Frontiers in Optics / Laser Science © Optica Publishing Group 2021

Quantum-Enhanced Interferometry Via Extreme Non-Degenerate Energy-Entangled Photons

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Abstract: We perform two-photon interference with highly non-degenerate frequency-entangled photons. Our system improves on existing interferometers by promising attosecond temporal resolution while offering robustness against dispersion, background, and loss.

1. Introduction

Optical interferometry is a key technology for many precision measurements. Typical implementations commonly employ "classical" interference, where an electromagnetic wave (or a single photon at the quantum level) travels in a superposition of two optical paths and interferes with itself on a 50:50 beamsplitter. The interference results in sinusoidal fringes that may be used to deduce phase (along with path and time delays). However, the measurement resolution (as determined by the fringe visibility) is reduced when dispersive media or unbalanced loss is present in one of the paths, or in the presence of optical background noise on the detectors.

An alternative interference effect is two-photon, or Hong-Ou-Mandel (HOM), interference [1]. In HOM interference two photons, one in each path, combine on a 50:50 beamsplitter. Due to complete destructive interference between the two processes in which the photons exit the beamsplitter in separate modes, indistinguishable pairs of photons will exhibit a "bunching" effect and exit together in the same beamsplitter output mode. By monitoring the coincidence rate between the two beamsplitter outputs while scanning through the photons' relative time-of-arrival, one will observe a dip in the coincidences when the photons are simultaneously incident on the beamsplitter. HOM interference offers several advantages over classical interference, including immunity to odd orders of group velocity dispersion [2] as well as robustness against optical background and unbalanced loss, which preserves the dip contrast even as the coincidence rate is reduced. However, these advantages are offset by the requirement of large-bandwidth photons to achieve high measurement resolution; generating such photons is non-trivial. While the resolution limitation can be addressed by measuring with an increased number of photons[1], such an approach is ill-suited for contexts where the measurement time needs to be minimized, e.g., when analyzing a time-varying delay.

The need to maximize the information gain per photon has led to a recently demonstrated solution utilizing frequency-entangled photon pairs [4]. If the photons are in the state

$$\frac{1}{\sqrt{2}}\left(|\omega_1\rangle_a|\omega_2\rangle_b+|\omega_2\rangle_a|\omega_1\rangle_b\right), \tag{1}$$

where a and b refer to the two input modes to the beamsplitter, then the coincidence probability is given by

$$P_c=\frac{1}{2}\left(1-\cos\left((\omega_1-\omega_2)\,\tau\right)e^{-2\sigma^2\tau^2}\right), \tag{2}$$

where τ is the relative delay between the photons and σ is the half-bandwidth of the frequencies ω_1 and ω_2. Unlike conventional HOM and its resolution dependence on the photons' bandwidth, here the dependence is dominated by the *detuning* between the two frequency modes. A first demonstration of this approach in [4] achieved a detuning of only a few tens of THz (tens of nanometers), limiting the attainable resolution to 0.64 femtoseconds (190 nm) over 10^4 trials. The performance of this technique can be greatly improved by utilizing highly non-degenerate entangled photon sources via spontaneous parametric down-conversion (SPDC), such as those developed by our group [5; 6], with which a detuning exceeding 1000 THz is achievable.

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[1] Few-attosecond resolution has been demonstrated with 10^9 photon pairs [3].

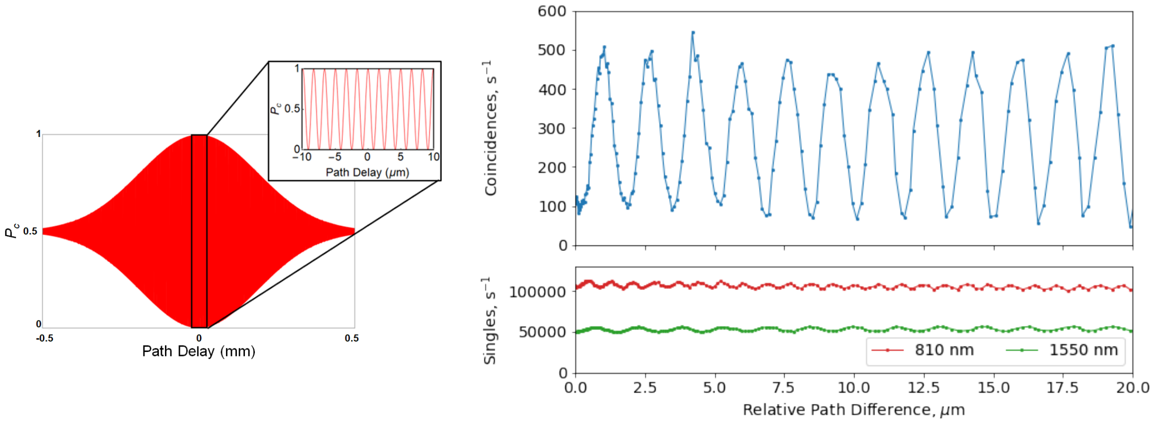

Fig. 1: *Left:* Theoretical fringes in the coincidence probability P_c as a function of relative path delay for a frequency-entangled photon pair with a detuning of 1110 THz. The overall envelope shows the coincidence dip obtained via conventional HOM interference; the increase in resolution afforded by frequency entanglement comes from the dense sinusoidal fringes within the dip as shown in the inset. *Right:* Preliminary data showing the expected two-photon interference while scanning through the relative lengths of the two paths leading to the interfering beamsplitter. An accidentals-corrected fringe visibility of $\sim 75\%$ is observed. The singles rates remain largely flat with only residual interference fringes visible, in contrast to the expected result for classical interference.

2. The Experiment

We convert our highly non-degenerate polarization-entangled photon pairs to the state (1), where $\omega_1 = 2,325$ THz (810 nm) and $\omega_2 = 1,215$ THz (1550 nm), i.e., a 1110 THz detuning. We made our interferometer compatible with both the 810- and 1550-nm wavelengths by using broadband optics (e.g., uncoated gold mirrors) and custom dual-band optics (e.g., beamsplitter). We have successfully observed the expected two-photon interference fringes in the coincidences between 810-nm photons at one of the beamsplitter outputs and 1550-nm photons at the other (Fig. 1). The system performance is currently being characterized and improved; theoretical modeling indicates a maximum attainable time resolution of <10 attoseconds (nanometer-scale path difference) for only 10^4 photon pairs, an improvement of ~ 2 orders of magnitude compared to [4].

3. Conclusion

The significantly enhanced performance of our interferometer compared to previous work will make possible quantum metrology via two-photon interference at the attosecond (nanometer) scale without needing ultra-broadband sources and with only 10^4 photon pairs. By combining high resolution with the HOM interference advantages of robustness against dispersion, optical background, and loss, our system enables metrological applications in regimes inaccessible to state-of-the-art classical interferometers, including investigating the topography of dispersive or lossy materials and conducting high-precision "stealth" long-distance ranging.

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