Observation of the quantum Gouy phase
Markus Hiekkaamäki1, Rafael F. Barros1, Marco Ornigotti1, and Robert Fickler1
1. Tampere University, Photonics Laboratory, Physics Unit, Tampere, FI-33720, Finland

Photonic N00N states, i.e., states of light where N photons are in an extremal superposition between two orthogonal states \( \frac{1}{\sqrt{2}} (|N, 0\rangle + |0, N\rangle) \), have increased phase-sensitivity in comparison to their classical counterparts. Using the sensitivity offered by N00N states, in conjunction with the intrinsic properties of transverse-spatial modes, enables new measurement schemes with sensitivities beyond the classically allowed limits and opens up possibilities to investigate the behaviour of different quantum states.

In the present study, we create transverse-spatial N00N states, in a single beam path, by bunching two photons into a superposition of two orthogonal transverse-spatial modes [1]. This is done by preparing the two-photons in a specific pair of two orthogonal superpositions, before bringing them into the same path, allowing the two photons to interfere and produce the wanted state [2]. Since we use these N00N states to investigate the quantum Gouy phase, or the Gouy phase acquired by photon number states, we choose two radial modes with different mode orders as our pair of modes and investigate their propagation through a focus [3].

In Fig. 1 a) we show the difference in behaviour between a classical superposition of radial modes and a corresponding N00N state. Fig.1 b) shows experimental data and theoretical fits verifying the expected behaviour.

In this work, we first theoretically derived the expected phase accumulation that photon number states experience during propagation [1]. We then experimentally demonstrated the predicted speed-up in Gouy phase accumulation and showed that the increased phase sensitivity of photon number states does extend to the Gouy phase as well. Our results also provided a few more insights, such as a nice corollary to Feng and Winful’s proposition on the origin of the Gouy phase [5] by further linking the speeding up of the quantum Gouy phase to an increasing spread in the transverse momentum of the state. We were able to additionally demonstrate, by investigating the related quantum Fisher information, that these results open up the possibility for supersensitive measurements of longitudinal displacement, with a single beam. The final thing our results highlighted was that the so-called photonic de Broglie wavelength is not sufficient for describing the behaviour of photon number states [6].

Our results demonstrate that through simple quantum interference experiments, we can study fundamental properties of light such as the Gouy phase of photon number states. With such a measurement scheme, we were able to gain a lot of insight about the behaviour of photons. We were additionally able to show an example of how engineering the quantum state and transverse-spatial profile of a set of photons could lead to quantum enhanced measurement precisions.

References
[1] M. Hiekkaamäki and R. Fickler, “High-Dimensional Two-Photon Interference Effects in Spatial Modes,” Phys. Rev. Lett. 126, 123601 (2021).
[2] M. Hiekkaamäki, F. Bouchard, and R. Fickler, “Photonic Angular Superresolution Using Twisted N00N States,” Phys. Rev. Lett. 127, 263601 (2021).
[3] M. Hiekkaamäki, R. F. Barros, M. Ornigotti, and R. Fickler, “Observation of the quantum Gouy phase,” Nat. Phot. 16, 828–833 (2022).
[4] E. Polino, M. Valeri, N. Spagnolo, and F. Sciarrino, “Photonic quantum metrology,” AVS Quantum Sci. 2, 024703 (2020).
[5] S. Feng and H. G. Winful, “Physical origin of the Gouy phase shift,” Opt. Lett. 26, 485-487 (2001).
[6] X. Gu and M. Krenn, “Phase anomaly brings quantum implications,” Nat. Photon. 16, 815–817 (2022).