

Abstract

This thesis investigates some protocols within the framework of quantum optical imaging and explores new opportunities for quantum light generation through nanoscale processes using quantum optical metasurfaces. Quantum imaging, a well-established area within quantum technologies, seeks to surpass conventional measurement capabilities by exploiting quantum states of light. Novel imaging techniques have emerged in this domain, enabling image acquisition in scenarios previously unattainable by traditional methods.

After an introductory section covering the quantum optics fundamentals needed to comprehend the subsequent chapters, the first main section of this thesis delves into a novel approach to ghost imaging (GI). GI is a method that reconstructs an object's shape not through the direct acquisition of spatially resolved images, but by exploiting correlations between two spatially identical intensity beams. GI is particularly suitable in the presence of turbulent and scattering media, allowing it to reconstruct clear images even when environmental conditions distort conventional imaging, and even in presence of background noise. Additionally, it does not require a detector to be placed behind the object, making it suitable for situations where direct line-of-sight detection is not possible, and it can operate across a range of different wavelengths, extending its versatility to infrared and other spectral regions. The research conducted in this thesis expands the application of GI into new scenarios where the object's distance is unknown. By incorporating light-field information, this method enables post-refocusing acquisition and allows for 3D reconstructions. Though the current work uses classical thermal light, this concept can be extended to quantum light, even down to single-photon levels, unlocking in remote sensing and potential biomedical applications.

In the second part of the thesis I will focus on low-illumination imaging. In fact one of the key advantages of quantum imaging is its ability to capture high-quality images with very few photons, where the shot-noise limit would make classical imaging

impossible. This capability is crucial in biological studies, as high photon doses can damage sensitive samples, as demonstrated in optical tweezers and microscopy experiments. Moreover, many biophysical processes, such as photosynthesis, are activated by one or few photons. Sub-shot-noise imaging experiment successfully achieved wide-field imaging by exploiting intensity correlations between beams generated via spontaneous parametric down-conversion (SPDC). This technique reduced noise by subtracting one beam's intensity from the other, enabling sub-shot-noise imaging of low-absorption objects. Building on this work, the second part of the thesis focuses on non-interferometric quantum-enhanced quantitative phase imaging, extending sub-shot-noise protocols to phase samples, which are essential for imaging transparent materials like biological tissues. This non-interferometric method offers advantages such as stability, ease of implementation, and the ability to function with partially coherent light, paving the way for broader applications in biological microscopy.

In the third and final part of this thesis, I will investigate novel approaches for nanoscale generation of quantum light using quantum optical metasurfaces. Most modern quantum light sources rely on SPDC in bulk non-linear crystal, which, despite being a cornerstone of quantum optics, remains an inefficient and non-deterministic method for producing quantum light. Moreover, the requirement to satisfy both energy and momentum conservation laws (commonly referred to as the phase-matching condition) necessitates precise source design and restricts the range of two-photon states that can be generated. As technology progresses towards microscale and nanoscale optics, SPDC faces challenges in keeping up due to these limitations. Recent research has focused on generating quantum light via SPDC at the nanoscale, inspired by advances in nonlinear nanoscale optics and metasurfaces. At this scale, SPDC becomes independent of phase matching, allowing the use of materials with greater nonlinear susceptibility and enabling more efficient photon generation with tailored properties such as angular distribution and polarization. However, many fundamental questions regarding these nanoscale processes remain unanswered, and the third and final part of this thesis contributes to the field by developing simulations based on quasi-normal mode decomposition to predict and investigate new possibilities for generating and engineering the behavior of quantum light through nanoscale processes utilizing quantum optical metasurfaces.