with background photons only due to environment photons and data traffic photons coupled in the QKD fiber is (4.76± 0.04) cps, showing that the technique adopted to stabilize the phase has a minimal impact on the number of photons present in the dark fiber.

## 4. CONCLUSIONS

We presented details of a recently proposed solution to the phase stabilization problem for real-world TF- QKD. We carefully analyzed the possible sources of background photons present in the quantum fiber and we reported practicalities and methods for their reduction, allowing to eliminate sources of background light and to perform phase stabilization by using a multiplexed solution.

## REFERENCES


[1] C. Clivati, et al.," Coherent phase transfer for real-world twin-field quantum key distribution", Nat. Commun. 13, 157, 2022.

[2] C. H. Bennett and G. Brassard, "Quantum cryptography: Public key distribution and coin tossing" Theor. Comput. Sci. 560, pp. 7-11, 2014

[3] S. K. Liao, et al. "Satellite-to-ground quantum key distribution", Nature 549, pp. 43–47, 2017

[4] M. Peev, et al., "The SECOQC quantum key distribution network in Vienna", New J. Phys 11, 075001, 2009.

[5] M. Lucamarini, Z. L. Yuan, J. F. Dynes and A. J. Shield, “Overcoming the rate–distance limit of quantum key distribution without quantum repeaters”, Nature, 557, pp. 400-403, 2018.
[6] C. Clivati, et al., “Optical frequency transfer over submarine fiber links”, Optica, 5, 893, 2018.
[7] M. Minder, et al. “Experimental quantum key distribution beyond the repeaterless secret key capacity”. Nat. Photon. 13, pp. 334–338 2019.
[8] S. Wang, et al., “Twin-field quantum key distribution over 830-km fibre”, Nat. Photon. 16, pp. 154–161, 2022
[9] Liu, Y. et al. “Experimental twin-field quantum key distribution through sending or not sending”, Phys. Rev. Lett. 123, 100505, 2019.
[10] X.-Q Zhong., J.-Y. Hu, M. Curty, L. Qian and H.-K Lo, “Proof-of-principle experimental demonstration of twin-field type quantum key distribution”, Phys. Rev. Lett. 123, 100506, 2019.
[11] X.-T. Fang, et al. “Implementation of quantum key distribution surpassing the linear rate-transmittance bound”, Nature Photonics, 14, pp. 422–425, 2020.
[12] J.-P. Chen, et al.”Sending-or-not-sending with independent lasers: secure twin-field quantum key distribution over 509 km”, Phys. Rev. Lett. 124, 070501, 2020.
[13] JP. Chen, et al. “Twin-field quantum key distribution over a 511 km optical fibre linking two distant metropolitan areas”, Nature Photonics 15, pp. 570–575, 2021.