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PhD topic proposal
Generating and teleporting entanglement for quantum networks

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Contents

1 Description of the immediate research area and its problems

In the rapidly advancing fields of quantum communication and quantum computing, the efficient transfer of secure quantum information is of great importance. A key quantum resource is entanglement, which facilitates processes such as quantum teleportation and entanglement swapping. However, conducting these experiments over long distances through optical fibers presents significant challenges due to transmission losses. To mitigate this, photons must be generated at wavelengths compatible with existing fiber-optic networks, particularly in the O and C near-infrared bands (1310 nm and 1550 nm, respectively), where transmission losses are minimal. These advances contribute to the broader goal of realizing quantum networks, which require robust capabilities for generating and characterizing quantum coherence and entanglement. Such networks rely on quantum interconnects, which convert quantum states between physical systems in a reversible manner, enabling the distribution of entanglement and the teleportation of quantum states across network nodes [1]. Additionally, free-space communication methods are being explored for applications in metropolitan areas [2]. To maximize the efficiency of these telecom networks for multiple users, the available bandwidth is divided into many frequency channels using Dense Wavelength Division Multiplexing (DWDM). The focus of this thesis is to implement a Sagnac interferometer source of polarization-entangled photons centered around 1560 nm, designed to be sufficiently broadband to accommodate multiple DWDM frequency channels. These photons will be generated via Spontaneous Parametric Down-Conversion [3] (SPDC) from a 50 mm periodically poled lithium niobate (PPLN) nonlinear crystal located at the center of the interferometer. The source will first be implemented and characterized in the laboratory through techniques such as Quantum State Tomography (QST), Clauser-Horne-Shimony-Holt (CHSH) inequality measurements [4], Hanbury-Brown and Twiss (HBT) interferometry [5], and Hong-Ou-Mandel (HOM) interferometry [6]. Subsequently, quantum teleportation [7] and entanglement swapping [8] experiments will be conducted in collaboration with the Jožef Stefan Institute, which will develop an identical entanglement source with our assistance. To ensure stability, the pump laser wavelength will be locked to an absorption line in Rubidium gas using atomic spectroscopy via the $^{87}Rb\ D_2$ transition [9]. These efforts are foundational for the development of quantum repeaters, a critical component for the future global quantum internet. Quantum repeaters may enable the distribution of entanglement over arbitrarily long distances by overcoming exponential loss scaling, even in low-loss fiber networks where attenuation is approximately 0.18 dB/km. Without such repeaters, entanglement distribution is limited to distances of only a few hundred kilometers. This thesis aims to achieve not only the first realization of a high-yield entanglement source at non-degenerate frequencies in Slovenia but also to demonstrate quantum teleportation and entanglement swapping. The entanglement will be generated by bi-directionally pumping the PPLN crystal in the center of the Sagnac interferometer, introducing photon indistinguishability essential for these protocols.

Key words: Quantum Entanglement, Quantum Key Distribution, Entanglement Swapping

2 Overview of related research and relevant literature

Since the idea of using entanglement for a means of superluminal communication has debunked [10] there has been a great effort in finding ways to circumvent these restrictions, not in hopes of breaking causality, but in secure commuication between two parties and enhancing cryptographic methods, as well as creating new quantum cryptographic methods of encoding data. Some of the more feasible ideas like BB84[11] E91 [12], and BBM92 [13] of which now there exist many devices for a commercial setting, and a large amount of research has been done in improving and fine tuning these methods and also providing proofs of security [14, 15].

Unlike prepare-and-measure protocosl like BB84, in order for some of these new methods (E91 and BBM92) to be used in applications there needs to exist sources of entanglement. After one of the first [16] demonstrations of a high intensity polarization entangled source was realized it also became apparent that they can be fully done on chip [17] for frequency-bin entanglement, polarization entangled [18] and also for hybrid frequency-polarization entangled states [19]. Latest research in this field is advancing quickly, specifically for Pulsed Wave laser (PW) sources which offer higher peak power and fewer synchronization constraints. There are fewer such papers for Continous Wave laser (CW) sources which have lower power and require higher levels of synchronization as well as postprocessing as we plan to use. A benefit to using CW as compared to PW is less maintainace, for instance in an industrial or government setting where access may be limited. Another benefit would be the ability to store data for postprocessing pourpuses (meh). Some notable mentions using a similar design with a Sagnac loop are by [20, 21]. In these works the entanglement is "generated" due to an ambiguity of of the origin of the photons. There are also many linear, or single pass, designs such as [22, 23]. Here, the entanglement is a product of ambiguity of momentum conservation, as only specific cross sections of the two generated light cones are indistinguishable. An important measure on wether a source is performing well is it's brightness and heralding. The brightness being a measure of how many "useful" photon pairs are produced, and the heralding being the probability, when measuring two photon correlations, of finding a correlated photon when detecting the 1st one. Both of these measures should be as high as possible in order to mitigate loss in fiber for fiber based networks, reduce preprocessing load, and for coupling to certain quantum devices such as quantum memories or repeaters.

In the case of the current thesis I will use a 50 mm PPLN Type-0 SPDC crystal placed in a bulk Sagnac interferometer which will be bi-directionally pumped by a CW 780.24 nm laser. The output beams of the crystals are rotated in polarization in such a way that both beams exit through the same output port of the Polarization Beam Splitter (PBS). The advantage of using SPDC for entanglement generation is that one can relatively efficiently generate the necesarry biphoton pairs compared to other methods (what are some other methods).

3 Statement of hypotheses, research questions and research goals

Goal 0 - Build a Sagnac source of entanglement and reach the currently know state of the art in performance metrics such as brightness and heralding.

Goal 1 - Once we have a fully working source, we need to characterize it using QST, CHSH, HBT, and HOMI for different pairs of DWDM channels (references).

Goal 2 - might need to introduce extra filtering – 100 GHz not enough -> Filtering cavities Long-term stability, locking, ...? Demonstrate Quantum Teleportation within the lab, and Entanglement swapping (we will use the same Φ^+ or Φ^- Bell state, then perform a Bell measurement on each part of the pair) with IJS, IJS Reactor, Beyond Semiconductor, where to do long distance stuff (need fibers) other distant parties,

Goal 3 - Free space application using OAM modes, try to do entanglement in this regime?? topological photons

Why use CW instead of Pulsed Wave (PW)? Advantages of Continuous Wave compared to Pulsed Laser entanglement sources: How to then generate entanglement How to stabilize the 780 laser to the Rubidium Gas Cell, some references for locking and such which we plan to use Introduce HBT, HOM, Teleportation, Entanglement Swapping, Zeillinger, Rainer, others,

4 Outline of research and research methods

We will use a Continous Wave (CW) 780 nm Toptica DLPro laser to pump a 50 mm nonlinear PPLN crystal which is phase matched for Type-0 SPDC (e $\rightarrow$ e + e, e meaning extraordinary polarization) for generating entangled photons. An existing Dark Fiber (DF) will be used for network testing once all of the local tests have been made, including QST, HBT, and HOMI. The DFs location is currently undisclosed.

5 Expected results and original contributions to science

6 Draft plan for management of research data

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