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Quantum Enhanced Non-Interferometric Quantitative Phase Imaging

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Abstract: We propose a technique which exploits entanglement to enhance quantitative phase retrieval of an object in a non-interferometric setting only measuring the propagated intensity pattern after interaction with the object

Introduction

Quantum optical sensing [1] has provided valuable advantages in different fields, from fundamental physics to biology and microscopy. In particular, quantum entanglement and squeezed light have been extensively studied to improve phase estimation and imaging beyond the classical limits. In quantum interferometry, different techniques were born, using the so-called NOON states or squeezed states both in linear- and non-linear interferometers. Although different proof of principles have been demonstrated, apart from some remarkable exceptions, quantum interferometry fails to provide quantum enhancement in multi-parameter wide-field mode, requiring raster scanning for extended samples. Other phase-imaging methods born in the quantum domain exploit second-order intensity correlation measurement, i.e. two-photon coincidence. Those methods require a large number of acquisitions and, although can improve resolution and mitigate external noise, they do not allow to beat the shot-noise-limit.

Here, we present a quantitative non-interferometric quantum-enhanced phase-imaging (NIQPI) scheme exploiting quantum correlations that do not belong to the aforementioned methods and allows real-time full-field phase retrieval measuring only the intensities of the phase effect on the free-propagating fields [2]. The NIQPI protocol exploits the scheme depicted in Fig. 1.

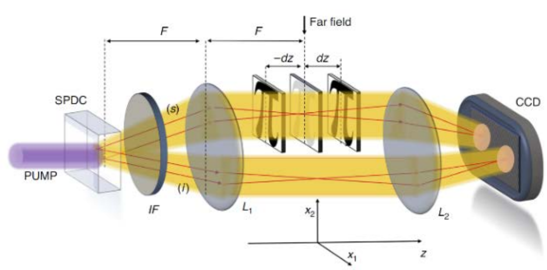

Fig.1. Scheme of the NIQPI (Images taken from [2])

Two quantum-correlated beams, usually called signal (s) and idler (i), are produced by spontaneous parametric down-conversion (SPDC). The two beams share the same spatial properties in the far field, even the shot noise fluctuation are identically reproduced, which is impossible in the classical domain. The signal beam interacts with a pure phase object and the far field is imaged into an efficient low noise CCD camera. Moving the object along the z-axis of propagation for two different 'defocused' positions $+dz$ and $-dz$ and measuring the two intensity patterns $I(\boldsymbol{x}, \pm dz)$ allows to retrieve the phase of the object $\Phi(\boldsymbol{x}, z=0)$ solving the transport of intensity equation (TIE) [3]:

$$-k\frac{\partial}{\partial z}I(\boldsymbol{x},z) = \nabla_{\boldsymbol{x}} \cdot [I(\boldsymbol{x},0)\nabla\phi(\boldsymbol{x},0)] \tag{1}$$

where the derivative is approximated by the finite difference of the two measurements out of focus and $I(\boldsymbol{x},0)$ is the far-field of the source. TIE is experimentally easy and computationally efficient and leads to a unique and quantitative wide-field image of the phase profile. However, the reconstruction obtained can be strongly affected by the shot noise if low illumination is used. Here, we show that the TIE can be combined with the well-established sub-shot-noise imaging protocol [4]. In fact, the information acquired by the image of the idler beam can be used to reduce the effect of shot noise on the signal beam, leading to an enhancement of the overall phase image reconstruction and reducing the uncertainty on the phase estimation.

Results

In our experiment, the number of photons per pixel is about $n \approx 10^3$ and a 'π'-shaped phase sample (thickness of about 65 nm etched on a glass slide, size 356 × 343 μm) is retrieved. In fig. 2 (a) the classical and quantum reconstructions for two different dz are reported, a clear advantage is visible in the quantum enhanced reconstruction confirmed by the Pearson correlation coefficient between reconstructed and reference images at different defocusing distances dz. The red curve corresponds to the reconstruction obtained by summing 100 intensity patterns, where the shot noise becomes negligible.

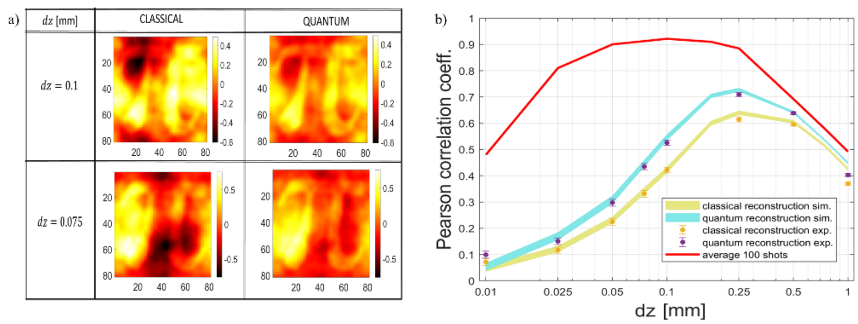

Fig. 2. Classical and quantum experimental reconstruction. (Images taken from [2])

In fig. 3 (a) the estimated value of the phase step is plotted at different defocusing distances while in fig. 3 (b) the uncertainty in the phase estimation for quantum and classical case demonstrates the quantum advantage.

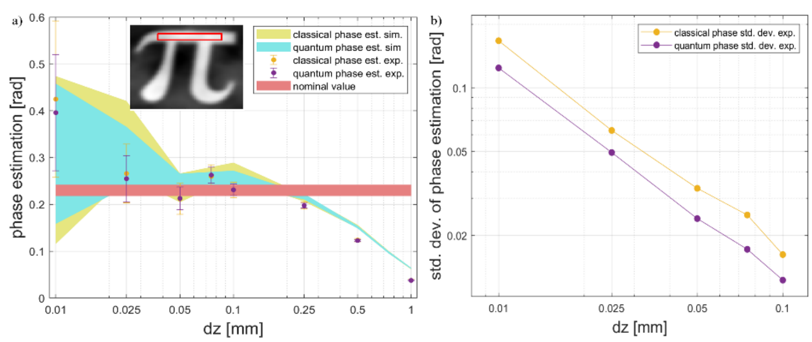

Fig. 3. Classical and quantum phase estimation. (Images taken from [2])

Conclusion

In this work we have demonstrated a genuine quantum enhancement in a non-interferometric phase imaging setup both in the discrimination of small details and in a clear reduction of the uncertainty in the quantitative phase estimation. This first proof of principle paves the way for applications at different wavelengths, e.g. X-ray or UV imaging, where reducing the photon dose is of utmost importance.

Reference

[1] Degen, C. L., Reinhard, F. & Cappellaro, P. Quantum sensing. Rev. Mod. Phys. 89, 035002 (2017).
[2] Ortolano, G., Paniate, A., et al. Quantum enhanced non-interferometric quantitative phase imaging. Light Sci Appl 12, 171 (2023).
[3] Teague, M. R. *Deterministic phase retrieval: a Green's function solution.* J. Opt. Soc. Am. **73**, 1434 (1983).
[4] Brida, G., Genovese, M. & Ruo Berchera, I. *Experimental realization of sub-shotnoise quantum imaging*. Nat. Photon. **4**, 227 (2010).