Restoring sub-shot noise phase sensitivity in a realistic two-photon interferometry

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Abstract: We demonstrate experimentally that a careful design of the spatial structure of interfered photons, combined with position-resolved coincidence detection, allows to recover sub-shot-noise phase sensitivity in regime that otherwise cannot even attain the shot-noise limit.

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Quantum mechanics holds a promise to enhance the precision in interferometry and metrology beyond the shot-noise limit, usually achieved by preparing collective states of multiple probes (e.g. photons, atoms) and implementing joint detection that exploits multiparticle interference effects. Unfortunately the imperfections in the modal structure of probes, such as spectral visibility of photons sent to an interferometer, could severely reduce its phase-sensivity and ultimately preclude beating the classical limits. In particular, in the canonical example of a balanced Mach-Zehnder interferometer [1] the 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 $\theta = \pi/2$ when the photons coalesce pairwise. However, recent advances in single-photon detection schemes offer now unprecedented opportunities to gather detailed information about each individual degree of freedom such as position or momentum. 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 nevertheless possible to achieve sub-shot-noise precision in the operating regimes that otherwise cannot even attain shot-noise limit.

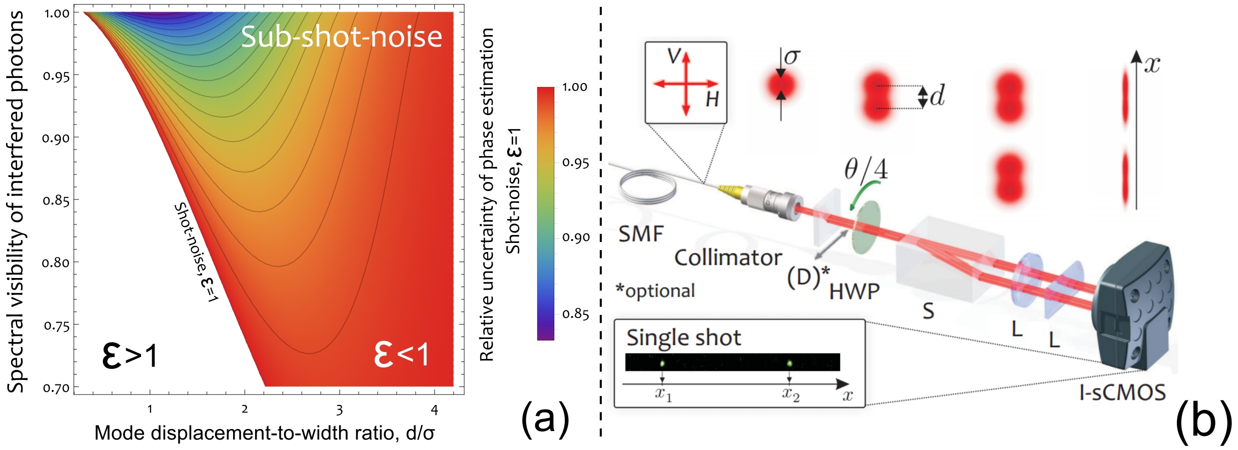

Fig. 1. (a) Numerically calculated relative uncertainty of phase estimation with respect to the shot-noise assuming full access to the spatial information about detected photons. (b) Detection part of the experimental setup along with interfered photons spatial modes cross-sections at its consecutive stages.

In our experiment we generate a pairs of photons via type-II SPDC process and filter them by a single-mode fiber which defines two orthogonally polarized modes corresponding to the input ports of the interferometer presented in

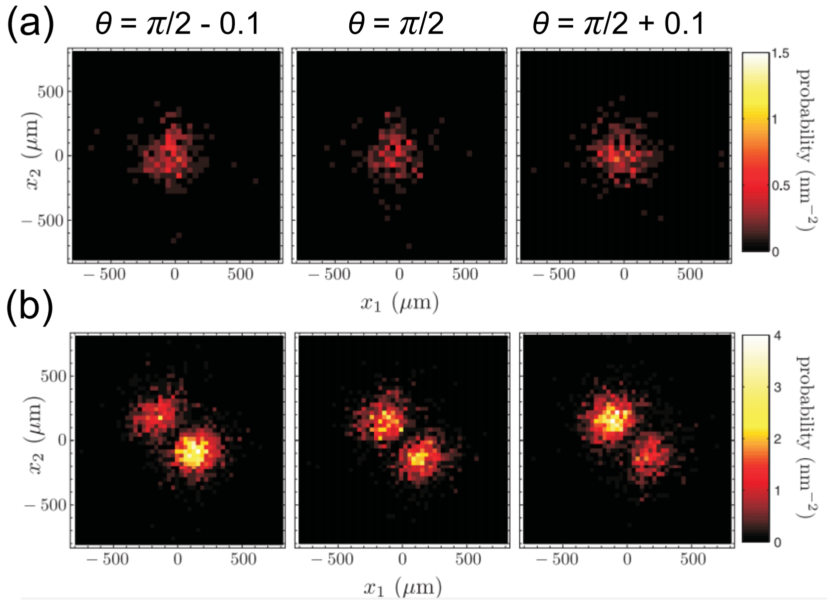

Fig. 2. Coincidence probabilities $p(x_1,x_2|\theta)$ measured for spatially overlapping modes where counts are mainly due to the non-perfect spectral indistinguishability (a). When the input modes are partially separated in space the sub-shot noise phase-sensivity is restored (b).

Fig.1 (a). The interferometer transformation is implemented in a common-path configuration as a half-wave-plate followed by a calcite crystal (S), whose rear surface is imaged onto the single-photon-sensitive I-sCMOS camera system [2] which provides the information about coordinates x_1,x_2 of detected photons for each registered coincidence event as presented schematically in Fig.1 (b). In Fig.2 (a) we show the spatial probability distribution $p(x_1,x_2)$ of the coincidence events for three phase-shift values θ centered around $\pi/2$ when input modes fully overlap and detected counts are mainly due to the residual distinguishability of pairs.

In the next step we spatially separate the input modes using the additional calcite (D) and the phase-sensivity revival manifests itself in the assymetry of obtained coincidence patterns with respect to the diagonal $x_1 = x_2$, as shown in Fig.2 (b). Exploiting the spatial information we performed the phase estimation and checked its quality for each phase shift, by dividing the gathered data into approximately 600 subsets of 10 detection events each, and applying the locally-unbiased estimator to all data subsets.

Phase shift	Relative uncertainty of estimation ε	$\delta\varepsilon$
$\pi/2-0.1$	0.9567	0.028
$\pi/2$	0.9126	0.026
$\pi/2+0.1$	0.9465	0.027

Table 1. Relative uncertainty of the phase estimation. Shot-noise limit $\varepsilon = 1$. Heisenberg limit $\varepsilon = 0.707$. Estimation lacking the spatial information $\varepsilon \to \infty$.

The results presented in Tab.1, clearly show that sub-shot noise performance has been successfully restored, revealing the potential of the manipulation of interfering photons modal structure in the realistic-scenario metrological applications.

References

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