1. PHD PROJECT DESCRIPTION (4000 characters max., including the aims and work plan)

1.1. Project title: Long distance quantum communication

1.2. Project goals:

The goal of the project is to apply the unique set of quantum-technological methods to improve long haul quantum communication (QC) with satellites and in fibers. The set of experimental techniques, which will be used in the project is based on the ability to generate, control and detect single photons. The quantum light is generated by means of the process of spontaneous parametric down conversion (SPDC). Here a photon from a laser beam, when traveling through a nonlinear crystal spontaneously decays into a pair of photons with lower energies. The detection of one of the photons can herald the existence of the other particle. The list of goals of this project includes:

a) Theoretical analysis an implementation of QC protocols for satellite based links.

b) Design, implementation and testing a multi-purpouse photon receiver.

c) Theoretical analysis and experimental implementation of quantum and coherent communication protocols.

1 1.3. Outline

Satellite QC. A basic functionality of a satellite QC link is a capability sending single optical information carriers between a satellite and a ground station. It is called a downlink or uplink depending on the direction of the signal transmission. Downlink features less attenuation as photons experience turbulence at the very last part of their journey to a receiver. This comes with the expense of significantly higher technical demand on the satellite design. The uplink configuration is much less expensive due to the receiver simplicity. In both cases an optical ground supporting equipment (OGSE) is based on a telescope equipped with a module capable of generating or analyzing single photons. The goal is design, implement and test a optical link between two telescopes allowing for classical and quantum communication based on coherent optical communication protocols.

Fiber based QC. Quantum information is typically encoded in polarization degree of freedom of single photons. However, spatial mode offers the ability to encode and measure multilevel quantum systems. For example, a simple slit system can be used for encoding and spatially resolved detection can serve as quantum measurement. The similar mathematical concept can be transferred to temporal mode of a single photon. In analogy to the separated spatial modes of logical qudits, here, the temporal modes are engineered and the measurements are done by resorting to time resolved detection. The goal is to implement high dimensional quantum states encoded in temporal modes of single photons propagating over long distances in fibers or in mixed links consisting of fibers and free space connections. The experimental capability of generating and measuring multilevel quantum states can be applied to implement QC protocols, in particular quantum key distribution (QKD).

1.4. Work plan

a) Multilevel quantum states. The experimental technique allowing to control and detect the temporal modes of single photons was demonstrated [Sedziak2019]. The encoding of multilevel quantum states will be based on a similar technique as already already reported [Sedziak2020]. It will require a modification of the existing experimental setup. Initial literature study and theoretical analysis is necessary. //12 months

b) ***Coherent optical communication.*** (1 year) The techniques described above shall be implemented for a free space or a hybrid (free space and fiber) link. The telescope-telescope link is envisioned as ultimately a coherent one, which requires active stabilization and therefore allows for coherent optical communication. //12 months

c) Quantum optical communication. A source for a satellite (free space) link generating a pair at 785 nm and 1550 nm is is available [Szlachetka2023]. A careful analysis of its performance and integration with a telescope will be needed. As a final step demonstrations of various quantum communication protocols will be performed. //18 months

Thesis preparation //6 months

1.5. Literature

[Pugh2017] C.Pugh et al, Airborne demonstration of a quantum key distribution receiver payload Quantum Sci. Technol., 2, 024009

[Shalm 2015] L. K. Shalm, et al, A strong loophole-free test of local realism Phys. Rev. Lett. 115, 250402

[Rideout 2012] D. Rideout, et al Fundamental quantum optics experiments conceivable with satellites reaching relativistic distances and velocities Classical and Quantum Gravity, 29, 224011

[Divochiy 2018] A. Divochiy, et al Single photon detection system for visible and infrared spectrum range Opt. Lett. 43, 6085 2

[Sedziak2019] K. Sedziak, et al Remote temporal wavepacket narrowing Sci. Rep., 9, 3111

[Sedziak2020] K. Sedziak-Kacprowicz, A. Czerwinski, P. Kolenderski Tomography of time-bin quantum states using time-resolved detection, arXiv:2003.11981

[Szlachetka2023] Jakub Szlachetka, Kaushik Joarder, Piotr Kolenderski, Ultrabright source of non-degenerate polarization-entangled photon pairs based on off-the-shelf polarization optics Appl. Phys. Lett. 123, 144001 (2023)

1.6. Required initial knowledge and skills of the PhD candidate:

Strong theoretical and experimental background in quantum optics or quantum communication or propagation of light in media.

1.7. Expected development of the PhD candidate's knowledge and skills

The PhD student will learn experimental and theoretical methods and protocols related to free space and fiber based quantum communication. He/She will get experience with symbolic and numerical algebra systems like Mathematica, Python or Matlab. The student will learn all the skills related to building an optical experimental setup.