Univerza *v Ljubljani*
Fakulteta za *matematiko in fiziko*

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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

Ljubljana, 2025

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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, 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, 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 afforementioned 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. 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.

The field has witnessed rapid advancements, particularly in the development of innovative materials and techniques that enhance the performance of entanglement sources. Recent breakthroughs, including quantum repeaters and high-yield entanglement distribution methods, have addressed challenges related to signal loss and fidelity in quantum communication networks. Despite these advances, challenges remain in terms of scalability, resource efficiency, and operational reliability. Many existing systems struggle to meet the demands for large-scale entanglement required for practical applications, with issues such as room temperature operation and the complexity of quantum protocols posing significant hurdles. The importance of entanglement sources in the realm of quantum technologies cannot be overstated, as they serve as the foundation for cutting-edge innovations in the quantum information fields.

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 Continous Wave lasers (CW) as compared to PL is less maintainace 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 wether 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 Hansbury-Brown and Twiss (HBT) [14], Hong-Oh-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]. The advantage of using SPDC for entanglement generation is that one can relatively efficiently generate the necesarry biphoton pairs compared to the other methods mentioned above.

[17, 18, 19]

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 braod 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 bandwiths for efficient coupling to quantum memories or quantum repeaters.

3 Statement of hypotheses, research questions and research goals

The thesis goal is to produce a high-yield broadband source of entanglement for use in quantum networks, and to also be used in a research network. There is a great demand for this in order for future quantum networks to be able to supply multiple users.

C1 - Build an enetanglement source which would be bright enough to supply entangled photons with high fidelity to Bell States and high tangle, and also broadband enough to supply multiple experiments and users in the lab.

R1 - Can we obtain better results than the current state of the art with current technologies?

R2 - Is it possible by using the DWDM channels, which are 100 GHz bandwidth channels, to perform certain interferometric measurements such as HBT or HOM?

C2 - Short distance free space application without using OAM modes, try to do entanglement in this regime??

C3* - 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,

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 Dense Wavelength Division Multiplexing (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 ariving to the PBS the beam is split into two. The reflected ($|V_{pump}\rangle$) beam first passes through a halfwaveplate in order to rotate the polarization from $|V_{pump}\rangle$ to $|H_{pump}\rangle$, as is required by phase matching conditions (reference), 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 combined 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 counterpropagating paths, consisting of a two quarter-wave plates (QWP), and a half-wave plate (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.

To 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 wether 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 half-wave plates (HWP) 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 Institutes entanglement lab, who will develop an identical entanglement source. All of the measurements will be performed using Superconducting Nanowire Single Photon Detectors (SNSPDs) ID281 from IDQuantique.

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 split into counterpropagating beams passing through a gas cell for cancelling Doppler broadening.

The last part of the thesis will be about active polarization control [24]. 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.

5 Expected results and original contributions to science

Depending on timing jitter how good the HOM would be, try to get as good as we can Maybe need a compromise between integrating and stuff 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.

References

[1] H. J. Kimble, "The quantum internet," *Nature*, vol. 453, no. 7198, p. 1023–1030, Jun. 2008.

[2] A. Kržič, S. Sharma, C. Spiess, U. Chandrashekara, S. Töpfer, G. Sauer, L. J. González-Martín del Campo, T. Kopf, S. Petscharnig, T. Grafenauer, R. Lieger, B. Ömer, C. Pacher, R. Berlich, T. Peschel, C. Damm, S. Risse, M. Goy, D. Rieländer, A. Tünnermann, and F. Steinlechner, "Towards metropolitan free-space quantum networks," *npj Quantum Information*, vol. 9, no. 1, p. 1–9, Sep. 2023.

[3] J. Catalano, "Spontaneous parametric down-conversion and quantum entanglement," jul 2014, supervisor: Andres La Rosa. [Online]. Available: https://pdxscholar.library.pdx.edu/cgi/viewcontent.cgi?article=1588&context=honorstheses

[4] P. G. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, A. V. Sergienko, and Y. Shih, "New high-intensity source of polarization-entangled photon pairs," *Physical Review Letters*, vol. 75, no. 24, p. 4337–4341, Dec. 1995.

[5] F. A. Sabattoli, L. Gianini, A. Simbula, M. Clementi, A. Fincato, F. Boeuf, M. Liscidini, M. Galli, and D. Bajoni, "A silicon source of frequency-bin entangled photons," *Optics Letters*, vol. 47, no. 23, p. 6201–6204, Dec. 2022.

[6] Y.-H. Li, Z.-Y. Zhou, L.-T. Feng, W.-T. Fang, S.-l. Liu, S.-K. Liu, K. Wang, X.-F. Ren, D.-S. Ding, L.-X. Xu, and B.-S. Shi, "On-chip multiplexed multiple entanglement sources in a single silicon nanowire," *Physical Review Applied*, vol. 7, no. 6, p. 064005, Jun. 2017.

[7] S. Francesconi, A. Raymond, R. Duhamel, P. Filloux, A. Lemaître, P. Milman, M. I. Amanti, F. Baboux, and S. Ducci, "On-chip generation of hybrid polarization-frequency entangled biphoton states," *Photonics Research*, vol. 11, no. 2, p. 270–278, Feb. 2023.

[8] S. P. Neumann, A. Buchner, L. Bulla, M. Bohmann, and R. Ursin, "Continuous entanglement distribution over a transnational 248 km fiber link," *Nature Communications*, vol. 13, no. 1, p. 6134, Oct. 2022.

[9] Y. Chen, S. Ecker, S. Wengerowsky, L. Bulla, S. K. Joshi, F. Steinlechner, and R. Ursin, "Polarization entanglement by time-reversed hong-ou-mandel interference," *Physical Review Letters*, vol. 121, no. 20, p. 200502, Nov. 2018.

[10] S. M. Lee, H. Kim, M. Cha, and H. S. Moon, "Polarization-entangled photon-pair source obtained via type-ii non-collinear spdc process with ppktp crystal," *Optics Express*, vol. 24, no. 3, p. 2941–2953, Feb. 2016.

[11] P. G. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, A. V. Sergienko, and Y. Shih, "New high-intensity source of polarization-entangled photon pairs," *Physical Review Letters*, vol. 75, no. 24, p. 4337–4341, Dec. 1995.

[12] R. S. Bennink, "Optimal co-linear gaussian beams for spontaneous parametric down-conversion," *Physical Review A*, vol. 81, no. 5, p. 053805, May 2010, arXiv:1003.3810 [quant-ph].

[13] D. Ljunggren, M. Tengner, P. Marsden, and M. Pelton, "Theory and experiment of entanglement in a quasi-phase-matched two-crystal source," *Physical Review A*, vol. 73, no. 3, p. 032326, Mar. 2006, arXiv:quant-ph/0510218.

[14] R. H. Brown and R. Twiss, “Lxxiv. a new type of interferometer for use in radio astronomy,” *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 45, no. 366, p. 663–682, Jul. 1954.

[15] C. K. Hong, Z. Y. Ou, and L. Mandel, “Measurement of subpicosecond time intervals between two photons by interference,” *Physical Review Letters*, vol. 59, no. 18, p. 2044–2046, Nov. 1987.

[16] J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, “Proposed experiment to test local hidden-variable theories,” *Physical Review Letters*, vol. 23, no. 15, p. 880–884, Oct. 1969.

[17] M. Halder, A. Beveratos, C. Jorel, H. Zbinden, C. Simon, V. Scarani, and N. Gisin, “Entanglement swapping with independent cw-sources,” in *2007 European Conference on Lasers and Electro-Optics and the International Quantum Electronics Conference*, Jun. 2007, p. 1–1. [Online]. Available: https://ieeexplore.ieee.org/document/4386931

[18] F. Samara, N. Maring, A. Martin, A. S. Raja, T. J. Kippenberg, H. Zbinden, and R. Thew, “Entanglement swapping between independent and asynchronous integrated photon-pair sources,” *Quantum Science and Technology*, vol. 6, no. 4, p. 045024, Sep. 2021.

[19] Y. Tsujimoto, M. Tanaka, N. Iwasaki, R. Ikuta, S. Miki, T. Yamashita, H. Terai, T. Yamamoto, M. Koashi, and N. Imoto, “High-fidelity entanglement swapping and generation of three-qubit ghz state using asynchronous telecom photon pair sources,” *Scientific Reports*, vol. 8, no. 1, p. 1446, Jan. 2018.

[20] D. F. V. James, P. G. Kwiat, W. J. Munro, and A. G. White, “Measurement of qubits,” *Physical Review A*, vol. 64, no. 5, p. 052312, Oct. 2001.

[21] D. Bouwmeester, J.-W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger, “Experimental quantum teleportation,” *Nature*, vol. 390, no. 6660, p. 575–579, Dec. 1997.

[22] T. Jennewein, G. Weihs, J.-W. Pan, and A. Zeilinger, “Experimental nonlocality proof of quantum teleportation and entanglement swapping,” *Physical Review Letters*, vol. 88, no. 1, p. 017903, Dec. 2001.

[23] T. Metger, “Saturated absorption spectroscopy of molecular iodine for laser locking,” jul 2017, supervisor: Christoph Fischer. [Online]. Available: https://ethz.ch/content/dam/ethz/special-interest/phys/quantum-electronics/tiqi-dam/documents/semester_theses/semesterthesis-Tony_Metger

[24] J. C. Chapman, “Continuous automatic polarization channel stabilization from heterodyne detection of coexisting dim reference signals.” [Online]. Available: https://arxiv.org/html/2411.15135v1