Abstract in English:

Quantum entanglement is a fundamental phenomenon in quantum mechanics. Entangled particles behave as a single unit, regardless of the distance separating them. Over the past few decades, photons have played a leading role in experimental research on quantum entanglement. Entanglement was present in various degrees of freedom, but photons' polarization was most commonly used due to the ease of manipulation of this degree of freedom. The polarization of a single photon is described by a two-dimensional Hilbert space – it allows one to physically realize a qubit. It turns out that higher-dimensional Hilbert spaces open up wider possibilities for transmitting and processing information, and the spatial degree of freedom of a photon can serve as a natural implementation of such "qudits".This thesis focuses on investigating the transverse spatial profiles of single photons and two-photon spatial entanglement. The thesis introduces experimental tools for fundamental research, and at the same time can lead to technological advances of considerable importance in the field of quantum communication and quantum imaging.

This thesis presents three main projects, which focus on characterizing the spatial degrees of freedom of heralded single photons and entangled photon pairs.

In the first project, we explore the quantitative characterization of the spatial profile of heralded single photons. However, this task is particularly difficult for single photons, given their indeterminate global phase. To tackle this issue, we introduce a self-referenced interferometric technique, relying on a single photon interfering with itself, that enables the complete characterization of a two-dimensional probability amplitude of a single photon.

In the second project, we characterize spatially entangled photon pairs generated using spontaneous parametric down-conversion (SPDC). In order to achieve this aim, we develop a hybrid intensified camera setup for observing their spatial correlations with a high acquisition rate. This hybrid single-photon camera combines an image intensifier with a high spatial resolution sCMOS sensor and a high temporal resolution single pixel detector (photomultiplier tube). This combination allows us to monitor and control the number of photons detected within each frame. This camera setup facilitates spatially resolved detection of single photons while increasing the data acquisition rate.

Lastly, we focus on a nonlinear Zou-Wang-Mandel (ZWM) interferometer where we utilize a technique known as quantum imaging with undetected photons (QIUP) for the characterization of quantum correlations. QIUP allows for image formation without requiring the detection of light that has interacted with the object being imaged. Instead, it is rooted in the generation of entangled photon pairs in a quantum superposition, originating from two distinct, spatially separated SPDC sources. In this process, one photon from the SPDC pair (idler photon), interacts with the object under investigation. Remarkably, this idler photon is never detected. Our setup facilitates the analysis of correlations of down-converted photon pairs without relying on coincidence measurements. This is enabled by the fact that the spatial resolution of QIUP is limited by the strength of momentum correlations. A stronger correlation leads to a higher resolution. We employ this interferometric technique for characterizing transverse momentum correlations of photons and also explore possibilities of characterization of high-dimensional entanglement involving orbital angular momentum.

Collectively, these projects expand the toolbox for spatial characterization of single photons and entangled photon pairs, contributing to the ongoing development of quantum communication, quantum imaging, and entanglement research.