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Toward Vibration Measurement via Frequency-Entangled Two-Photon Interferometry

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ABSTRACT

We present progress toward measuring nanometer-scale vibrations via a frequency-entangled two-photon interferometer. Unlike classical interference, two-photon – or Hong-Ou-Mandel – interference allows for optical metrology with resilience against imbalanced loss, dispersion, and optical background. However, the resolution of traditional degenerate frequency two-photon interference is limited by the photons' bandwidths, requiring large bandwidths or long integration times to achieve nanometer-scale resolution. We have implemented a two-photon interferometer utilizing highly non-degenerate frequency-entangled photon pairs at 810 nm and 1550 nm, drastically increasing measurement sensitivity while retaining the advantages of two-photon interference. This enhancement comes via a beat note with frequency proportional to the photon detuning of 177 THz. The resulting measurement saturates the quantum Cramér-Rao bound, maximizing the information extracted per photon. We have demonstrated a measurement resolution of 2.3 nm with fewer than 18,000 detected photon pairs, orders of magnitude better than previous results. By reflecting one photon from the pair off a target surface, we may use our system to study small-scale vibrations.

Keywords: Frequency entanglement, precision sensing, two-photon interference

1. INTRODUCTION

Many high-resolution imaging techniques used today rely on classical interferometry, including gravitational-wave detection, long-baseline astronomy, and optical coherence tomography.[1–3] In classical interference, light traveling in a superposition of two paths can be made to interfere with itself on a 50:50 beamsplitter, resulting in constructive or destructive interference based on the relative path lengths of the two interferometer arms. By monitoring the output power of one of the beamsplitter ports and tuning the relative delay, sinusoidal fringes can be observed with wavelength equal to that of the interfering photons. Likewise, these well-defined fringes allow us to infer the relative phase of the interferometer arms to great precision, information which can be used for high-resolution measurements of distance and time. However, classical interference is inherently susceptible to noise caused by background light, as well as reduction in fringe visibility due to dispersion and imbalanced loss. These sensitivities create problems when probing lossy or distant targets, particularly in the regime where high illumination power is infeasible.

We propose a measurement scheme which instead relies on two-photon interference of frequency-entangled photon pairs. This system exhibits per-photon resolution on par with classical interference, but with the robustness of two-photon interference. We have constructed and characterized a frequency-entangled interferometer and demonstrated its capabilities by measuring nanometer-scale vibrations.

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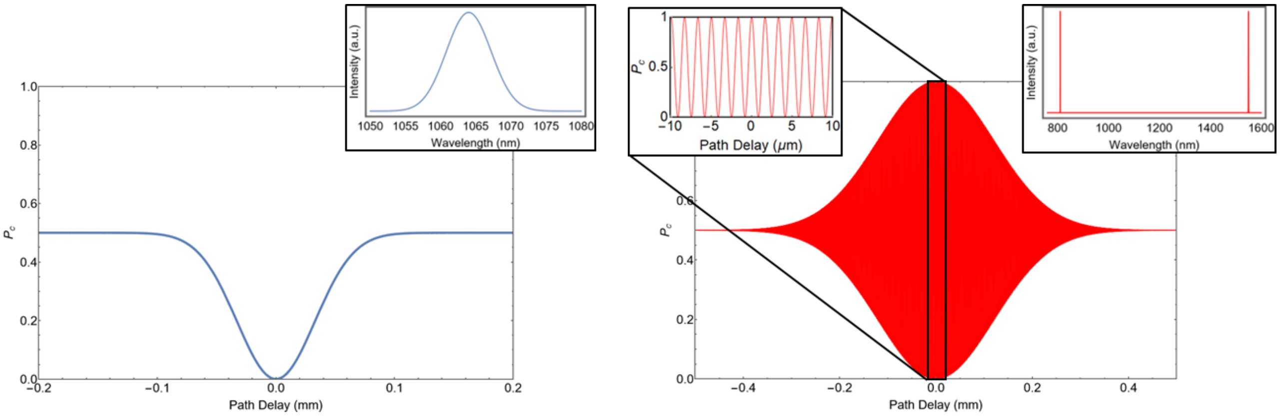

(a) (b)

Figure 1. Hong-Ou-Mandel interference patterns for (a) degenerate photon pairs centered at 1064 nm (inset), and (b) frequency-entangled photons with center wavelengths 810 nm and 1550 nm (right inset).

2. FREQUENCY-ENTANGLED HONG-OU-MANDEL INTERFERENCE

In two-photon interference – also known as Hong-Ou-Mandel (HOM) interference – two photons impinge upon a 50:50 beamsplitter. If the interfering photons are indistinguishable in all degrees of freedom, photon "bunching" occurs and no coincidences are detected between the two output ports of the interferometer. Tuning a relative path delay between the photons can be used to controllably introduce distinguishability, resulting in the characteristic HOM "dip" (Figure 1a),

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

with σ the photons' half-bandwidth and τ the relative temporal delay ($\tau = 0$ corresponds to exactly simultaneous arrival of the two photons at the beamsplitter). From a metrological perspective, this dip may be utilized to estimate the time delay imparted by a sample, with resolution inversely proportional to the photons' bandwidth (which determines the interference dip width). Further, HOM interference is resilient to imbalanced interferometer loss, odd orders of group velocity dispersion,[4] and background light, making it an ideal candidate for probing targets in noisy and lossy environments., e.g., for (quantum) optical coherence tomography.

Degenerate HOM interference has one key drawback: its reliance on bandwidth for determining the interference dip width means high resolutions necessitate large-bandwidth photons. In practice, large-bandwidth photons are non-trivial to produce and prohibit background suppression via tight spectral filtering; moreover, optical systems to transport such large bandwidths can be very challenging to implement. While nanometer-scale resolution may also be achieved with smaller, practically realizable bandwidths, this requires large numbers ($\sim 10^{11}$) of detected photon pairs.[5] More required photon pairs in turn implies longer integration times and makes degenerate HOM ill-suited for nanometer-scale vibrational measurements in lossy environments, as vibrational measurements set strict limits on the maximal integration time allowed for each measurement sample.

Recent work has shown that an alternative method for achieving high resolution with HOM interference is to utilize frequency-entangled photon pairs.[6] When the entangled photon pair is in the state $\left(|\omega_1\rangle_a |\omega_2\rangle_b + |\omega_2\rangle_a |\omega_1\rangle_b\right)/\sqrt{2}$ where the subscripts a, b indicate the two modes of the interferometer and ω_1, ω_2 are the photons' central frequencies, the resulting coincidence probability is

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

The form of the dip resulting from (2) is like that of the degenerate case, but now modulated by sinusoidal fringes at the beat note frequency $\omega_1 - \omega_2$. In this case, the metrological resolution is primarily determined by the detuning between the two entangled frequencies, rather than the photons' bandwidth. By utilizing extremely detuned photons, nanometer-scale measurement resolution can be obtained for as few as 10^4 detected

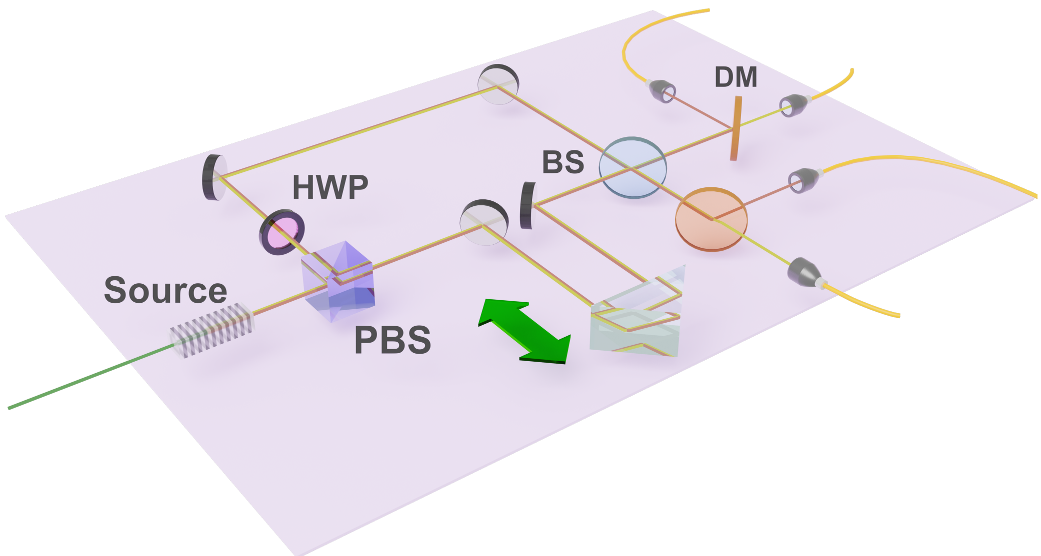

Figure 2. Simplified system diagram for laboratory experiments. Nondegenerate polarization entangled photon pairs are generated at 810 nm and 1550 nm (177 THz detuning) and converted to frequency entanglement via a polarizing beamsplitter (PBS) and a half-wave plate (HWP). One photon is sent to a vibrating target, here simulated by a retroreflector mounted on a piezoelectric translation stage. Both photons are interfered on a 50:50 beamsplitter (BS), after which the wavelengths are separated by dichroic mirrors (DM). Finally, coincidences are measured via superconducting nanowire single-photon detectors (SNSPDs).

coincidences. Further, this measurement method has been shown to saturate the quantum Cramér-Rao bound,[6] and thus represents a scheme for maximal information extracted per photon pair.

3. EXPERIMENTAL DETAILS

Shown in a simplified form in Figure 2, our system consists of four components: (1) a high-rate nondegenerate frequency-entangled pair source, (2) a dual-wavelength interferometer, (3) a controllable vibrating target, and (4) a wavelength-specific detection system. To generate high-rate, high-quality frequency entanglement, a 532-nm continuous-wave (CW) diode laser pumps a temperature-tuned PPLN crystal to create photon pairs at 810 nm and 1550 nm (177 THz detuning) via type-0 spontaneous parametric down-conversion (SPDC). The source is operated within a beam displacer interferometer,[7] with each arm pumping a separate crystal to create $|H\rangle_{810}|H\rangle_{1550}$ and $|V\rangle_{810}|V\rangle_{1550}$ respectively. When both processes are indistinguishable and driven coherently, the polarization-entangled state $(|H\rangle_{810}|H\rangle_{1550} + |V\rangle_{810}|V\rangle_{1550})/\sqrt{2}$ results. We have characterized our source to have high brightness (1M+ pairs/s/mW emitted) and high entanglement quality (purity > 0.85, concurrence > 0.9). The polarization-entangled photons are transformed into the state $(|H\rangle_{810}|V\rangle_{1550} + |V\rangle_{810}|H\rangle_{1550})/\sqrt{2}$ then routed to a polarizing beamsplitter (PBS), which also serves as the input to our dual-wavelength interferometer. Here the polarization-entangled state is converted to the desired frequency-entangled state $\left(|810\rangle_a |1550\rangle_b + |1550\rangle_a |810\rangle_b\right)/\sqrt{2}$, with a and b denoting the two arms of the two-photon interferometer. The two photons may now be used to perform relative time-of-flight metrology, with one photon being used as a probe while the other serves as a reference.

The probe photon is reflected off a retroreflector mounted atop a piezoelectric nanopositioning translation stage with 1-nm step resolution. The time delay of the reference photon is adjusted to approximately match that of the probe photon, and the pair is interfered on a 50:50 beamsplitter designed to operate at both wavelengths. Dichroic mirrors (DM) are then used to separate the wavelengths for individual collection and detection by superconducting nanowire single-photon detectors (SNSPDs). Finally, detection events are electronically correlated via a time-tagger for analysis. The split-wavelength detection scheme allows for the direct measurement of both photon antibunching (coincidences) and bunching (anticoincidences). This reduces the collection time

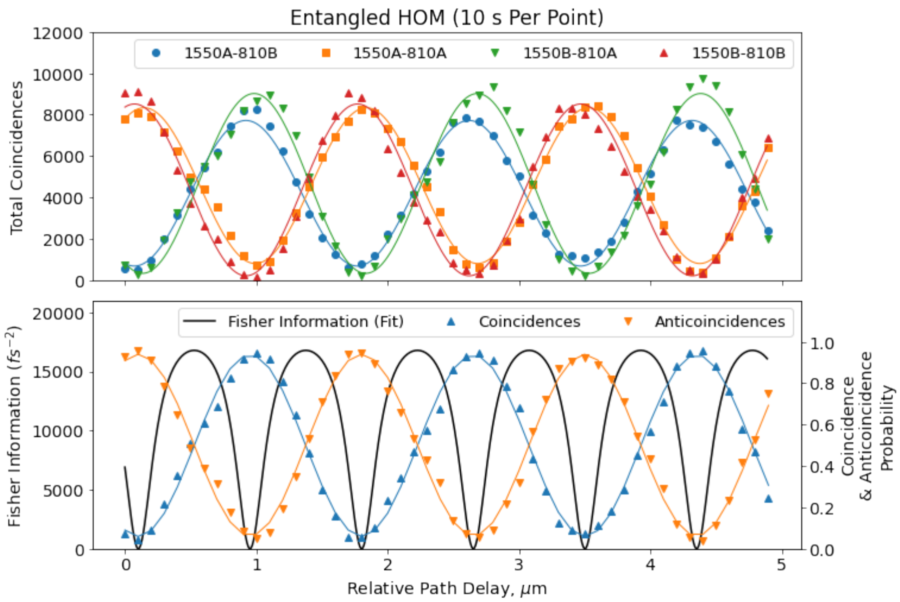

Figure 3. Characterization results for the nondegenerate frequency-entangled interferometer. (Top) Coincidences (blue and green) and anticoincidences (orange and red) measured as a function of relative path delay. (Bottom) Net coincidence and anticoincidence probabilities (blue and orange), along with extracted Fisher information. As expected, Fisher information is maximized when the slope is steepest.

required for a given measurement resolution over previous methods and allows for easier extraction of P_c.[6] To measure a static displacement, such as from the insertion of a sample, two measurements are taken: first with the interferometer tuned to its maximal resolution point ($P_c = 0.5$, $\tau \approx 0$), and a second with the sample inserted. A maximum likelihood estimator (MLE) can then be used to return the optical path length (modulo π phase) added by the sample based on any observed change in P_c. For vibrating targets, coincidence and anticoincidence fringes are recorded as the signal oscillates in time. A Fourier transform is then applied to the resulting oscillations to extract the vibrational frequencies.

4. RESULTS

We have successfully implemented and characterized our frequency-entangled interferometer system using frequency-entangled photons at 810 nm and 1550 nm. The top plot in Figure 3 shows coincidence and anticoincidence fringes obtained by sweeping the relative optical path delay between photons across a range of 5 μm, integrating for 10 seconds at each point. Fitted fringe visibilities range from $82 \pm 1.7\%$ to $95 \pm 2.7\%$, with visibility limited by interferometer alignment, as well as by the fidelity of the frequency-entangled state generated by our entanglement source. Fisher information is extracted for each delay and plotted in the bottom of Figure 3. From this we compute the maximum resolution of the system to be 7.72 as (2.3 nm) from a total of 17,700 detected photon pairs (10.3 as, 3.1 nm for 10^4 pairs). This corresponds to an 88% saturation of the quantum Cramér-Rao bound of 6.77 as (2.0 nm) for the same 17,700 photon pairs (9.0 as, 2.7 nm for 10^4 pairs), shown in Figure 4.

We have also used our interferometer to observe nanometer-scale vibrations, see Figure 5. Here our target is a mirror oscillating with an amplitude of 25 nm. We oscillate the mirror using two different frequency patterns, a sinusoidal wave at 1 Hz (Figure 5a), and a square wave at 0.5 Hz (Figure 5b). Both measurements are sampled at $\sim$4 Hz. The top plot shows the raw coincidence (blue and green) and anticoincidence (orange and red) fringes measured during the 30-second scan. This is then processed to produce the coincidence probability curve shown in the middle plot, from which the vibrational frequency is extracted via a Fourier transform at the bottom. In both cases we see good agreement between theory and experiment, with improved performance possible with improved pair rates from our entanglement source (higher pair rates also enable measurements of higher frequency vibrations).

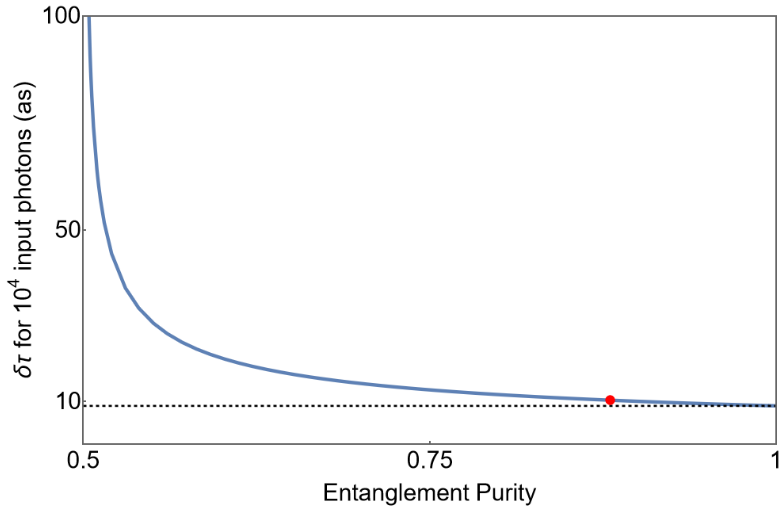

Figure 4. Relationship between entanglement purity and measurement resolution ($\delta\tau$) for 10^4 detected photon pairs, approaching the quantum Cramér-Rao bound as purity increases. Our current result of 10.3 as resolution (red circle) represents an 88% saturation of the bound.

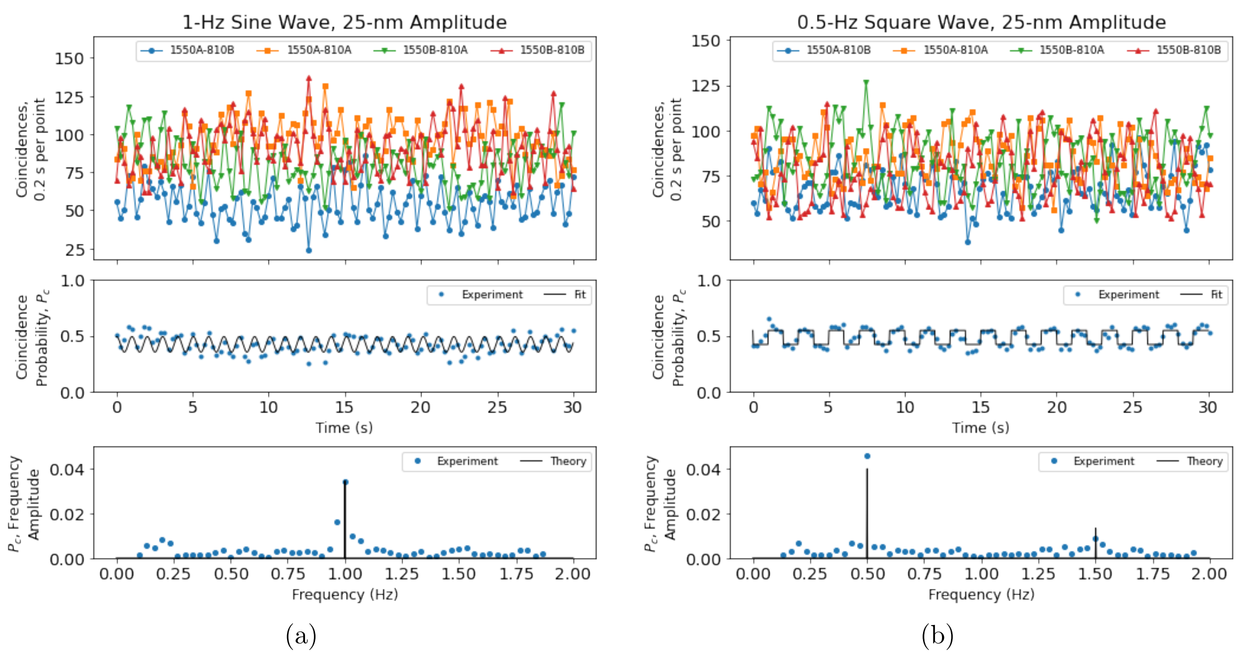

Figure 5. Measurement of 25-nm vibrations using frequency entangled interferometry for (a) a 1-Hz sine wave, and (b) a 0.5-Hz square wave. (Top) Raw coincidences (blue and green) and anticoincidences (orange and red) measured during 30 second scan. (Middle) P_c calculated from both coincidences and anticoincidences during the scan. (Bottom) Fourier transform of P_c used to extract the vibrational modes.

5. CONCLUSIONS

Frequency-entangled two-photon interferometry provides unique advantages for measuring small vibrations. By combining the per-photon resolution of classical interferometry with the robustness of two-photon interferometry, nanometer-scale vibration detection is possible even in regimes with large loss and background. We have designed a measurement system to take advantage of this effect, and have demonstrated proof-of-principle experiments for each of the individual components comprising the interferometer. High-quality frequency entanglement of extremely nondegenerate photons has been generated and used to measure 25-nm vibrations from a controlled oscillator. We have demonstrated near-saturation of the quantum Cramér-Rao bound (88%), with improvement possible with tweaks to our entanglement source. In regimes where allowable photon flux is limited and loss is high, such as when measuring biological samples or long-range remote sensing (quantum LIDAR), frequency-entangled two-photon interferometry is a promising alternative to classical methods.

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