Development of temporally correlated photon pair sources

PhD thesis booklet

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(2025)

Introduction

The rapidly evolving fields of telecommunications and information processing broadly utilize technologies based on both classical and quantum optical solutions. Several data transfer protocols and computational schemes have been proposed, many already tested, using individual photons as bits of information. Two notable application areas are: quantum key distribution, which is a prospective way of secure data transmission, and all-optical quantum computing, that is believed to provide a solution to enigmatic problems, such as factorization to primes.

Systems serving any of the previous purposes require an appropriate source of single photons or correlated photon pairs. Such devices can be realized via different approaches, each having strengths and weaknesses. Some rely on spontaneous emission of isolated two-level systems. Though these provide photons on demand, the achievable flux is quite limited. Another type utilizes spontaneous parametric down-conversion (SPDC) occurring in highly nonlinear optical materials, whereby a high-energy pump photon splits into a pair of lower energy ones. These so-called signal and idler photons exhibit temporally correlated properties: energy, momentum, and in case the circumstances of their generation are carefully selected, polarization entanglement is also realizable.

The generation of polarization-entangled photon pairs via SPDC has been standing as a cornerstone of experimental quantum optics, quantum information processing, and quantum communication since the end of the 20th century. SPDC taking place in nonlinear crystals became the dominant method due to its relative simplicity and the high quality of entanglement achievable.

Since the initial demonstrations, a wide variety of polarization-entangled photon pair sources has been developed to address different experimental and practical demands. These include interferometric configurations for enhanced stability and phase control, sources operating at telecommunication wavelengths for fiber-based quantum networks, and designs optimized for deployment in space environments. Pulsed pump implementations have been introduced to improve timing resolution and enable synchronization with other quantum systems.

These sources have been successfully applied in experimental quantum key distribution field trials, though they share common drawbacks, such as low level of integration, instability, sensitivity to environmental effects, lack of modularity, complicated setup, long and awkward alignment process. In addition, most industrial and laboratory applications require photons to be coupled into single-mode fibers, which poses further challenges in terms of coupling efficiecy.

Objectives

The Department of Atomic Physics took part in the HunQuTech (National Quantum Technology Program) project and is a contributor to the still ongoing QNL (Quantum Information National Laboratory Hungary) program for the study and development of quantum optical processes and technologies. My research centers on the design and optimization of SPDC sources to address these issues. In collaboration with colleagues of the quantum optics research team at the Department, I aimed to develop solutions to as many of the aforementioned challenges as possible. I investigated various nonlinear materials and source configurations to identify optimal operational parameters.

Modularity and flexibility were key priorities, enabling easy transitions between operational modes to support diverse experimental and educational applications. Portability was another focus, ensuring the sources could be utilized beyond the confines of the laboratory.

Beyond overcoming technical obstacles, my work also emphasizes the development of novel principles for photon source operation. My thesis presents the design schematics and underlying physics of each source, along with detailed descriptions of alignment procedures. By integrating practical improvements with theoretical advancements, the goal is to contribute versatile and high-performance photon sources to the expanding field of quantum optics.

Achievements

Over the span of the project, I designed and constructed three distinct SPDC-based photon sources. The design process encompassed both theoretical modeling and hands-on engineering, including optical layout planning, mechanical component design, and precise assembly. Two of these sources were developed with special attention to engineering challenges, such as environmental robustness, fiber compatibility, and compactness — qualities necessary for out-of-laboratory deployment. All my sources utilize single-mode fiber coupling to facilitate straightforward interfacing with existing quantum optical systems.

One of these devices is currently operating in an experimental quantum key distribution setup at the Department of Networked Systems and Services, Faculty of Electrical Engineering and Informatics, BME. This confirms not only the practical usability but also the application-readiness of the developed photon source, thereby achieving technology readiness level 5 (TRL 5).

Beyond source engineering, I proposed and experimentally demonstrated two distinct methods for generating polarization entanglement. The first converts transverse momentum correlation into polarization entanglement using wavefront-splitting interferometry. This method requires minimal optical components and no active phase stabilization, offering a simple yet effective configuration for entangled photon generation. The second approach, more unconventional, applies the inverse Hong-Ou-Mandel effect within a Sagnac interferometer using two consecutively placed, type-0 nonlinear crystals — completely avoiding the use of polarization optics. While the latter was constrained by the limitations of available components, the concept was successfully demonstrated, and a feasible path toward improved fidelity was proposed.

Furthermore, I introduced a technique for separating frequency-degenerate polarization-entangled photon pairs using the dispersion properties of optical glass to control the phase of inverse HOM interference. This method was integrated into a custom-built source and expands the functionality of HOM-based devices by enabling fine control over photon pair separation.

Taken together, my research addresses both foundational and applied aspects of photon pair source design. By introducing new entanglement-generation strategies and improving system compactness, fiber compatibility, and robustness, I hope to contribute to the broader field of quantum optics.

New scientific results

1) I designed and built a compact, portable, single-mode fiber-coupled correlated photon pair source based on noncollinear, frequency-degenerate spontaneous parametric down-conversion utilizing critical type-I phase matching, that has a higher photon pair flux ($1.3 \cdot 10^5$ pairs/s/mW), and a larger bandwidth (202 nm) compared to sources of similar approach. [H1],[H2],[H3]

2) I proposed a method for converting the transverse momentum correlation of photon pairs into polarization entanglement by using wavefront-splitting interference and single-mode fibers, demonstrated the operation of the technique by incorporating it into the photon pair source presented in Thesis 1) and validated the method by determining state fidelity yielding $F = 0.95$. [H4]

3) For the phase tuning of inverse Hong-Ou-Mandel interference in a Sagnac loop I proposed a simple and reliable method based on the wavelength dispersion of optical glass, described its theoretical background and experimentally demonstrated the effect in a custom-built photon pair source by using it for the separation of frequency-degenerate correlated photon pairs. [H5]

4) I described an approach to implement polarization entanglement with two, consecutively placed type-0 collinearly phase-matched nonlinear crystals in a Sagnac interferometer without the need of dual-wavelength polarization optics utilizing the inverse Hong-Ou-Mandel effect, and experimentally demonstrated its operation by tuning the source of Thesis 3) to produce a Bell state with $F = 0.914$ fidelity. [H5]

Own publications connected to the theses:

[H1] **Cs. T. Holló**, G. Erdei, and T. Sarkadi (2020, September). Increasing the correlation level of polarization entangled photon pairs generated by type-II SPDC in BBO, in Laser Science (Optica Publishing Group, Washington, DC, 2020), pp. JTh4A-36.

[H2] **Cs. T. Holló**, T. Sarkadi, M. Galambos, D. Bíró, A. Barócsi, P. Koppa, and G. Erdei, Compact, single-mode fiber-coupled, correlated photon pair source based on type-I beta-barium borate crystal, Opt. Eng. 61, 025101 (2022).

[H3] **Cs. T. Holló**, T. Sarkadi, M. Galambos, B. Bodrog, A. Barócsi, P. Koppa, and G. Erdei, Compact, portable, fiber-coupled correlated photon pair source with enhanced performance, in Quantum 2.0 Conference and Exhibition (Optica Publishing Group, Washington, DC, 2022), p. QTu2A.18.

[H4] **Cs. T. Holló**, T. Sarkadi, M. Galambos, A. Barócsi, P. Koppa, V. Hanyecz, and G. Erdei, Conversion of transverse momentum correlation of photon pairs into polarization entanglement by using wavefront-splitting interference, Physical Review A 106, 063710 (2022).

[H5] **Cs. T. Holló**, T. Sarkadi, A. Barócsi, P. Koppa, and G. Erdei, Phase-tunable inverse Hong-Ou-Mandel interference: principles and demonstration in a photon pair source, Physical Review A 111.1, 013531 (2025)

Other own publications:

[H6] **Cs. T. Holló**, K. Miháltz, M. Kurucz, A. Csorba, K. Kránitz, I. Kovács, Z. Zs. Nagy, G. Erdei, Objective quantification and spatial mapping of cataract with a Shack-Hartmann wavefront sensor, Scientific Reports 10 (1), 1-10, 2020.