Spectral phase coherence in HOM interferometry

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Abstract: We examine the role of spectral phase in Hong-Ou-Mandel interference by comparing interferograms for pure and mixed states. We find that HOM interference cannot be taken as a signature of coherent frequency superpositions.

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Hong-Ou-Mandel (HOM) interference [1] is a ubiquitous form of two-photon quantum interferometry and an important tool in quantum optics. However, the information conveyed by HOM is not widely understood. Features in HOM traces have been taken as evidence of entanglement [2, 3] or the presence of phase-coherent frequency-bin pairs [4]. We study the impact of spectral phase coherence in the case of biphoton frequency combs (BFCs), which are rapidly growing in interest as a platform for quantum information processing, focusing in particular on periodic HOM revivals and their relationship to biphoton phase coherence across comb line pairs.

Figure 1(a) is an illustration of our HOM interferometer. Time-energy entangled photons are generated by type-II spontaneous parametric down-conversion (SPDC) in a fiber-pigtailed, periodically poled lithium niobate ridge waveguide (PPLN; HCPhotonics) with a quantum efficiency of $\sim 10^{-7}$. The PPLN is pumped with light from a tunable, continuous-wave laser (CW laser; New Focus). The orthogonally polarized signal and idler photons are separated using a fiber polarizing beam splitter (PBS). Downstream of the fiber PBS are pairs of collimators and longpass filters for rejecting residual pump light. One arm of the HOM interferometer includes a pulse shaper (Finisar), while the other includes manual (coarse; DL1) and motorized (fine; DL2) delay lines. The pulse shaper is used to modify the amplitude of the BFC spectrum. Although the pulse shaper acts on only one of the photons, this is sufficient for producing comb-like correlations in the joint biphoton spectrum; coincidence measurements effectively postselect only photons with energy-matched frequencies in the other arm. The photons are then recombined using a fiber-based polarization-maintaining 50:50 coupler. The output of the 50:50 coupler is routed to two superconducting nanowire single-photon detectors (SNSPDs) and a time interval analyzer, which logs photon arrival times and extracts coincidences.

The pump wavelength (779.79 nm) was chosen to ensure degenerate signal/idler emission, confirmed by minimizing the coincidences at matched delay without any filtering applied. The ensuing spectrum was determined by recording singles counts after opening successive 18 GHz bins in the pulse shaper [see Fig. 1(b)]. The full HOM interference trace was recorded as delay in the interferometer was scanned over a 40 ps range [see Fig. 1(c)]. The triangular shape matches theory for a sinc-shaped biphoton spectrum, and the high visibility (97.8%) confirms both frequency degeneracy and interferometer stability within the correlation time of the photons.

To determine the role of phase coherence between comb pairs in HOM, we examine two-photon interference for pure and mixed frequency-bin entangled states, created by carving the continuous SPDC spectrum using the pulse shaper. The inset of Fig. 1(b) provides an illustration of three 30 GHz-wide (FWHM) Gaussian filters (green dashed;

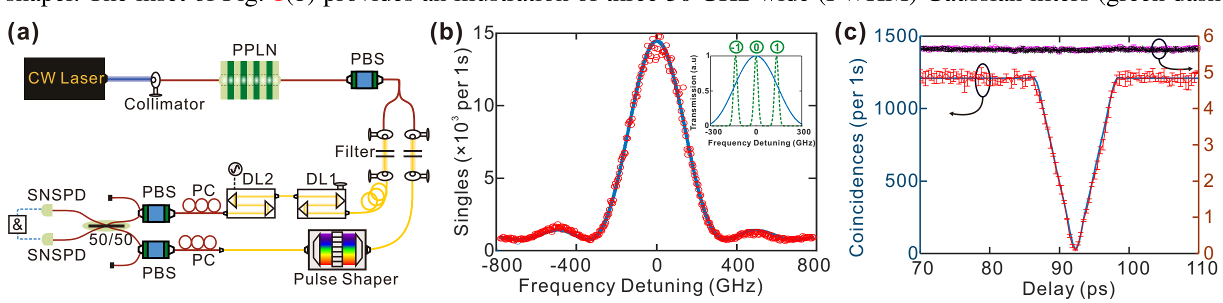

Fig. 1. (a) Experimental setup. (b) SPDC spectrum and position of frequency bins (inset). (c) HOM trace confirming spectral indistinguishability ($V = 97.8\%$). (Red: five 1-s measurements. Blue: theoretical prediction, scaled and vertically offset to match the data points via linear least squares.)

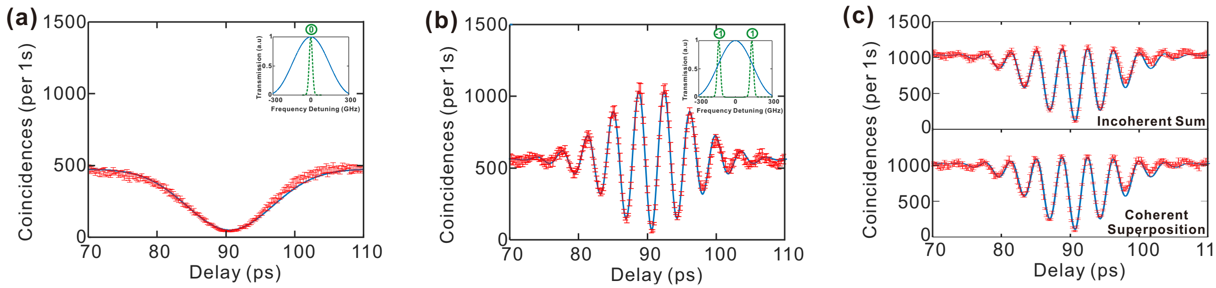

Fig. 2. HOM interference traces for states (a) $|\Psi_0\rangle$ and (b) $|\Psi_1\rangle$. (c) The incoherent sum of two traces in (a) and (b), and HOM trace for pure state $|\Psi_0\rangle + |\Psi_1\rangle$. (Red and blue: see Fig. 1 caption.)

bins -1, 0, and 1) spaced 90 GHz apart. The location of these bins relative to the SPDC spectrum (blue solid) is also shown. A filter response that passes only bin 0 projects the biphoton onto state $|\Psi_0\rangle = \int d\Omega\, \phi(\Omega) f_0(\Omega)\, |\Omega, -\Omega\rangle_{SI}$, where $\phi(\Omega)$ is the initial complex broadband spectrum (as a function of signal frequency offset Ω) and $f_0(\Omega)$ is the lineshape function for bin 0. Likewise, a filter response that passes bins -1 and 1 projects the biphoton onto $|\Psi_1\rangle = \int d\Omega\, \phi(\Omega) [f_{-1}(\Omega) + f_1(\Omega)]\, |\Omega, -\Omega\rangle_{SI}$, where the lineshape functions are centered on their respective bins. (Dispersion was found to be negligible over these bandwidths, so all spectra are taken as real to good approximation.)

HOM traces were generated for both states by scanning the motorized delay line over a 40 ps range and recording the coincidences at each delay increment. The results are presented (without background subtraction) in Fig. 2(a) and (b). The interference trace for the incoherent (mixed) state ($\hat{\rho} \propto |\Psi_0\rangle\langle\Psi_0| + |\Psi_1\rangle\langle\Psi_1|$) is simply given by the sum of the individual HOM interference traces in (a) and (b) [Fig. 2(c), top]. The pure state $|\Psi_0\rangle + |\Psi_1\rangle$ was carved from the SPDC spectrum by passing all bins through the pulse shaper. The measured HOM interference trace for the coherent superposition is shown in Fig. 2(c) (bottom). The near-perfect agreement between the HOM traces suggests that no conclusion can be drawn about phase coherence across comb-line pairs from this measurement.

At first glance, this result may seem counterintuitive—particularly given the narrow temporal features observed, which necessitate involvement of the full biphoton bandwidth—but it proves fully consistent with established HOM theory [5]. In general, the biphoton state consists of contributions from distinct frequency pairs; this occurs by nature with CW pumping or, as additionally emphasized here, through discrete frequency-bin pairs, e.g., $|\Psi_0\rangle$ (a "collapsed" pair with zero separation) and $|\Psi_1\rangle$. These pairs are spectrally distinct, and because all operations required for HOM interference (beamsplitter, filtering, delay) preserve frequency content, the measurement results corresponding to different pairs are in principle distinguishable; their results add incoherently, regardless of whether the underlying states are mutually coherent at the input. On the other hand, the phase relation *within* a single frequency-correlated pair does matter, for it is impossible, even in principle, to tell whether a coincidence corresponding to a specific pair of frequencies occurs from both photons being reflected or transmitted—a phase difference between these possibilities is precisely what produces HOM interference. To appropriate Dirac's famous statement, then, we can say, "In HOM, each *frequency pair* then interferes only with itself. Interference between two different *frequency pairs* never occurs."

Finally, this result can be understood as another example of a recurring theme in ultrafast optics, quantum or classical: slow detectors are insensitive to spectral phase [6]. Thus, in order to adequately probe biphoton phase coherence, either fast timing resolution [7] or active frequency mixing [8] should be employed. In this way, HOM—while insightful, powerful, and ubiquitious—must never be mistaken for the final word in biphoton phase coherence.

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