Congratulations to New ICFO PhD Graduate

Dr Arturo Villegas graduated with a thesis entitled ?Optical parameter sensing: sensitivity limits and the advantages of using spatial modes of light'

April 26, 2023

We congratulate Dr Arturo Villegas who defended his thesis today in ICFO's Homage Room. Dr Villegas obtained his MSc in Applied Physics from the Delft University of Technology. He joined the Quantum Engineering of Light research group at ICFO led by Prof Dr Juan P Torres as a PhD student. Dr Villega's thesis entitled ?Optical parameter sensing: sensitivity limits and the advantages of using spatial modes of light' was supervised by Prof Dr Juan P Torres.

ABSTRACT:

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 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 to calculate the parameters of entangled photon pairs in the frame of a quantum Lidar System. Second, we show the dependency of the lower bound on the photonic model selection, showing a discrepancy between N copies of a single photon and a multimode coherent state with average photon number N.

two particular models. Third, we study the effects of lossy environments in the informational content of the quantum state.

Additionally, we present the conditions that a measuring strategy must satisfy to allow attainability of the fundamental limit.

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 limits.

For specific scenarios of interest, measurement methods based on the use of spatial modes 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 measurement strategies based on probing or sensing using spatial modes. In this thesis we include an overview of spatial modes of light, their generation and detection, and their use for optical sensing. We present a method for optical beam localization in the transverse plane using spatial mode information. Moreover, we propose a technique to retrieve the full modal decomposition of an arbitrary beam; which combined with the adequate set of modes allows to estimate certain parameters of an optical state with the maximum precision possible.

Thesis Committee:

Dr. Pablo Loza, ICFO

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Thesis Committee