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Seeing clearly with entangled biphotons

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Abstract

Position-correlated biphoton Shack-Hartmann wavefront sensing is proposed and experimentally demonstrated. Based on this approach, the biphoton correlation propagating through phase turbulence can be measured and corrected, thus enabling adaptive quantum imaging against phase disturbances with only a single-shot measurement.

Keywords: Quantum imaging, Entanglement, Adaptive optics

Entangled photons are a cornerstone of quantum information science, enabling secure communication, enhanced sensing, and novel imaging approaches. Among their many applications, quantum imaging[1–4] is particularly notable for its ability to utilize the spatial correlations of photon pairs to achieve effects that classical optics cannot. Well-known examples include ghost imaging[5], imaging with undetected photons[6], and interaction-free imaging[7–9], all of which rely on the peculiar correlations between entangled photons to extract information about objects in unconventional ways. These techniques support applications ranging from fundamental quantum tests[10] to low-light biological imaging[11,12] and pattern recognition[13,14]. However, a persistent challenge remains: phase aberrations introduced by atmospheric turbulence or imperfections in optical elements degrade image quality in quantum imaging systems.

In the classical setting, adaptive optics provides a powerful remedy for wavefront correction. A representative example is Shack-Hartmann wavefront sensing[15], in which a microlens array measures phase distortions induced by turbulence or optical imperfections, enabling their subsequent correction using spatial light modulators or deformable mirrors. Sensorless approaches[16] utilize the zero-frequency component of the beam as a feedback metric to optimize the correction phase until this component reaches its maximum.

In quantum imaging, efforts to counteract phase distortions in entangled photons have included biphoton holography using polarization entanglement[17] or a reference beam[18], as well as strategies that use classical light to infer aberrations by leveraging the consistency between the propagation of the pump beam and the entangled biphoton correlations[19,20]. Researchers have also explored adapting classical adaptive optics to the realm of quantum imaging[21,22]. A particularly creative approach was demonstrated by Cameron *et al.*, who used the sharpness of the biphoton centroid distribution at the Fourier plane as the metric for phase correction, thereby realizing label-free adaptive quantum imaging[23].

Recently, Yi Zheng *et al.* conducted a new study to introduce an elegant solution: a position-correlated biphoton Shack-Hartmann wavefront sensor (PCB-SHWS)[24]. As illustrated in Fig. 1, this technique achieves single-shot measurement of the phase gradients experienced by position-correlated entangled photon pairs as they traverse turbulence. A compensating phase is then applied via a spatial light modulator to correct phase gradients induced by imperfect optics or turbulent media, enabling clear quantum imaging even under adverse conditions. This development is significant for two

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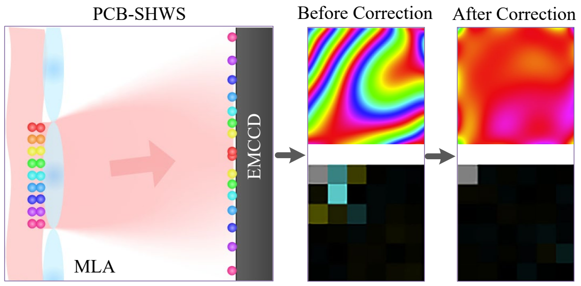

Fig. 1 Schematics of the proposed PCB-SHWS for quantum adaptive imaging. (Left) Schematic of turbulence phase measurement. Owing to phase aberrations, entangled photon pairs (represented by spheres) passing through a microlens array (MLA) exhibit centroid deviations, which are recorded by an electron-multiplying charge-coupled device (EMCCD) camera. The phase gradient is then retrieved from the recorded photon distribution. (Middle) Measured phase gradient of a plastic film. (Right) Phase aberrations induced by the film are compensated. Measured images reproduced from Ref. 24.

reasons. First, it brings a cornerstone tool of classical adaptive optics, the Shack-Hartmann sensor, into the quantum domain, bridging conceptual and technical gaps. Second, by enabling direct and efficient phase measurement of entangled photons, it paves the way for robust quantum imaging systems capable of operating in realistic, aberration-prone environments.

From biomedical microscopy to free-space quantum communication, the capability to maintain clear imaging with entangled photons in the presence of phase disturbances may accelerate the transition of quantum imaging from laboratory demonstrations to practical applications. This work illustrates a broader trend in quantum technologies: adapting classical techniques in ways that respect and leverage unique quantum resources. In the future, as researchers continue to refine tools such as the PCB-SHWS, the prospect of practical, high-resolution, and noise-resilient quantum imaging will increasingly come into focus.

Data availability

All data are available from the corresponding authors upon reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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References

1. Moreau, P. A. et al. Imaging with quantum states of light. *Nature Reviews Physics* **1**, 367-380 (2019).
2. Defienne, H. et al. Advances in quantum imaging. *Nature Photonics* **18**, 1024-1036 (2024).
3. Altmann, Y. et al. Quantum-inspired computational imaging. *Science* **361**, eaat2298 (2018).
4. Li, P. M. et al. Ghost imaging, development, and recent advances [invited]. *Chinese Optics Letters* **22**, 112701 (2024).
5. Pittman, T. B. et al. Optical imaging by means of two-photon quantum entanglement. *Physical Review A* **52**, R3429-R3432 (1995).
6. Lemos, G. B. et al. Quantum imaging with undetected photons. *Nature* **512**, 409-412 (2014).
7. Bornman, N. et al. Ghost imaging using entanglement-swapped photons. *npj Quantum Information* **5**, 63 (2019).
8. Qiu, X. D., Guo, H. X. & Chen, L. X. Remote transport of high-dimensional orbital angular momentum states and ghost images via spatial-mode-engineered frequency conversion. *Nature Communications* **14**, 8244 (2023).
9. Sephton, B. et al. Quantum transport of high-dimensional spatial information with a nonlinear detector. *Nature communications* **14**, 8243 (2023).
10. Moreau, P. A. et al. Imaging Bell-type nonlocal behavior. *Science Advances* **5**, eaaw2563 (2019).
11. Morris, P. A. et al. Imaging with a small number of photons. *Nature Communications* **6**, 5913 (2015).
12. Zhang, Y. D. et al. Quantum imaging of biological organisms through spatial and polarization entanglement. *Science Advances* **10**, eadk1495 (2024).
13. Qiu, X. D. et al. Structured-pump-enabled quantum pattern recognition. *Physical Review Letters* **122**, 123901 (2019).
14. Malik, M. et al. Quantum ghost image identification with correlated photon pairs. *Physical Review Letters* **104**, 163602 (2010).
15. Platt, B. C. & Shack, R. History and principles of Shack-Hartmann wavefront sensing. *Journal of Refractive Surgery* **17**, S573-S577 (2001).
16. Booth, M. J. Wave front sensor-less adaptive optics: a model-based approach using sphere packings. *Optics Express* **14**, 1339-1352 (2006).
17. Defienne, H. et al. Polarization entanglement-enabled quantum holography. *Nature Physics* **17**, 591-597 (2021).
18. Zia, D. et al. Interferometric imaging of amplitude and phase of spatial biphoton states. *Nature Photonics* **17**, 1009-1016 (2023).
19. Lib, O., Hasson, G. & Bromberg, Y. Real-time shaping of entangled photons by classical control and feedback. *Science Advances* **6**, eabb6298 (2020).
20. Vernière, C. & Defienne, H. Hiding images in quantum correlations. *Physical Review Letters* **133**, 093601 (2024).
21. Defienne, H., Reichert, M. & Fleischer, J. W. Adaptive quantum optics with spatially entangled photon pairs. *Physical Review Letters* **121**, 233601 (2018).
22. Zheng, Y. et al. Characterizing biphoton spatial wave function dynamics with quantum wavefront sensing. *Physical Review Letters* **133**, 033602 (2024).
23. Cameron, P. et al. Adaptive optical imaging with entangled photons. *Science* **383**, 1142-1148 (2024).
24. Zheng, Y. et al. Position-correlated biphoton wavefront sensing for quantum adaptive imaging. *Light: Science & Applications* **14**, 311 (2025).