Univerza *v Ljubljani*
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DISPOZICIJA DOKTORSKE DISERTACIJE

Ustvarjanje in teleportiranje prepletenosti za kvantna omrežja

Generating and teleporting entanglement for quantum networks

ADVISER: Rainer O. Kaltenbaek, assoc. prof. dr.

Znanstveno področje: Fizika

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Zadeva: Prošnja za odobritev teme doktorske disertacije

Spoštovani člani odbora,

Pišem vam, da bi se uradno prijavil za temo svoje doktorske disertacije. Sem na doktorskem študijskem programu Fizika. Moje raziskave na področju kvantne komunikacije potekajo pod mentorstvom izrednega profesorja Dr. Rainerja Oliverja Kaltenbaeka, Osredotočam se na razvoj visoko zmogljivega vira prepletenih fotonov. Naslov disertacije je „Generiranje in teleportiranje prepletenosti za kvantna omrežja“. Cilj moje študije je zasnovati vir, ki je dovolj širokopasovni, da lahko hkrati služi več odjemalcem, s čimer bi izboljšali praktičnost in razširljivost kvantnih omrežij.

Svoje raziskave želim nadaljevati na Univerzi v Ljubljani, Fakulteti za matematiko in fiziko, in se veselim te priložnosti, da bom lahko prispeval k temu vznemirljivemu področju.

Zahvaljujem se vam za vaš čas in razmislek. Veselim se vašega odgovora.

S spoštovanjem,
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Short CV

I am a PhD candidate in physics at the University of Ljubljana, Faculty of Mathematics and Physics (FMF), working in the Laboratory for Quantum Optics under the supervision of Assoc. Prof. Dr. Rainer O. Kaltenbaek. My research focuses on developing a high-yield, broadband source of entangled photons for quantum communication. I received a Master's degree in physics from the University of Rijeka, where I conducted research on transient signals in dark matter detection, and a Bachelor's degree in physics, with a thesis on spectral analysis of AGN Markarian 421 in the very high-energy gamma region. I have experience in quantum and nonlinear optics from my work at my supervisors laboratory at FMF.

Kratki življenjepis

Sem doktorski kandidat fizike na Fakulteti za matematiko in fiziko Univerze v Ljubljani (FMF), kjer delam v Laboratoriju za kvantno optiko pod mentorstvom doc. dr. Rainerja O. Kaltenbaeka. Moje raziskave se osredotočajo na razvoj visokozmogljivega, širokopasovnega vira prepletenih fotonov za kvantno komunikacijo. Na Univerzi na Reki sem magistriral iz fizike, kjer sem raziskoval prehodne signale pri odkrivanju temne snovi, in diplomiral iz fizike z nalogo o spektralni analizi AGN Markarian 421 v območju zelo visokih energij gama. Izkušnje na področju kvantne in nelinearne optike imam iz dela v laboratoriju svojega mentorja na FMF.

Mentor's consent

(Mentor's consent addressing Senate UL FMF)

Application for writing a doctoral dissertation in English

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Dear Committee Members,

I hope this message finds you well. I am writing to formally request permission to write my PhD thesis in English. As an international student and non-native speaker of Slovenian, I believe that completing my thesis in English would be beneficial for both academic and practical reasons. Firstly, English is the primary language in my field of study, and the majority of relevant literature, research articles, and publications are available in English. Writing my thesis in English would enable me to engage more directly with this body of work and ensure that my research is positioned within the global academic discourse. Secondly, my supervisor, Assoc. Prof. Dr. Rainer Oliver Kaltenbaek, who is also a non-native speaker of Slovenian, has advised that conducting and evaluating the research in English would facilitate clearer communication and collaboration throughout the thesis process. Furthermore, writing in English would allow for smoother peer review and potential publication in international journals. Lastly, most, if not all of the literature that I am using in my doctoral studies are in English and I believe it would slow down my progress to translate all of the terminoligy and nomenclature to Slovenian. I greatly appreciate your understanding and consideration of this request. I am confident that writing my thesis in English will enhance its academic impact and contribute positively to my development as a researcher. Please let me know if further clarification or documentation is required to support this appeal. Thank you for your time and attention. I look forward to your response.

Yours sincerely,
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Disposition of doctoral dissertation (in English)

1 Description of the immediate research area and its problems

In the rapidly advancing fields of quantum communication and quantum computing, sensing, and simulators the efficient transfer of secure quantum information is of great importance. A key quantum resource is entanglement, which facilitates experiments such as quantum teleportation and entanglement swapping. 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 C near-infrared band where transmission losses are minimal. These advances contribute to the broader goal of realizing quantum networks, which require robust capabilities for generating and characterizing aforementioned quantum processes. 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 [2] are being explored for applications in metropolitan areas.

While these technologies are essential for local and metropolitan quantum networks, scaling to a global level requires overcoming the inherent limitations of photon loss over long distances. This is where quantum repeaters and high-yield entanglement sources play a critical role for the future global quantum internet. High-yield entanglement sources in in-between nodes, coupled to quantum repeaters may enable the distribution of entanglement over arbitrarily long distances by overcoming exponential loss scaling, even in fiber networks where attenuation is low. Without such sources and repeaters, entanglement distribution is limited to distances of only a few hundred kilometers.

This work seeks to establish the technical bedrock for future scalable quantum networks. These efforts do not exist in isolation; they directly feed into the broader mission of transforming theoretical quantum advantages into real-world systems. I aim to achieve not only the first realization of a high-yield polarization entanglement source at non-degenerate frequencies in Slovenia but also to demonstrate quantum teleportation and entanglement swapping using continuous wave lasers. Ongoing research efforts aim to bridge the gap between theoretical advancements and practical applications, driving the quest for more efficient and accessible quantum systems that could transform various sectors, including telecommunications and healthcare. As these technologies mature, they are poised to redefine our understanding of information processing and secure communications in the quantum era.

Key words: Quantum Entanglement, Quantum Communication, Entanglement Swapping

2 Overview of related research and relevant literature

Quantum entanglement sources are pivotal components in the field of quantum mechanics, enabling the generation of entangled states that are essential for a range of applications, including quantum computing, cryptography, simulations, and communication. These sources can produce pairs of entangled photons through various techniques such as cavity-enhanced configurations, quantum dot mechanisms, and by far the most widely used method being Spontaneous Parametric Down-Conversion [3] (SPDC). The ability to create reliable and efficient entangled states has garnered significant interest due to their implications for advancing quantum technologies and facilitating secure information transfer across long distances.

Entanglement sources are crucial for quantum technologies, but scalability, efficiency, and reliability remain challenges. Advances like quantum repeaters and high-yield distribution have improved fidelity and signal loss, yet practical implementation faces hurdles such as room-temperature operation and protocol complexity.

After one of the first [4] demonstrations of a high-intensity polarization entangled source was realized it also became apparent that they can be fully done on chip [5] for frequency-bin entanglement, polarization entanglement [6], and also for hybrid frequency-polarization entangled states [7]. Latest research in this field is advancing quickly, specifically for Pulsed Laser (PL) sources which offer higher peak power and fewer synchronization constraints. A benefit to using Continuous Wave lasers (CW) as compared to PL is less maintenance and lower cost, for instance in an industrial or government setting where access may be limited. Some notable mentions using a similar design with a Sagnac loop [8, 9] in which the entanglement is generated due to an ambiguity of the origin of the photons. There are also many linear, or single pass, designs such as [10, 11] where the entanglement is a product of ambiguity of momentum conservation, as only specific cross sections of the two generated SPDC light cones are spatially indistinguishable.

An important measure on whether a source is performing well is its brightness, bandwidth, and heralding [12, 13]. The brightness being a measure of how many photon pairs are being produced, bandwidth corresponds to how well defined they are in frequency, as this is a limiting factor for certain interference measurements like Hanburry Brown and Twiss (HBT) [14], Hong Oh and Mandel (HOM) [15], and also for coupling to quantum memories, and the heralding being the probability, when measuring two photon correlations, of finding a correlated photon when detecting the 1st one. Brightness and heralding should be as high as possible in order to mitigate loss in fiber for fiber based networks, reduce preprocessing load, and the bandwidth to be as narrow as needed for efficient coupling to quantum devices such as quantum memories or repeaters, or for certain measurements as HBT and HOM, which will need to be performed for a full characterisation of the source. We will also perform Quantum State Tomography (QST) measurements, and CHSH inequality measurements [16].

One of the first [17] experimental demonstrations of entanglement swapping by use of CW lasers has shown that it is entirely possible to not use pulsed lasers for this purpose, but with less efficiency. Afterwards, there were very few reports on this. Somewhat recently, two [18, 19] interesting papers came out showing entanglement swapping using a micro-ring resonator and a PPLN waveguide. In the case of the micro-ring resonator, four-wave mixing was used in order to generate the entangled pairs in the two source setups, while in the case of the PPLN waveguide a single laser was used for pumping both SPDC crystals. To the best of my knowledge, we will be the first to try to show entanglement swapping by two completely independent bulk sources, using completely independent measurement and analysis tools.

We want to build a new high-yielding source of entangled photons which can later be used as part of a research network for conducting multiple experiments simultaneously. It should be broad enough to supply these demands, and bright enough that further filtering does not diminish the signal to an unusable amount. This will become important for future quantum networks as well, as they may require narrower bandwidths for efficient coupling to quantum memories or quantum repeaters.

The main reason for using a CW laser is due to our involvement in a EuroQCI project called the Slovenian Quantum Communication Infrastructure Demonstration (SiQUID). The source will be used also for various QKD protocols based on entanglement. For this purpose, a CW laser was chosen.

3 Statement of hypotheses, research questions and research goals

The overarching goal of this thesis is to develop a high-yield, broadband source of entangled photons suitable for quantum networks and laboratory-based quantum research. Future quantum networks must be capable of supplying entangled photon pairs to multiple users with high fidelity and efficiency. This requires a source that is not only bright and stable but also spectrally broad enough to support multiple experiments and network nodes. The main gaols (C) and questions (R) of this thesis are listed as follows:

C1 - Develop a broadband entanglement source that generates high-fidelity Bell states with high tangle. The source should be bright enough to support multiple concurrent experiments and users in a research setting.

C2 - Demonstrate quantum teleportation and entanglement swapping between the entanglement source and quantum nodes at FMF and JSI, contributing to the development of real-world quantum network architectures.

C3 - Investigate the feasibility of implementing entanglement swapping over a short free-space link without relying on orbital angular momentum (OAM) modes. This could serve as a valuable test-bed for alternative methods of entanglement distribution within Ljubljana.

R1 - Can this entanglement source achieve performance surpassing the current state of the art relating to CW entanglement swapping using existing technology?

R2 - How large must the cavities be in order to reduce the bandwidth of the SPDC photons for the HOM interference measurement?

R3 - Under which conditions can Dense Wavelength Division Multiplexing (DWDM) channels, each with a 100 GHz bandwidth, be utilized to perform quantum optical measurements such as HOM interference, and after filtering what would be the new bandwidth by performing a HBT experiment?

These objectives and research questions define the scope of this thesis, guiding the experimental work and theoretical analysis required to advance the state of broadband entanglement sources for quantum communication and networking.

4 Outline of research and research methods

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. In the case of the current thesis I will use a 50 mm Periodically polled Lithium Niobate (PPLN) Type-0 SPDC

($e_{pump} \rightarrow e_{signal} + e_{idler}$, e meaning extraordinary polarization) crystal placed in a Sagnac interferometer which will be bi-directionally pumped by a CW 780.24 nm laser.

The pump will be set to a diagonal polarization state ($\frac{1}{\sqrt{2}}(|H_{pump}\rangle + |V_{pump}\rangle)$). On arriving to the Polarization Beam-Splitters (PBS) the beam is split into two. The reflected ($|V_{pump}\rangle$) beam first passes through a half-wave plate (HWP) in order to rotate the polarization from $|V_{pump}\rangle$ to $|H_{pump}\rangle$, as is required by phase matching conditions (in the actual setup the crystal is rotated by 90° along the beams axis), then through the crystal where it generates two $|H_{signal\ (idler)}\rangle$ photons around 1560 nm, and then through the PBSs $|H\rangle$ output where it gets recombined with the now two $|V_{signal\ (idler)}\rangle$ photons from the counter propagating branch.

After the two bi-photon pairs pass through the PBS they are reflected by a dichroic mirror, and diverted into a collimating lens after which they are finally coupled into fiber. The photons from opposing directions will then be in a $\Phi = \frac{1}{\sqrt{2}}\left(|H_{signal}H_{idler}\rangle + e^{i\phi}|V_{signal}V_{idler}\rangle\right)$ Bell state. In order to choose any of the four available Bell states (including the two complex ones), in the pump beam path, we will have a relative phase setter between the two counter propagating paths, consisting of a two quarter-wave plates (QWP), and a HWP between them. The QWPs are set to $\frac{\pi}{4}$, and the HWP is used to set the appropriate phase to select one of the Φ Bell states. maximize the efficiency of these telecom networks for multiple users, the available bandwidth (approximately 7400 GHz, or 60 nm) is divided into many frequency channels using a DWDM.

For all of the tests a DWDM of roughly 100 GHz channel bandwidth, or 0.81 nm, will be used. For simply checking whether the source produces entangled pairs it is enough to do a CHSH measurements. We have chosen to do this in the linear basis as it requires only two HWPs and two PBSs. The measurement basis for this are on each channel are offset by $\frac{\pi}{8}$. After this we will perform a QST measurement to reconstruct [20] the density matrix of the entangled state. In order to measure the actual bandwidth of our DWDM channels a HBT measurement will be performed, and also a HOM measurement. Subsequently, quantum teleportation [21] and entanglement swapping [22] experiments will be conducted in collaboration with the Jožef Stefan Institute JSI entanglement lab, who will develop an identical entanglement source.

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 [23]. A small percentage of the pump beam will be diverted into a separate setup where it will be further split into counter two propagating beams passing through a gas cell for cancelling Doppler broadening, and a reference beam going straight through the gas cell. The reference beam and one of the counter propagating signal beams will be coupled to a balanced photodiode, and the error signal will be fed into the laser controller for locking.

In order for two distant parties to be able to measure the correct time tags for analysis, each party will have to synchronize to a reference. Options are currently being explored on how to exactly do this. A proposed idea is to use GPS clocks which are disciplined regularly.

Regarding the short distance free space test, we will likely engineer or buy a basic telescope sender and receiver station. We will follow the procedure developed here by [24]. Upon completion, I will test entanglement swapping via free space link. This setup will be used primarily for another project of the group, where 1560 nm photons will be generated in a non-degenerate SPDC process along with 853 nm photons in order to couple to a quantum memory device built by JSI. For this purpose, they must teleport the entanglement from a local 853 nm photon generated by our group to the IJS group, and in order to do so we need the 1560 nm free space link continuous wave swapping protocol completed.

The last part of the thesis will be about active polarization control [25]. In order to measure the correct states, the idea is to use an electronic polarization controller in the experimental network to create an algorithm which will be able to ensure the correct polarization state is being received on the measurement stage.

All of the measurements for this thesis will be performed using Superconducting Nanowire Single Photon Detectors (SNSPDs) ID281 from IDQuantique. The measurements at JSI will be performed using SNSPDs from Single Quantum.

5 Expected results and original contributions to science

Lastly, I will talk about the expected entanglement swapping rate that we hope to achieve, and also the HOM interference visibility, which is an important measurement for achieving entanglement swapping. Currently, without any optimizations in regards to heralding or brightness the source is capable of producing around 35000 correlated pairs per second, per branch of the Sagnac loop. Using this, and the estimated coincidence window of 300 ps, a rate of around 0.3 four-folds per second should be achievable. This would mean that in order to gather enough four-folds for a HOM measurement, one would have to integrate for roughly 10 minutes per point. To the best of my knowledge, this would be a new record for CW HOM, and it might open other possibilities for further research. I have assumed that the jitter profile of the detectors and time tagger is Gaussian.

Assuming 100 GHz bandwidth of the SPDC photons, which corresponds to roughly 10 ps coherence time, and assuming the total timing jitter is 44 ps by using the Root Sum of Variances method, the maximum visibility of the HOM interference measurement one can hope for is around 20%, which is well below the minimal value for violating Bells inequality. This then leads to a rough value for minimum of the coherence time of our SPDC photons to around 100 ps for the HOM measurement, possibly even larger. Hypothetically, assuming such a total timing jitter without including synchronization jitter we can expect to get a visibility of at most 91%. Clearly, adding in synchronization will reduce this number even farther for that coherence time.

In order for the integration to not take too long, but still give desirable results, there might need to be a compromise between the bandwidth and integration time for the HOM measurement. Filtering will of course also reduce the amount of coincidences we will be able to see.

Depending on visibility of the HOM this reduces the tangle of the source and whatnot Check when visibility destroys entanglement

Original contributions: More engineering - filtering, jitter, Getting good SNR with CW -> In future maybe go to PL - working principle may be the same and might bring great imrpovement of HOM

Currently making good progress with brightness - but needs improvement of coupling/heralding

Working together with a company (mention maybe the experimental network from SiQuid)

6 Draft plan for management of research data

During my doctoral research, I will collect and analyze time tagger data, which records photon detection events with precise timestamps. The data will be stored in CSV files and analyzed using C++ and Python scripts.

To ensure data integrity and reproducibility, I will organize my research data as follows:

- Raw data (time tagger outputs) will be stored in a structured directory on one of our laboratory computers, sorted by experiment date and parameters.
- Processed data (results of filtering, calibration, and analysis) will be saved in separate CSV files, maintaining a clear relationship with the raw data.
- Analysis scripts (C++ and Python code) will be version-controlled using Git.

For long-term storage and accessibility, I plan to deposit my research data in an appropriate open-access data repository, such as Zenodo, Figshare, or the University of Ljubljana Repository. The dataset will include: Raw and processed CSV data. Metadata describing the experiment setup, parameters, and conditions. Documentation explaining the data structure and how to reproduce the results using the provided scripts. The data will be made available upon request unless confidentiality or ethical restrictions apply. When sharing, I will ensure compliance with FAIR principles (Findability, Accessibility, Interoperability, and Reusability) by providing proper documentation and referencing my datasets in publications.

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