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Non-Interferometric Quantitative Phase Imaging Enhanced by Quantum Correlations

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Abstract: We exploit quantum correlations 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 entanglement and squeezing have been demonstrated to significantly improve phase estimation beyond the classical limits in both linear- and non-linear-interferometry at a fixed mean number of photons. However, quantum interferometric phase estimation usually fails to provide enhancement in full-field mode, requiring raster scanning for extended samples and system stability on the scale of a fraction of the light wavelength.
On the other hand, for a broad class of non-interferometric phase imaging methods vastly used in the classical domain, e.g. diffraction imaging, wave-front sensing, and differential contrast microscopy, a demonstration of quantum advantage has not been achieved till now.
Here, we present a non-interferometric quantum-enhanced phase-imaging (NIQPI) scheme that is quantitative and works in full-field mode and in real-time [1]. The quantum enhancement is obtained by removing the shot noise in the measured intensity distribution by exploiting a second quantum-correlated reference beam [2,3]. Our first experimental demonstration in the optical domain paves the way for applications at different wavelengths, e.g., X-ray or UV imaging, where reducing the photon dose is of utmost importance.

Methods

The NIQPI protocol exploits the scheme depicted in Fig. 1. 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 of the source; even the shot noise fluctuation is 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 and low-noise CCD camera.

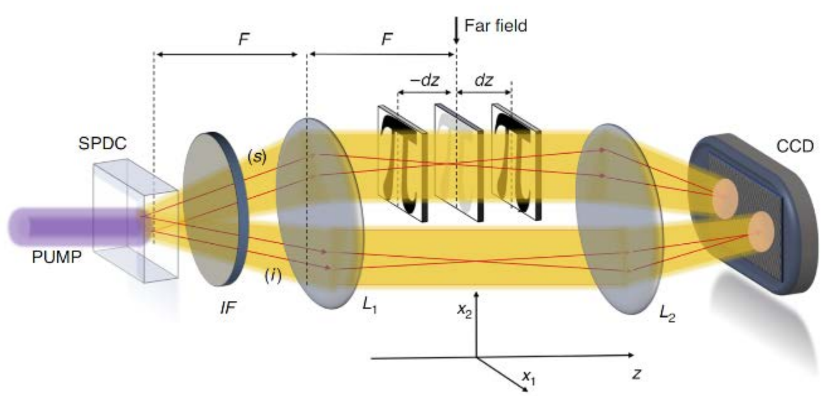

Fig.1. Scheme of the NIQPI (Image taken from [1])

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 so-called transport of intensity equation (TIE) [4]:

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

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 to implement and computationally efficient and leads to a unique and quantitative wide-field image of the phase profile. Note that TIE works also with partial coherent light, thus it is perfectly compatible with multimode emission from travelling wave SPDC. The reconstruction obtained in the single branch can be strongly affected by the shot noise if low illumination is used. However, the noise can be separately measured in the idler beam and subtracted. Removing the shot-noise from the defocused intensity images leads to an enhancement of the overall phase image reconstruction and a reduction of 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 estimated value of the phase step is plotted at different defocusing distances. The phase value is calculated by averaging the reconstructed images in the area represented by the red rectangle (see the inset in fig. 2 (a)). For a suitable range of defocusing distances, namely up to *dz* =0.2, the TIE is able to recover correctly the true value of the phase, represented by the red line. The experimental uncertainty bars are also in agreement with the 1-sigma confidence band obtained by the simulation. In fig. 2 (b) the standard deviation in the phase estimation for quantum and classical case demonstrates a quantum advantage up to a 40%.

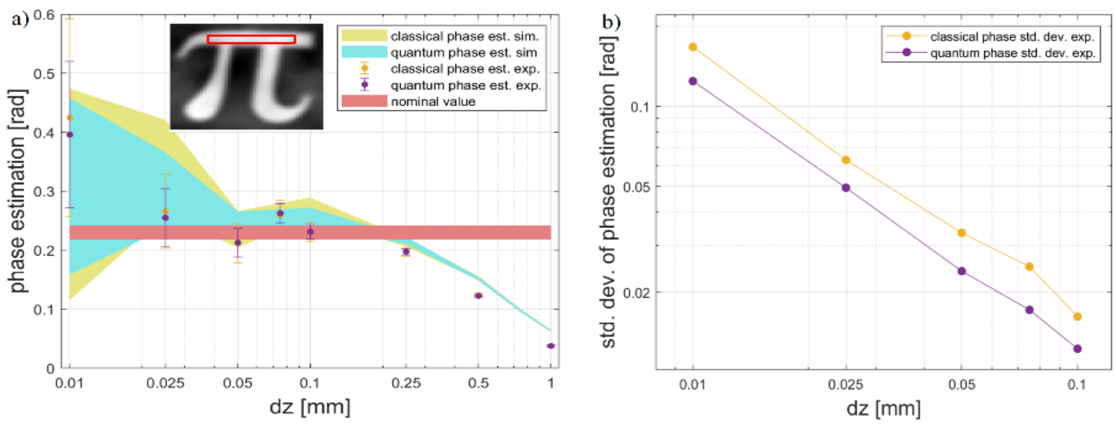

Fig. 2. Classical and quantum phase estimation. (Images taken from [1])

Reference

[1] Ortolano, G., Paniate, A., Boucher, P. et al. *Quantum enhanced non-interferometric quantitative phase imaging*. Light Sci Appl **12**, 171 (2023).
[2] Brida, G., Genovese, M. & Ruo Berchera, I. *Experimental realization of sub-shot-noise quantum imaging*. Nat. Photon. **4**, 227 (2010).
[3] Samantaray, N., Ruo-Berchera, I., Meda, A. et al. *Realization of the first sub-shot-noise wide field microscope*. Light Sci Appl **6**, e17005 (2017).
[4] Teague, M. R. *Deterministic phase retrieval: a Green's function solution*. J. Opt. Soc. Am. **73**, 1434 (1983).