Development of temporally correlated photon pair sources

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The evolving fields of telecommunications and information processing 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, and all-optical quantum computing. Systems serving any of these purposes require an appropriate source of single photons or correlated photon pairs. Such devices can be realized via different approaches: spontaneous emission of isolated two-level systems, or 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 of right circumstances, polarization entanglement is also realizable. Since the initial demonstrations, a wide variety of polarization-entangled photon pair sources has been developed. 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.

My research at the Department of Atomic Physics, BME TTK centers on the design and optimization of SPDC sources to address these issues. My thesis presents the design schematics and underlying physics of each source, along with detailed descriptions of alignment procedures. 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. All my sources utilize single-mode fiber coupling. One of these devices is currently operating in an experimental quantum key distribution setup at the Department of Networked Systems and Services, BME VIK. 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 different methods for generating polarization entanglement. The first converts transverse momentum correlation into polarization entanglement using wavefront-splitting interferometry. The second approach, applies the inverse Hong-Ou-Mandel (HOM) effect within a Sagnac interferometer using two consecutively placed, type-0 nonlinear crystals. 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 as a whole, 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.