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Attosecond Quantum Metrology via Highly Non-Degenerate Frequency-Entangled Photons

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Abstract: We have demonstrated highly non-degenerate frequency-entangled two-photon interference. A timing resolution of 7.3 attoseconds was observed with only 24,000 coincidence detections. Our system enables fast, single-photon-level nanometer-scale measurements with loss, background, and dispersion tolerance.

1. Introduction

Two-photon interference is useful for various quantum metrology applications. Also known as Hong-Ou-Mandel interference [1], this effect is distinct from classical interference in that two photons mix on a 50:50 beamsplitter, as opposed to a single electromagnetic field (or a single photon) in a superposition state. When the photons are completely indistinguishable, destructive interference arises between the processes that lead to the photons exiting the beamsplitter in separate modes. As a result, the photons will bunch together and always exit the beamsplitter from the same port. By monitoring the coincidence rate between the two output modes while introducing distinguishability — typically by varying the photons' relative time of arrival — one will observe a dip in the coincidences when the photons reach the beamsplitter simultaneously. Unlike classical interference, the dip visibility is immune against odd orders of group velocity dispersion [2], optical background, and imbalanced loss between the two input modes, all advantages with significant utility in precision metrology.

A drawback of two-photon interference, however, is that achieving high resolution requires large-bandwidth photons. In practice, these are challenging to produce and manipulate. While increasing the number of coincidence detections via a longer integration time has been demonstrated to improve the resolution [3], this strategy precludes the fast measurements necessary for tasks such as studying time-varying signals or live samples. Recently, another solution was demonstrated in which the two interfering photons are frequency-entangled in the following state [4]:

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

Here, a and b refer to the two beamsplitter input modes. The presence of entanglement introduces a beat note between the two frequencies such that the coincidence probability acquires a sinusoidal factor with a frequency proportional to the photons' detuning $\omega_1-\omega_2$, introducing interference fringes within the Hong-Ou-Mandel dip:

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

Here, τ is the relative delay between the photons and σ is the half-bandwidth of the frequencies ω_1 and ω_2. Consequently, when the frequency detuning is large, high resolution is attainable even with a small σ. This measurement scheme is also optimal in that it saturates the quantum Cramér-Rao bound.

2. Experiment

We have built upon the concept demonstrated by [4] by utilizing a highly non-degenerate entanglement source [5]. Our source produces polarization-entangled photons at 810 nm and 1550 nm; a polarizing beamsplitter converts this state to the frequency entangled state (1) with a detuning of $2\pi*177$ THz (compared to $2\pi*5$ THz in [4]). We have constructed a dual-wavelength free-space interferometer compatible with both 810-nm and 1550-nm light. We have also implemented an improved detection system compared to [4]. Instead of a single detector at each output of the interfering beamsplitter, each output mode has a dichroic mirror that separates the two wavelengths for individual detection. This enables the direct measurement of both bunching (when both photons exit in the same port) and anti-bunching (when each photon exits in separate ports) effects while scanning through the beat note interference fringes. Measuring both types of events doubles the data collection rate and reduces calibration complexity compared to measuring only bunching with a two-detector system.

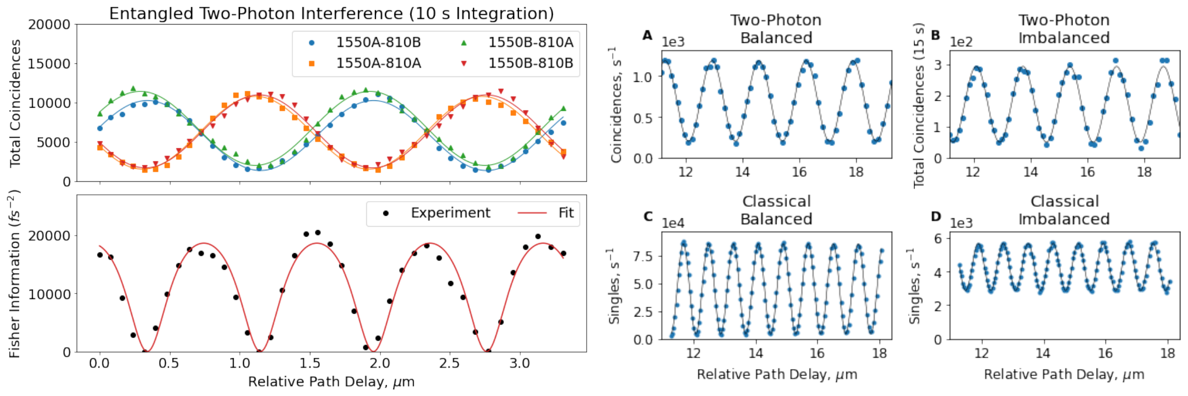

Fig. 1: *Left:* Experimentally observed beat note between interfering frequency-entangled photons as a function of relative path delay between the two beamsplitter input modes (denoted A and B). The corresponding Fisher information is also shown, with the theoretical curves derived from the beat note sinusoidal fits. Peak information (and resolution) occurs when the beat note slopes are at their steepest. *Right:* Experimental demonstration of the robustness of our system against imbalanced loss. Introducing loss to one of the input modes does not affect the two-photon interference fringe visibility (A and B) while the classical visibility is degraded (C and D).

3. Results

We measured four pairs of coincidences (two bunching and two anti-bunching) while scanning through the two photons' relative time of arrival by varying the relative path delay between the beamsplitter input modes with a tiltable 1-mm thick glass window. The beat note was observed (Fig. 1), with an average fringe visibility of $74.0 \pm 1.7\%$ obtained from sinusoidal fitting. By calculating the Fisher information from the detected coincidences, we estimate our measurement resolution to be 7.3 attoseconds (with a theoretical maximum of 5.8 attoseconds) with only 24,000 coincidence detections (10 s integration time). Our result illustrates the benefit of large detuning; the resolution in [4] is limited to 640 as with 10^4 detected coincidences by their $2\pi * 5$ THz detuning. Our result also highlights the efficiency of the entangled approach; to achieve attosecond resolution with conventional two-photon interference, [3] required more than 10^{11} photon pairs collected over a timescale of hours.

We also observed the robustness of two-photon interference against imbalanced loss between the two beamsplitter input modes. Neutral density filters inserted in each input achieved a $\sim 70\%$ ($\sim 40\%$) relative transmission reduction for 810 nm (1550 nm). Fig. 1 shows both two-photon and classical interference fringes obtained with and without the imbalanced loss. The two-photon visibility remains unchanged ($\sim 71\%$), albeit with a reduced coincidence rate, while the classical visibility drops from $\sim 90\%$ to $\sim 33\%$.

4. Conclusion

We have demonstrated two-photon interference between highly non-degenerate frequency-entangled photon pairs ($2\pi * 177$ THz detuning). With 24,000 coincidence detections, a maximum measurement resolution of 7.3 attoseconds is achieved. Our system enables rapid, loss-tolerant measurements on the nanometer scale at the single-photon level. Work is ongoing to study robustness against dispersion and optical background, along with improving the resolution and measurement rate with a high-brightness source producing higher quality entangled states.

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