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Ph.D. DISSERTATION DEFENSE

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Degree: Doctor of Philosophy
School/Department: Charles V. Schaefer, Jr. School of Engineering and Science / Physics
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Title: Signal Optimization by single photon quantum frequency conversion

Chairperson: Dr. Yuping Huang, Department of Physics, School of Engineering & Sciences

Committee Members: Dr. Yong Meng Sua, Department of Physics, School of Engineering & Sciences
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ABSTRACT

Adequate signal to noise is a prerequisite for quantum communications, computation, sensing, and imaging. To this end, high dimensional signal encoding can maximize channel and bandwidth utilization for high data rates. Extracting information from photon-starved and noisy environments allows long-distance ranging, sensing, and imaging. This dissertation presents low-noise quantum frequency conversion (QFC) and its various implementations using lithium-niobate crystals, waveguides, and nanophotonic circuits, and explores their applications in sensing and communications.

In the first application, we aim at photon-efficient quantum communications, where we demonstrate a parametric mode sorter capable of selectively addressing high-dimensional signals in a composite spatiotemporal Hilbert space. By shaping the spatiotemporal profiles of the pump light for the QFC, we achieve selective mode up-conversion using Laguerre-Gaussian spatial modes and Hermite-Gaussian temporal modes. This approach enhances mode-sorting performance by coupling the up-converted light into a single-mode fiber and operating near the edge of phase matching, achieving over 12~dB extinction for mutually unbiased basis (MUB) sets of modes. This programmable, efficient system enables high-dimensional quantum communication, computation, and metrology by facilitating precise control over quantum states encoded in spatiotemporal modes.

In the second application, we demonstrate fast and efficient imaging by combing low-noise QFC and single photon counting, even when the targets are obscured. This is achieved by transducing near infrared signals to visible wavelengths for photon counting, ensuring low loss and high efficiency operation. Utilizing far-detuned 10~ns pump pulses and an electronic delay line, our system supports rapid voxel scanning with sub-centimeter ranging resolution across a 1.5~meter spatial range. With superior noise suppression, it achieves a measurement rate of 50×50×1000

voxels at 10 frames per second, making it well suited for LiDAR applications in noisy, low photon environments, including autonomous navigation and aerospace missions.

In conclusion, this work has explored new realizations of quantum communications and imaging with high-dimensional data encoding and mode-resolving single photon counting. It addresses key challenges facing quantum communications, sensing, and imaging, and suggests practical approaches to unlocking the power of quantum optical information processing.