Quantum-limited spectrotemporal measurement through mode-selective sum-frequency generation

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It is often useful to reframe imaging problems in the context of parameter estimation. For example, when attempting to find the distance separations δ between two incoherent emitters, it is standard practice to take a full image and extract the single parameter δ from it. In these scenarios, the smallest precisely measurable separation is limited by the point-spread function on the image plane, with a vanishingly small amount of information available for smaller and smaller separations. This behaviour, known as Rayleigh's curse in diffraction-limited imaging contexts, has recently been shown to not apply when considering all possible measurements through the quantum Cramér-Rao bound [1]. Through phase-sensitive measurements, it is possible to estimate arbitrarily small separations. For Gaussian point-spread functions, this can be accomplished optimally through projective measurements onto the Hermite-Gauss basis, with the vast majority of the available information contained in the first two Hermite-Gauss modes for small separations [2]. While there have been multiple experimental results confirming these predictions, they have thus far been limited to spatial imaging problems. As the mathematical descriptions of the spatial-momentum and time-frequency properties of light have near-exact analogies to one another, it is natural to ask whether these same methods can be transferred to other domains.

In this work, we extend these techniques to the spectral and temporal domain and identify analogous advantages. We find that, even for frequency or time shifts smaller than the bandwidth or temporal width of the optical pulses measured, mode-selective measurements are capable of estimating the separation accurately in a regime where spectral or temporal intensity measurements would be ineffective. We implement spectrotemporal mode-selective measurements through the quantum pulse gate (QPG), a sum-frequency generation process in a group-velocity engineered waveguide, as sketched in Fig. 1a. 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 [3]. Measuring only the first two Hermite-Gauss modes allows us to estimate the sub-bandwidth spectral separation between two incoherently mixed pulses, as seen experimentally in Fig. 1b. This same technique is applicable to ultrashort temporal separations, and can be extended to larger parameter estimation problems or non-Gaussian point-spread functions through higher-order projective measurements and alternative bases.

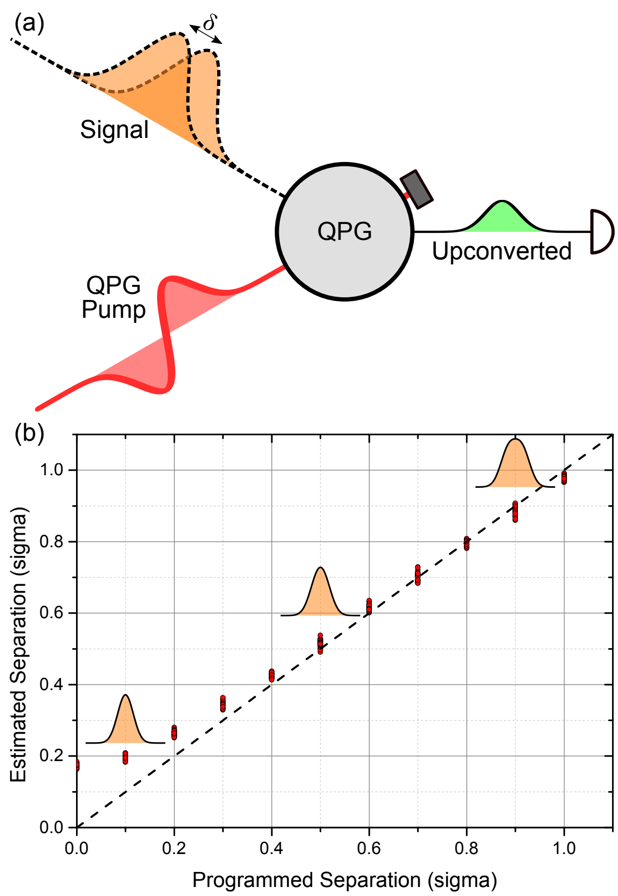

Figure 1: (a) In the experiment, an incoherent mixture of two pulses with a spectral or temporal separation of δ is measured with a quantum pulse gate (QPG), a nonlinear process mediated by a shaped pump pulse. The upconverted output power is equivalent to a projective measurement onto the spectrotemporal mode defined by the pump and, for the proper measurements, can be used to infer the parameter δ. (b) Experimental data for incoherent mixtures of spectral bins, separated by fractions of a standard deviation, with 40 data points per setting. The mode-selective measurement is capable of detecting spectral shifts even when hidden in intensity measurements, as seen with the inset curves depicting separations of 0.1 σ, 0.5 σ, and 0.9 σ. The 1540 nm pulses have a spectral intensity standard deviation of $\sigma = 190$ GHz. The reduced accuracy for shifts on the order of $\sigma/10$ can be attributed to the limits of QPG mode-selectivity [3].

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