Classical analogues of two-photon quantum interference

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Chirped-pulse interferometry (CPI) captures the metrological advantages of quantum Hong-Ou-Mandel (HOM) interferometry in a completely classical system. Modified HOM interferometers are the basis for a number of seminal quantum interference effects. Here, the corresponding modifications to CPI allow for the first observation of classical analogues to the HOM peak and quantum beating. They also allow a new classical technique for generating phase super-resolution exhibiting a coherence length dramatically longer than that of the laser light, analogous to increased two-photon coherence lengths in entangled states.

Quantum-optics experiments demonstrated a wide range of interference phenomena that had never before been seen in classical systems. Prominent examples include: automatic dispersion and aberration cancellation [1, 2, 3], phase-insensitive interference [4], nonlocal interference [5, 6], ghost imaging [7] & ghost diffraction [8], phase super-resolution [9, 10, 11], and phase super-sensitivity [12, 13, 14, 15]. Some of these phenomena form the basis for applications in quantum computing and metrology that promise to outperform their classical counterparts in terms of speed and precision, respectively. Recently, ghost imaging [16, 17], automatic dispersion cancellation [18, 19, 20], phase super-resolution [21], and phase insensitive interference [19] have been observed in classical optical systems exploiting correlation, but not entanglement. Chirped-pulse interferometry (CPI) [19] is a new, completely classical technique producing the same interferogram as a Hong-Ou-Mandel (HOM) interferometer [4] based on frequency-entangled photon pairs, but with vastly higher signal. It has been shown that modifications to the HOM interferometer can produce a wide array of quantum interference effects such as the HOM peak [22], quantum beating [23, 24], and phase super-resolution [9]. In the present work, we show how similar modifications to CPI can produce the analogous interferometric signatures with only classical resources. Thus we rule out the HOM peak and quantum beating signatures as uniquely quantum and demonstrate phase super-resolution in a classical context with important differences from previous work [21].

Hong-Ou-Mandel interference [4] is ubiquitous in optical quantum information processing, underlying such effects as quantum teleportation [25, 26] and linear-optics quantum computation [27]. It occurs when two photons are coherently combined on a beamsplitter, and manifests as a dip in the coincidence rate of two detectors. A typical HOM interferometer, apart from the bandpass filters, is depicted in Fig. 1b) (upper). HOM interference with frequency-entangled photons exhibits automatic dispersion cancellation, phase insensitivity and robustness against loss, rendering it a promising tool for quantum metrology and imaging [1, 25, 29]. We have recently demonstrated chirped-pulse interferometry [19], a completely classical technique that exhibits all of these important features of HOM interference. This classical approach can be viewed as a time-reversed version of the HOM interferometer [21], see Fig. 1b) (middle). Instead of down-converting a narrow frequency photon and detecting photons with anticorrelated frequencies, we prepare light with anticorrelated frequencies and detect a narrow frequency band. The CPI setup can be seen in Fig. 1b) (bottom) where a pair of oppositely-chirped laser pulses enter into a cross-correlator. A narrow bandwidth of the output sum-frequency generation (SFG) is detected on a standard photodiode as a function of the time delay, $\Delta \tau$. We have shown that CPI can be used in place of HOM interference to obtain the same benefits of quantum-optical coherence tomography [28] with dramatically larger signal and a straightforward means of control over intrinsic signal artifacts [20].

Several quantum-interference effects are based on modifications of the HOM interferometer, such as the three shown in Figs. 1a)-(c) (upper). In Fig. 1a) photon pairs are detected in one output. The photon bunching leading to the HOM dip gives rise to phase-insensitive constructive interference, a HOM peak, in the coincidence rate of these detectors [22]. In Fig. 1b) bandpass filters centered at different wavelengths are placed before the detectors. The coincidence rate in this device exhibits phase-sensitive interference, but at a wavelength that depends on the frequency difference of the filters [23, 24]. The wavelength of the interference, referred to as quantum beating, can be much longer than the wavelength of the light. In Fig. 1c) the output of the HOM is fed into a Mach-Zehnder interferometer. The output of the first interferometer can be approximated by a two-photon NOON state, $|\psi\rangle \sim |2\rangle |0\rangle + |0\rangle |2\rangle$, which exhibits phase super-resolution (PSR), manifesting as a wavelength of interference two times shorter than that of the light passing through the interferometer.

For the experimental realization of classical analogues of these three quantum effects, we use a modelocked
tisapphire laser (centre wavelength 790 nm, pulse duration 100 fs FWHM, average power 2.8 W, repetition rate 80 MHz) as the light source. The beam is split at a 50:50 beam splitter. Its two outputs pass through a grating-based stretcher [30] and compressor [31] to generate chirped pulses approximately 54 ps long and anti-chirped pulses 48 ps long (FWHM), respectively. The difference in pulse durations is due to slightly different bandwidths rather than different chirp rates. Because the stretcher and the compressor are aligned to generate an equal but opposite chirp rate, at any given time the sum of the instantaneous frequencies of the two pulses is constant. For more details, see [19].

Fig. 1(b)(lower) shows the basic CPI setup. The horizontally-polarized chirped and antichirped beams are combined at a 50:50 beam splitter. From there the outputs travel along two different spatial paths, one of which contains an adjustable path delay. The polarization in one of the paths is rotated to vertical by a half-wave plate. This allows the recombination of the beams into a single spatial mode, but with orthogonal polarizations, at a polarizing beam splitter. That mode is focused onto a 0.5 mm thick type-II phase-matched β-Barium Borate crystal for SFG. High-pass filters separate the SFG from the fundamental signal. A narrow bandwidth of the SFG is filtered using gratings and a slit and is detected using an amplified Si photodiode (Thorlabs PDA36A).

The HOM peak can be observed in the quantum interferometer shown in Fig. 1(a) (upper). Time-reversing this setup requires combining the oppositely-chirped laser pulses at a beamsplitter before the input to the cross-correlator as shown in Fig. 1(b) (middle). Fig. 1(a) shows the resulting interferogram as a function of delay. The path length was varied in the delay arm of the cross-correlator by moving a motor with a constant velocity of 0.500 ± 0.005 mm/s. Simultaneously, data was acquired with a sample rate of 12 kHz. The gratings and the slit were adjusted to filter the SFG with a bandwidth of 0.4 nm FWHM around the center wavelength 395.2 ± 0.1 nm. The sole feature in the interferogram is a phase-insensitive constructive interference peak with visibility 76 ± 2%. In Ref. [32] it was shown that an absorber that removes a narrow portion of the spectrum near the centre frequency $\omega_0$ in front of the single-photon detectors leads to a reduced coincidence rate close to the HOM peak. This feature can be interpreted as enhanced absorption through a photon exchange effect. In our experiment, we achieve an analogous signal by blocking a 2.0 ± 0.3 nm band of the spectrum at the centre frequency by placing an Allen key in the beam inside the stretcher. Fig. 2(a) is the resulting interferogram clearly showing the appearance of two dips for delay positions just outside the peak.

Quantum beating was originally observed in the quantum interferometer shown in Fig. 1(a) (upper) [22]. This is a standard HOM interferometer where interference filters with different bandpasses are placed in front of the detectors after the interferometer. Time-reversing this setup requires filtering different bandwidths of the chirped and anti-chirped beams before the interferometer. We inserted razor blades into the stretcher and compressor to block spectral components of the light. The measured spectra for two different positions of the razor blades are shown in Figs. 3(b) and d). We measured the SFG signal as a function of delay by moving a motor in the delay path in steps of 3 μm. Note that in this configuration we used a stepper motor and took data at discrete positions, whereas for the other data we moved the motor and took data continuously. This accounts for the qualitative difference between the appearance of these data sets and the others. The SFG signal was detected within a bandwidth of 0.3 ± 0.1 nm FWHM around 394.5 ± 0.1 nm.

The resulting CPI interferograms as functions of path delay are shown in Figs. 3(a) and c). Both signals clearly exhibit interference fringes but with periods much larger than the wavelength of the light. This is the same charac-
FIG. 2: Phase-insensitive constructive interference in CPI. The system was set up as depicted in Fig. 1a) (bottom) as the time-reversed version of the two-photon interferometer in Fig. 1a) (top). In b) the configuration was the same as in a) except that we blocked $2.0 \pm 0.3$ nm near the centre wavelength of the chirped pulses in the stretcher. Both plots show the measured photodiode signal as a function of delay. The data in a) shows a phase-insensitive interference peak with visibility $76\pm2\%$ and FWHM $42\pm2\mu$m. The data in b) shows a peak with similar visibility and width, but with two new features where the signal drops at $\pm 50\pm 4\mu$m by $20\pm 1\%$ of the plateau signal level.

A characteristic feature that was observed in the quantum beating experiment [23, 24]. For Figs. 3a) and c) the difference frequency, as determined by the peaks of the spectra, between chirp and anti-chirp is $17 \pm 1$ ps$^{-1}$ and $45 \pm 1$ ps$^{-1}$, respectively. From these difference frequencies, we expect the corresponding fringe spacings to be $111 \pm 7$ $\mu$m and $42 \pm 1$ $\mu$m. Both are in good agreement with the measured fringe spacings, $115 \pm 15$ $\mu$m and $40 \pm 2$ $\mu$m, and much larger than either the wavelength of the SFG, $0.395$ $\mu$m, or the chirped pulses, $0.790$ $\mu$m.

Two-photon phase super-resolution can be observed in the interferometer shown in Fig. 1c) (upper). The output of a balanced HOM interferometer is fed into a Mach-Zehnder interferometer. HOM interference causes photon pairs to bunch together, creating number-path entangled states. These exhibit interference fringes, as measured in the coincidence rate of the detectors, at half the classical period. For the time-reversed version, one could employ a spatial encoding as depicted in Fig. 1c) (middle). However, we used an equivalent transformation on the polarization degree of freedom by simply inserting a half-wave plate, oriented at $22.5^\circ$, before the SFG as shown in Fig. 1c) (bottom).

Figs. 4c) & d) show the results of a continuous scan of the SFG signal over the path delay in the cross-correlator. For comparison, Figs. 4a) & b) show a white-light interferogram taken by replacing the half-wave plate with a polarizer at $45^\circ$ and measuring the fundamental light with a fast photodiode (Thorlabs DET100A). In both cases, the path delay was continuously scanned by moving a motor with a velocity of $0.500 \pm 0.005$ mm/s while the signal was recorded with a sample rate of 250 kHz. The SFG signal was detected within a bandwidth of $0.09$ nm FWHM around $394.9 \pm 0.1$ nm. The entire data set took 7 s to accumulate with a resolution of about 100 points per fringe. The fringes in Figs. 4a) & c) have $87.1\pm0.2\%$ and $84.5\pm0.5\%$ visibility, respectively.

One can clearly see that the CPI fringe period, $395 \pm 4$ nm, is half that of the white light, $795 \pm 8$ nm, demonstrating phase super-resolution. The PSR signal in Fig. 4b) is centered around $-500\mu$m to show it free of residual white-light interference due to imperfect alignment. Comparing Figs. 4b) & c) we see another characteristic in our classical system often associated with quantum interference. The coherence length for the white-light interference pattern is $635\pm0.3\mu$m FWHM, in good agreement with expectations from the bandwidth of the chirped pulse of $10$ nm FWHM at $790$ nm. The width of the PSR interferogram, on the other hand, is approximately $5$ mm FWHM, a factor of 80 larger. Under ideal conditions, perfect mode overlap, matching chirp rates and bandwidths, and assuming Gaussian spectra, the width of the interferogram is calculated to be $19$ mm,
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FIG. 4: White-light interference pattern and phase super-resolution in CPI. a) & b) shows the white-light interference pattern generated by the chirped pulse. c) & d) show the SFG signal detected in the modified CPI depicted in Fig. 1c) (lower). By comparing b) & d) one can clearly see the reduction of the fringe wavelength in CPI; this is phase super-resolution. In addition, by comparing the signals in a) & c), we see that the CPI coherence length is roughly 80 times longer than the white-light coherence length.

Phase super-resolution has previously been shown in a multiport classical interferometer in the coincidence rate between a set of photon counters [21]. The CPI approach demonstrated here is different in two important ways. It does not rely on single-photon detection facilitating rapid data accumulation. Furthermore, it is the first observation of a classical analogue to dramatically different one-photon and two-photon coherence lengths that have been reported in entangled quantum systems [33, 34].

We have shown classical analogues to three archetypical quantum interference effects by making modifications to chirped-pulse interferometry. This work demonstrates the first observation of classical analogue of the Hong-Ou-Mandel peak and quantum beating. We have also demonstrated a new method for observing phase super-resolution in a classical interferometer suitable for rapid data acquisition and exhibiting a coherence length much longer than that of the laser light. These results constitute a step toward answering a central question in quantum information science as to which phenomena require quantum resources and which can be achieved classically.

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