PhD THESIS DEFENSE: Quantum-enhanced imaging with SPAD array cameras

ROBIN CAMPHAUSEN

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15:30
Auditorium

Entangled photon pairs can enhance optical imaging capabilities. Phase imaging allows detecting fine detail of transparent samples without potentially invasive fluorescent labelling, and here entanglement enables a higher signal-to-noise ratio (SNR) than possible with only classical light. Spatial correlations from spontaneous parametric down conversion (SPDC) photon pair sources can also be used to increase spatial resolution and robustness to noise and aberrations in imperfect optical systems. Quantum imaging therefore represents a powerful approach to push imaging science beyond its current limits.
Until recently, the principal barrier to implementing useful quantum imaging schemes based on entangled photons has been technological, as scalable image sensors capable of multi-photon imaging were unavailable. However, this situation has changed with the

development of single photon avalanche diode (SPAD) array cameras, as well as efficient high brightness entangled photon pair sources based on SPDC. These advances have led to the required components now approaching relative technological maturity, opening the window towards engineering useful and scalable systems that exploit entanglement in order to improve optical imaging.
In this thesis, we show the development of a quantum imaging platform able to perform practical and fast spatially resolved multi-photon coincidence imaging with high SNR. Special focus is placed on wide-field entanglement-enhanced phase imaging capability, in order to extend experimental sensitivity beyond limits imposed by classical light. The main components of our platform are: sources of hyper-entangled photon pairs, a large field-of-view optical imaging system with phase measurement capabilities, and coincidence imaging using SPAD array cameras. More specifically, the thesis describes:

The first realization of a wide-field entanglement-enhanced phase imager. Wide-field here refers to the ability to acquire images across the entire field-of-view simultaneously (i.e. without need for pixel-to-pixel scanning, sometimes also called full-field). Quantum-enabled super-sensitivity in phase imaging beyond the capability of equivalent classical measurement is demonstrated by careful experimental noise and resource analysis methods. Our system's capabilities were tested through several sample measurements corresponding to use cases with real-world relevance, including nanometre-scale feature step heights in transparent material, biomedical protein microarrays, as well as birefringent phase samples.
The development of general experimental and numerical tools to calculate photon pair coincidence images and videos from SPAD array cameras, with photon-counting and time-tagging readout modalities, as well as the retrieval of phase images resulting from multi-photon entanglement interference, by adapting techniques from interferometry and holography. We performed also a detailed study and optimization of the influence of different experimental parameters resulting image quality factors.
The evolution and optimization of our system towards real-time quantum imaging capability. Acquisition speed is a key element of usefulness, and in this thesis we integrate, first, a visible-wavelength entangled photon source, and second, a novel time-tagging SPAD array camera. The resulting entanglement-enabled imager presents an improvement by at least four orders of magnitude in measurement speed compared to previous state-of-the-art demonstrations, resulting in the ability to record ?Hz frame rate entangled photon pair coincidence videos. We show that this system, besides phase imaging, has additional applications in the form of real-time entangled state fidelity monitoring, and real-time point spread function characterization of optical systems, which has important applicability to adaptive optical imaging.

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Thesis Director: Prof Dr. Valerio Pruneri

Hosted by: Prof. Dr. Valerio Pruneri