Restoring quantum enhancement in realistic two-photon interferometry

Michał Jachura,[1,*] Radosław Chrapkiewicz, Rafał Demkowicz-Dobrzański, Wojciech Wasilewski, and Konrad Banaszek
[1]*Faculty of Physics, University of Warsaw, ul. Pasteura 5 02-093 Warsaw, Poland*

Quantum mechanics holds the promise to enhance the precision of interferometric measurements below the shot-noise limit through the use of collective states of many probes (e.g. photons or atoms) and joint detection exploiting multiparticle interference effects [1]. However, imperfections in the modal structure of probes, such as photons feeding an interferometer, could severely undermine precision and ultimately prevent beating the standard limit.

In the canonical example of a two-photon Mach-Zehnder interferometer, residual spectral distinguishability of interfering photons has a dramatically deleterious effect on the precision of local phase estimation which becomes divergent around the operating point around $\theta_0 = \pi/2$ when the photons coalesce in pairs at the interferometer outputs. However, recent advances in single-photon imaging offer now unprecedented opportunities to gather detailed information about a specific degree of freedom such as position. Here we present a proof-of-principle experiment which reveals that by controlling carefully the spatial structure of interfering photons and extracting complete spatial information at the detection stage it is possible to achieve sub-shot-noise precision in operating regimes that otherwise cannot even attain shot-noise limit.

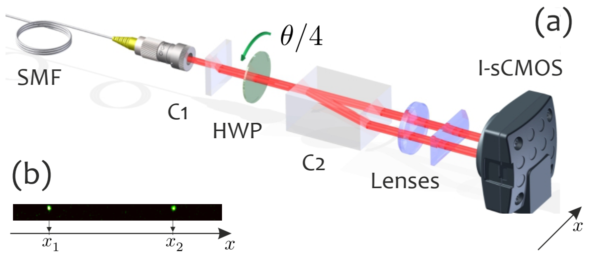

FIG. 1. (a) Detection part of the experimental setup. (b) A registered two-photon event with the retrieved transverse coordinates.

In our experiment, shown in Fig. 1(a), we generate pairs of photons in a type-II SPDC process and filter them through a single-mode fiber which defines two orthogonally polarized modes corresponding to the input ports of the interferometer. The interferometer transformation is implemented in a common-path configuration as a half-wave-plate followed by a calcite crystal C2. Its output surface is imaged onto a single-photon-sensitive camera system [2] providing information about positions x_1, x_2 of detected photons for each registered coincidence event as illustrated in Fig. 1(b). In Fig. 2(a) we show the joint spatial probability distribution $p(x_1, x_2)$ of coincidence events for three phase-shifts $\Delta\theta$ centered around θ_0 when input modes fully overlap and detected counts are mainly due to the residual distinguishability of pairs. Alternatively, we partly separate in space the input modes using an additional calcite (C1). As shown in Fig. 2(b), the phase-sensivity is restored, manifesting itself in the asymmetry of coincidence patterns with respect to the diagonal $x_1 = x_2$.

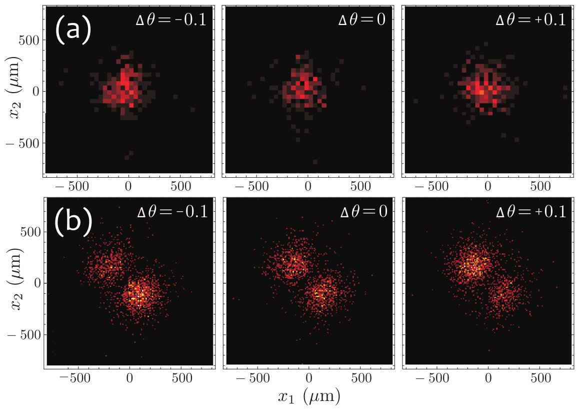

FIG. 2. (a) Coincidence probabilities $p(x_1, x_2|\theta)$ measured for spatially overlapping modes where counts are mainly due to the residual spectral distinguishability. (b) When the input modes are partly separated in space the phase-sensitivity is restored.

We performed phase estimation including available spatial information and characterized its precision for each phase shift $\Delta\theta = -0.1, 0, +0.1$ by dividing collected data into approx. 600 subsets of 10 detection events each, and applying a locally-unbiased estimator to individual data subsets. Results presented in Tab. 1 clearly indicate that sub-shot noise performance has been successfully restored, revealing the benefits of manipulating the modal structure of interfering photons in realistic metrologic scenarios.

Phase shift $\Delta\theta$	Relative estimation uncertainty ϵ	$\delta\epsilon$
−0.1	0.9567	0.028
0	0.9126	0.026
+0.1	0.9465	0.027

TABLE I. Relative uncertainty of the phase estimation $\epsilon = 1$ defined with respect to the shot-noise limit. The Heisenberg limit corresponds to $\epsilon = 1/\sqrt{2} \approx 0.7071$. Without spatial information $\epsilon \to \infty$ at $\Delta\theta = 0$.

---

[*] michal.jachura@fuw.edu.pl

[1] R. Demkowicz-Dobrzański, M. Jarzyna, and J. Kołodyński, "Quantum limits in optical interferometry", arXiv:1405.7703
[2] R. Chrapkiewicz, W. Wasilewski, and K. Banaszek, "High-fidelity spatially resolved multiphoton counting for quantum imaging applications", Opt. Lett. 39, 5090 (2014).