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Achieving the ultimate optical resolution

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Abstract. The accurate estimation of the separation between two signals is at the core of many modern technologies. We show new quantum-inspired schemes able to estimate that separation at the quantum limit. The method works in the spatial, temporal, and frequency domains. The question of whether the optical coherence brings any metrological advantage to mode projections is discussed.

In optics, when attempting to find the separations s between two incoherent emitters, the standard way of proceeding is to take a full image and extract the single parameter s from it. In such scenarios, the smallest precisely measurable separation is limited by the point-spread function (PSF), with a vanishingly small amount of information available for smaller and smaller separations, especially when photon shot noise is the dominant noise source (as in, for example, astronomical observations).

This limit is usually formalized in terms of the Fisher information, which quantifies the amount of information accessible per photon detection and is directly associated with the time-honored Cramér-Rao lower bound. For direct intensity imaging, the Fisher information drops to zero for separations smaller than the spread of the optical field, sometimes referred to as the Rayleigh curse, which limits the usefulness of photon counting for metrology.

Surprisingly, when one calculates the quantum Fisher information [1, 2] (i.e., optimised over all the possible quantum measurements), the associated quantum Cramér-Rao lower bound maintains a fairly constant value for any separation of the sources. This shows the potential for parameter estimation of distributions with precision unaffected by Rayleigh's curse. The key behind these techniques is phase-sensitive measurement in mode bases other than intensity [3].

In this work, we extend these techniques and show how mode-selective measurements can be utilised to estimate separations well below the spread of the source light [4]. These quantum-inspired measurements are capable of estimating the separation accurately in a regime where intensity-only measurements would be ineffective.

We implement these ideas in the temporal domain by performing spectrotemporal mode-selective measurements through the quantum pulse gate (QPG), a sum-frequency generation process in a group-velocity engineered waveguide. By shaping the strong QPG pump pulse and measuring the upconverted photon, the QPG implements a projective measurement onto the spectrotemporal mode defined by the QPG pump [5]. For Gaussian pulses, the optimal measurement is the Hermite-Gaussian basis. Measuring only the first two Hermite-Gauss modes allows us to estimate the sub-bandwidth spectral separation between two incoherently mixed pulses, well below the Cramé-Rao lower bound for conventional intensity detection.

Furthermore, we go beyond single-parameter and show how our technique can be used for simultaneous multiparameter estimation of the centroid, the separation, and the relative intensities of two incoherent sources [6, 7], in both frequency and time. This is possible by performing optimal detection, in this case, extending our projective measurements to higher-order Hermite-Gauss modes and their superpositions. By outperforming standard intensity-only detection, our quantum multiparameter estimation scheme can bring benefit to many practical scenarios.

The discussion thus far assumes incoherence between the signals. This conforms with the conditions underlying Rayleigh's criterion. However, a recent heated debate addressed the role of coherence in the resolution limits [8–11], with diverging conclusions.

We show here that coherence by itself does not provide a direct metrological advantage; incoherent superpositions set the ultimate limits in all cases [12]. However, we stress that coherence can be exploited as an information sorter, distributing information about different parameters into different channels.

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