Reply to referee reports QT10022N (Shen et al.)

Dear Editor,

first, we would like to thank all reviewers for their careful reading of the manuscript, and the constructive remarks to improve it. In the following, we address the points raised by the reviewers.

Reviewer 1

1. Although I find the introduction gives a good background to the paper, some of the references are outdated. The reference regarding 'recent' demonstrations of QKD is from 2009, I would recommend citing more recent publications such as [1]. The 'inter-continental' demonstration cited (citation [11] in the paper) is not the actual demonstration, this can be found in reference [2].

ANS: We thank the reviewer for pointing out this problem; the references [7],[10],[11] are updated in the revised manuscript to more recent or more suitable papers, as the reviewer suggested.

[7] R. I. Woodward, Y. Lo, M. Pittaluga, M. Minder, T. Paraïso, M. Lucamarini, Z. Yuan, and A. Shields, Npj Quantum Inf. **7**, 58 (2021).

[10] J.-P. Chen, C. Zhang, Y. Liu, C. Jiang, W.-J. Zhang, Z.-Y. Han, S.-Z. Ma, X.-L. Hu, Y.-H. Li, H. Liu, *et al.*, Nat. Photonics **15**, 570 (2021).

[11] S.-K. Liao, W.-Q. Cai, J. Handsteiner, B. Liu, J. Yin, L. Zhang, D. Rauch, M. Fink, J.-G. Ren, *et al.*, Phys. Rev. Lett. **120**, 030501 (2018).

2. At the end of the introduction, the authors state that their key rate is 5,172 s^{-1} , stating this is significantly larger than other implementations. Please include relevant references to other implementations to support this claim.

ANS: We thank the reviewer for pointing out this problem; the relevant references are now included next to the statement.

[23] H. Hübel, M. R. Vanner, T. Lederer, B. Blauensteiner, T. Lorünser, A. Poppe, and A. Zeilinger, Opt. Express **15**, 7853 (2007).

[24] A. Treiber, A. Poppe, M. Hentschel, D. Ferrini, T. Lorünser, E. Querasser, T. Matyus, H. Hübel, and A. Zeilinger, New J. Phys **11**, 045013 (2009).

[25] S. Wengerowsky, S. K. Joshi, F. Steinlechner, J. R. Zichi, S. M. Dobrovolskiy, R. van der Molen, J. W. Los, V. Zwiller, M. A. Versteegh, A. Mura, *et al.*, Proc. Natl. Acad. Sci. U.S.A. **116**, 6684 (2019).

3. In Section III, the authors report a loss in visibility of a few percent between measurements in the H/V and D/A bases. Can the authors comment on what factors are contributing to this reduction in the visibility?

ANS: We think that the reduction in visibility could be attributed to the chromatic dispersion caused by the BBO displacement crystal. The phase ϕ of the entangled state $|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|HH\rangle - e^{i\phi}|VV\rangle)$ could not always stay exactly at 0 due to the dispersion of the downconverted photons in the BBO crystal. We included this argument in the manuscript.

4. I would note that the wavelength of 586 nm is very close to the transition frequencies of the rare-earth ion quantum memory $^{151}Eu^{3+}:Y_2SiO_5$, which has a specific transition around 580 nm. Noting that the authors are able to tune the wavelength of their source using temperature, is it possible to tune the source such that the photon at 1310 nm remains in the zero dispersion window, while the second becomes compatible with such a memory? This could be especially interesting for future implementations of repeater networks. If indeed possible, I would suggest a small mention of this point to add further weight to the suitability of their source for communication purposes, possibly alongside an additional minor plot in the Appendix demonstrating that it is possible to achieve overlap with the memory while still remaining in the zero-dispersion regime.

ANS: We thank the reviewer for the excellent suggestion; we have included the argument in the manuscript.

Reviewer 2

1. Brightness: In the manuscript, it is claimed that the 1 MHz/mW entangled pair generation rate is the highest, and is at least 1 order of magnitude higher than previously reported. However, an entanglement pair rate of 10^5 pairs/GHz/mW was reported in 2009 [OE 17, 1033(2009)], which is equivalent to 12 MHz/mW considering the bandwidth. In more recent studies, "an entangled photon source with 1 GHz generation rate" [PHYSICAL REVIEW LETTERS 120, 140405 (2018)], "photon-pair generation at high rates of 8.5 and 36.3 MHz using only 3.4 and 13.4 μW pump power" [PHYSICAL REVIEW LETTERS 125, 263602 (2020)], "2.79×10^{11} Hz/mW photon-pair rate and 1.53×10^9 Hz/(nm mW) spectral brightness" [PHYSICAL REVIEW APPLIED 15, 064059 (2021)] are reported. These results are obviously brighter than the entanglement source reported in the manuscript.

ANS: Instead of directly comparing the brightness of the source, we claim in the conclusion of our manuscript that our source has a higher entangled pair rate compared with literature *after* distribution through the 50 km long optical fiber. For such a scenario, the papers cited by the reviewer do not necessarily report a better result. In most of the papers listed by the referee an integrated/waveguide/on-chip source is used, which is well known to have a high generation brightness owing to the well confined spatial mode of the pump light. However, at least the reported sources suffer from a high on-chip scattering loss, resulting in a low measured pair rates. Another limitation for these sources is that usually only a pump power of nW to μW can be applied, because multi-photon emission starts to dominate at higher pump power and reduces the two-photon entanglement. Moreover, coupling photons from these sources into single mode fibers is usually associated with a huge loss. Thus, for the [OE 17,1033(2009)], [PHYSICAL REVIEW LETTERS 125, 263602(2020)] and [PHYSICAL REVIEW APPLIED 15, 064059 (2021)] the measured pair rates without any fiber distribution are only 330 pairs/second, on the order of 10^4 pairs/second, and 4792 pairs/second, respectively. Notably the last two papers are using superconducting detectors with a much higher quantum efficiency, and do not involve polarization entangled photon pairs. In contrast, we have observed 10^4 photon pairs/second with a high entanglement quality and relatively simple single photon detectors, and showed robust transport through 50 km standard telecommunication fiber.

In [PHYSICAL REVIEW LETTERS 120, 140405 (2018)], the authors use a bulk crystal to generate degenerate photon pairs source at 810 nm to simulate an entanglement distribution to the moon in free space by using a high loss local attenuator. The high brightness is granted by both the type-0 SPDC process and the large bandwidth of the pair source. Both the wavelength and bandwidth are disadvantageous for fiber transmission. Therefore, all of these mentioned papers are irrelevant to the scope of entanglement distribution or entanglement based QKD in a metropolitan fiber network and we did show a higher measured entanglement photon pair rates even compare with them, which gives a solid stand point for our manuscript.

2. QKD Secure Key Rate: it is claimed that a 5000 Hz secure key rate can be generated at 50 km theoretically. However, this secure key rate is not high. On the contrary, in recent studies, "1-Mbps real-time key generation" [IEEE J. Quantum Electron. 48, 542–550 (2012)], "over 10^5 bps key generation at 90km" [Optica 4, 163–167 (2017)], are reported; "16-kbit sifted key with a quantum bit error rate of 6.9 % was successfully generated after 100 km fiber transmission" with the BBM92 protocol mentioned in the manuscript [Quantum Electronics and Laser Science Conference] is reported with higher secure key rate at even longer distance.

ANS: The first two papers, [IEEE J. Quantum Electron. 48, 542–550 (2012)] and [Optica 4, 163–167 (2017)], both implement a decoy-state BB84 protocol, which has no connection to entanglement distribution. The last paper implements a BBM92 protocol, which is related to this work but the entanglement state is encoded in time bins. There, the authors state that a 16-kbit sifted key was generated in 8 hours, which corresponds to 0.57 sifted key bits per second, while our source could generate more than 5,000 sifted key bits per second. In the same paper, the authors also use a dispersion shifted fiber, which is not as widely deployed as the most common optical fiber (SMF28e) used in our work, as well as superconducting detectors which we try to avoid. Thus, we believe that our work demonstrates a significant advance compared to the work reported there.

3. Technologies: The authors selected an O-band entanglement source for zero-dispersion. However, the dispersion can be compensated in fiber with a known distance, in a normal C-band, with much lower attenuation. The authors need to discuss the advantage compared to the case using dispersion compensated fiber. Moreover, the non-degenerate entanglement source was developed and tested. The authors need to identify the novelty of the presented experiment.

ANS: We agree with the reviewer that the dispersion can be compensated. However, the transmission difference between the O-band and C-band is merely about 1 dB over 10 km, which will not introduce a huge difference over a metropolitan distance. Practically, additional compensations optics will also introduce extra insertion loss. The main idea of our work is that in the 50 km range our source does not require any spectral filter, dispersion compensation, dispersion-shifted fiber and sophisticated detectors, yet it is still able to achieve a high entangled pair rate, which makes it very useful for entanglement distribution over metropolitan distances.

Minors:

4. I would encourage the authors to discuss the purity and the fidelity of the source, which may be of advantage compared with other nonlinear crystals, e.g., PPLN.

ANS: The property of a narrow optical bandwidth of the pair source arises from the high non-degeneracy of target modes, where the phase matching condition can be easily broken when the signal and idler wavelength are slightly offset. For a crystal like PPLN, the source would require pump light in the visible regime, because it is not transparent at pump wavelength in blue or UV. As a consequence, for a given signal wavelength at 1310 nm, it cannot be as non-degenerate as our source, resulting in a larger optical bandwidth. Overall, our work focuses more on proposing an alternative for a high-performance and easy-to-implement fiber-based entanglement distribution scheme; therefore, we would want to avoid diverting the focus to the crystal materials.

5. The references should be updated, e.g., the citations to works related to QKD [7-12] are out of date.

ANS: The references have been revised and updated.

6. The single photon detection efficiency is not accurately calibrated, why?

ANS: The rough efficiency of commercially available APDs is well known to the QKD community. From those references, we assume a relatively optimistic value for the detectors when we estimate the performance of the source. At the end, we are focusing on the observed pair rates. We believe this is sufficient within the scope of this work.

7. In Fig 1, the pump beam waist at PPKTP may be shifted due to the splitting at BBO. How much will this affect the collection efficiency and visibility?

ANS: The BBO crystals are about 1 cm long which only introduces less than one millimeter of optical path length difference for the two pump beams. Since our pump mode has a Rayleigh length of about 6 cm, the impact on the collection is expected to be negligible. In our experimental setup, the crystal is mounted on a translation stage which has a travelling range of 1 cm along the pump direction to fine-adjust the relative position between the pump and crystal. In the end, we observe that the BBO crystals do not change the coupling efficiency significantly, in agreement with our estimation.

8. In Fig 2(c), there is a sudden drop in the coincidence date of 0 km near the peak. What is the possible reason?

ANS: We suspect that this feature is due to jitter of the timestamp device (around 50 ps), which could result in redistribution in time bins for the time stamping data. Nonetheless the 50 ps jitter should be more than enough for QKD application using APDs.

9. It might be helpful to discuss the dispersion of 50 km fiber with a source at the 1550nm band, and compare the possible performance with the source discussed in the manuscript.

ANS: For 1550 nm photons with similar sub-nm bandwidth, the dispersion is around 18 ps/km/nm for a standard telecommunication fiber. This in turn introduces about dispersion of 1 ns in a 50 km fiber, close to our coincidence window width. Consequently, the SNR will decrease, and equivalently the QBER will increase by about factor of two without compensation. The dispersion effect will be more obvious for lower timing jitters APDs or superconducting single-photon detectors.

With this, we hope to have addressed the comments from the reviewers, and look forward for your consideration of our updated manuscript. For reference, we added a diff file to highlight the changes from the previous manuscript

With Best Regards on behalf of all authors,

Christian Kurtsiefer