PhD THESIS DEFENSE: Optical parameter sensing: sensitivity limits and the advantages of using spatial modes of light

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Resolution enhancement in modern optical metrology techniques has been possible due to significant technological improvements. The accurate and precise control of wavelength, bandwidth, and power of light sources; homogeneity, high-quality composition materials and surface smoothness of optical elements; and highly stable nanopositioners and optomechanical components, allow more sensitive imaging and sensing, in certain scenarios even beyond the standard diffraction limit. This has motivated a more detailed study of the fundamental resolution limitations of an optical system.
The chosen approach to address this problem is to consider optical imaging as a parameter

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estimation problem. With this in mind, the theory of quantum estimation and statistical inference provides the tools to determine the estimation precision limits. Starting by considering the state of light as a quantum state that carries information of interest; the Cramer-Rao lower bound provides a fundamental limit for the achievable precision. This lower bound is directly associated to optical resolution in practical terms.

In this thesis, we present an overview of the useful tools of quantum estimation theory that can be applied to optical metrology. We focus on the Cramer-Rao lower bound, and provide methods to calculate it. Since the bound depends on specific characteristics of the system, we explore three specific possibilities.

First we present with an example the validity regimes for different bounds; explicitly t calculate the parameters of entangled photon pairs in the frame of a quantum Lidar Syst m. Second, we show the dependency of the lower bound on the photonic model selecti n, showing a discrepancy between N copies of a single photon and a multimode coherent s ate with average photon numbe

N. two particular models. Third, we study the effects of lossy environments in the informati nal content of the quantum st

te. Additionally, we present the conditions that a measuring strategy must satisfy to a low attainability of the fundamental li

it. If the measurement strategy is not feasible or it is not possible to implement, one can evaluate the resolution improvement of the available technique by comparing to the standard and fundamental lim

ts. For specific scenarios of interest, measurement methods based on the use of spatial m des of light allow to asymptotically attain the resolution limit. This has drawn attention to the information carried by specific modes, and has motivated the design of measure ent strategies based on probing or sensing using spatial modes. In this thesis we includ an overview of spatial modes of light, their generation and detection, and their use for opt cal sensing. We present a method for optical beam localization in the transverse plane u ing spatial mode information. Moreover, we propose a technique to retrieve the full m dal decomposition of an arbitrary beam; which combined with the adequate set of modes al ows to estimate certain parameters of an optical state with the maximum precision possi

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