Abstract

The time-phase encoding has emerged as a promising tool for quantum information technology. Modulating time and phase of quantum light enables generating qubits, or high-dimensional quantum states which can be further used for noise-resilient quantum technologies. Among quantum communication techniques, quantum key distribution (QKD) stands out as a leading solution to address the growing demand for secure communication systems in the face of potential threats posed by quantum computing advancements.

Current QKD systems based on qubit encoding have been widely demonstrated, particularly with time-phase and polarization degrees of freedom. Time-phase encoding is particularly attractive due to its compatibility with telecom infrastructure, robustness to polarization drift, and potential for efficient, high-speed implementations. In this work, I investigate the benefits of extending time-phase QKD toward high-dimensional encoding to further enhance noise tolerance and key generation efficiency.

The overall goal of this thesis is the construction of a quantum key distribution (QKD) link using time-phase encoding. I developed a system capable of transmitting and detecting high-dimensional quantum symbols, allowing encoding multiple bits of information per photon. The main achievement is the experimental demonstration of the advantages provided by high-dimensional encoding, along with a theoretical analysis comparing the impacts of imbalanced measurement probabilities between key-generation and control bases.

Initially, I investigated the potential of photonic integrated circuits (PICs) for generating optical communication symbols. I characterized the properties of on-chip components, verifying their performance and key parameters. Using integrated modulators, I generated optical pulses with tailored temporal and spectral properties. I experimentally validated the parameters through time-to-frequency mapping and time-correlated single-photon counting techniques. These results demonstrate the feasibility of using generic indium phosphide PIC platforms for applications in QKD.

Subsequently, I proposed a novel detection method for detecting high-dimensional time-bin quantum superpositions based on the temporal Talbot effect—a time-domain counterpart of the well-known near-field diffraction self-imaging phenomenon. By carefully tuning the temporal parameters and dispersion properties, I achieved frequency-to-time mapping with substantially lower dispersion requirements compared to the standard approach. Additionally, I analyzed the effects of post-selection strategies and timing noise on the correct discrimination of quantum superpositions.

The primary achievement of this thesis is the experimental demonstration of QKD using two- and four-dimensional quantum superpositions, detected through a newly introduced method based on the temporal Talbot effect. I performed controlled laboratory tests and extended the validation to the fiber-optic infrastructure at the University of Warsaw. Through these experiments, I demonstrated that high-dimensional encoding enhances noise resilience and increases information entropy per detection event. I analyzed the experimental results using two different security models—both accounting for and neglecting detection efficiency imbalances—and observed significant differences in the achievable key rates. The findings pave the way for the development of secure QKD systems based on both high-dimensional states and traditional qubits. Further theoretical refinements could improve the modeling of QKD systems, particularly under finite-key conditions.