Quantum enhanced optical measurements

Original
Quantum enhanced optical measurements / Losero, Elena. - (2020 Feb 25), pp. 1-175.

Doctoral Dissertation
Doctoral Program in Metrology (32.nd cycle)

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Doctoral Examination Committee:
To be defined

Politecnico di Torino
October 31, 2019

Summary

Quantum mechanics was formulated in the first half of the last century. The development of this new theory leads to the rising of ground-breaking technologies as for example the laser and the transistor. These technologies could be understood and developed only thanks to quantum mechanics; they are based on bulk effects, where many quantum degrees of freedom are manipulated at once. We usually refer to them as product of a first quantum revolution. According to the European quantum technologies flagship program started in 2018 [1], we are now currently experiencing a second quantum revolution [2]. In fact, more and more technologies (usually named as quantum technologies) are being developed which manipulate individual quantum states to exploit their peculiar quantum properties, such as superposition and entanglement. Quantum communication [3, 4], quantum computation [5], quantum sensors [6] and metrology devices [7–11] are example of promising quantum technologies. This thesis will be mainly focused on the last technology mentioned: quantum metrology. There are different physical systems being investigated for its development, among them photons certainly have an important role [12]. Being optical measurements widespread in all the branches of science, from chemistry and biology to physics and material science, light appears to be a natural choice. According to this observation, we will focus on optical measurements. In general, aim of quantum metrology is to exploit quantum effects to achieve the ultimate quantum limit, i.e. the highest precision allowed by quantum mechanics laws [13, 14]. Typically, in order to increase the signal-to-noise ratio of a noisy measurements the classical approach consists in repeating N independent measurements and then averaging the measurement results. This approach allows to increase the sensitivity as $1/\sqrt{N}$, this scaling is known as standard quantum limit. If limited to classical resources, this limit cannot be beaten. Nonetheless, it is not fundamental, and quantum resources allows reducing the uncertainty below it, ideally down to the so called ultimate quantum limit. In real environments decoherence must be taken into account and necessarily prevents to attain the ultimate quantum limit, however several examples of quantum enhanced measurements, i.e. measurements whose uncertainty is below the ”classical” uncertainty, have been so far demonstrated. The first demonstrations were mainly conceived as proof of principle experiments, while nowadays more and more works try to fill the gap to move toward real applications [15].

In this thesis I discuss three examples of quantum enhanced optical measurements,

presenting in each case a theoretical model and the experimental results. The first experiment shows how using quantum states of light it is possible to increase the sensitivity in the estimation of the mean absorption coefficient of a sample. The second experiment consists in exploiting quantum resources for imaging, in particular a reconstruction imaging protocol known as ghost imaging, and some possible variations, are discussed and the performance in terms of signal-to-noise ratio compared to the classical strategies. In both these applications the quantum resource exploited is the non-classical correlation in the photon number between two beams in the so called multi-mode twin-beam state. The last example demonstrates how quantum states of light can enhance the sensitivity in correlated interferometry, i.e. in estimating the phase correlation between two interferometers. While quantum light is currently used in a single interferometer to enhance its sensitivity, being gravitational wave detectors a primary example [16], it is the first time that quantum light is applied to a double interferometric set-up. We perform two different experiments: in the first case squeezed states of light are exploited, in the second case twin-beam like state are used. The first scheme is an extension of the approach currently used in single interferometers, while the second approach has no analogous in conventional interferometry and, according to the theoretical work, could lead to unprecedented sensitivity. In all the cases, in order to pave the way toward real applications, the role of losses and other experimental imperfections is thoroughly discussed. At the same time, the conditions where quantum resources offer a substantial advantage over their classical counter part is highlighted.

Structure of the thesis

This thesis consists in five chapters:

- Ch. 1. In this chapter I give all the theoretical elements which are necessary for the subsequent chapters. In particular, some basic elements of quantum optics are reviewed and the main properties of the quantum states of light used in the subsequent works presented.

- Ch. 2. Here the quantum states of light used in the subsequent works are described under the experimental point of view. In particular, the experimental set-ups used for their generation are described and different characterization measurements reported.

- Ch. 3. This chapter is based on the published article [17]. Here, the advantages of photon-number quantum correlations in multi-mode twin-beam state for mean absorption estimation measurements are discussed. Different absorption estimators are compared from both the theoretical and the experimental sides. A best quantum advantage of (1.51 ± 0.02) is experimentally demonstrated.

- Ch. 4. This chapter is based on the article [18]. Here the photon-number quantum correlations in multi-mode twin-beam state are applied to different ghost imaging protocols. In particular, I extend to the quantum regime a protocol named differential ghost imaging and I propose an optimization of it, useful in presence of experimental imperfections. In order to pave the way to real applications, also the imaging of biological objects is considered.

- Ch. 5. This chapter is based on the article [19]. Here, the first feasibility test of quantum enhanced correlated interferometry is demonstrated. The advantages of two different quantum states of light are considered, both theoretically and experimentally. The experimental set-up, consisting in a system of two Michelson interferometers, has been built in Denmark, thanks to a collaboration with the Danish Technical University (DTU). I participated to the set-up realization and the data collection spending four months in the danish laboratories, in the group led by Ulrik Lund Andersen.

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