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## Abstract

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# Quantum-enhanced sensing of time-varying signals at the nanometer scale

Colin P. Lualdi<sup>a,b</sup>, Joshua Rapp<sup>c</sup>, and Paul G. Kwiat<sup>a,b</sup>

<sup>a</sup>Department of Physics, The Grainger College of Engineering, University of Illinois Urbana-Champaign, Urbana, IL, USA

<sup>b</sup>Illinois Quantum Information Science and Technology Center, The Grainger College of Engineering, University of Illinois Urbana-Champaign, Urbana, IL, USA

<sup>c</sup>Mitsubishi Electric Research Laboratories, Cambridge, Massachusetts 02139, USA

## ABSTRACT

The resilience of quantum two-photon interference against optical loss and background sets it apart from classical single-photon interference for the purpose of sensing. However, achieving fast measurements at the nanometer scale with two-photon interference is challenging, as attaining high resolution typically requires either ultra-broadband photons or many probe photons. To realize nanometer-scale measurements in a matter of seconds or less, we greatly increase the per-photon information content via highly non-degenerate energy entanglement. Our fast measurements thereby enable us to probe time-varying signals at the nanometer scale. To further develop our capabilities, we have drawn on single-photon imaging techniques to implement a robust protocol for reconstructing periodic signals from our relatively sparse detection data, complete with amplitude and frequency information. With this analysis regimen, we have successfully extracted complex multi-frequency signals as well as kHz-range acoustic vibrations. We review our method and present the results of an example measurement to illustrate our capabilities.

**Keywords:** Quantum sensing, quantum interference, two-photon interference, energy entanglement, time-varying signals, vibrometry

## 1. INTRODUCTION

Optical interferometry can be an effective tool for the study of time-varying signals (e.g., vibrations), as evidenced by the extensive body of work surrounding techniques such as laser Doppler vibrometry.<sup>1</sup> Classical “single-photon” interference—where light travels in a superposition of two paths and interferes with itself on a balanced beamsplitter—can be used to detect such signals. However, there are advantages to instead using quantum two-photon interference, in which two photons meet on a balanced beamsplitter. If the photons are indistinguishable in all degrees of freedom (e.g., temporal, spatial, frequency, etc.), the photons will “bunch” and exit the beamsplitter in the same port.<sup>2</sup> Since two-photon measurements are required to observe this interference effect, it offers greater resilience against imbalanced path loss and optical background compared to classical interference.<sup>3</sup> Many studies can benefit from this resilience, such as when dealing with a weak return signal or solar background.

Despite these advantages, the use of quantum interference to study time-varying signals at the nanometer scale has been limited. This limitation stems from the difficulty of simultaneously achieving fast sampling and high measurement resolution. For example, while nanometer-scale resolution via two-photon interference has been demonstrated,<sup>4</sup> accumulating the required number of detection events required hours-long measurements, which preclude the study of dynamic systems. Furthermore, while sensitivity to temporal indistinguishability can be greatly increased by utilizing ultra-broadband photon pairs,<sup>5,6</sup> producing and working with such photons present significant technical challenges. As a solution, we have recently demonstrated how introducing extreme energy entanglement between the two photons undergoing interference significantly reduces the number of photon

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Further author information: (Send correspondence to C.P.L.)  
C.P.L.: E-mail: clualdi2@illinois.edu

pairs required for nanometer-scale resolution,<sup>3</sup> thereby enabling fast and high-resolution measurements without needing ultra-broadband photons. We discuss how this, in turn, has enabled the sensing of vibrational signals at the nanometer scale.

## 2. METHOD

As discussed in Ref. 3, we perform two-photon interference with the energy-entangled state

$$|\psi\rangle = \frac{1}{\sqrt{2}} (|\omega_1\rangle_a |\omega_2\rangle_b + |\omega_2\rangle_a |\omega_1\rangle_b), \quad (1)$$

where  $a$  and  $b$  indicate the two inputs of the beamsplitter and  $\omega_i$  is the photon’s angular frequency. During measurements, we monitor the probability that each photon from a pair exits in its own port and results in a “coincidence” detection between detectors placed in each output port. Given our two-photon state (Eq. 1), the coincidence probability exhibits a beat note as a function of  $\tau$ , the relative temporal delay between inputs  $a$  and  $b$ :

$$P_C = \frac{1}{2} \left\{ 1 - \cos[(\Delta\omega)\tau] e^{-2\sigma^2\tau^2} \right\}. \quad (2)$$

The delay  $\tau$  may be readily introduced by adjusting the relative path-length difference between the two inputs. In Eq. 2,  $\Delta\omega \equiv \omega_1 - \omega_2$  is the angular frequency detuning of the entangled photons, which have an angular frequency half bandwidth of  $\sigma$ . When  $\Delta\omega$  is large (177 THz in our case) and  $\tau$  is set at a value close to zero corresponding to  $P_C \approx 0.5$ , the coincidence probability is highly sensitive to small changes in  $\tau$ . Specifically, by using the speed of light to convert between temporal and path-length delays, we have observed  $\sim 1$ -nm resolution with only  $\sim 60,000$  photon pairs collected in 1 second.<sup>3</sup>

In the case of time-varying signals,  $\tau$  is time dependent. To monitor  $\tau$  as a function of time, one could repeatedly sample  $P_C$  with  $N$  photon pairs, as has been demonstrated with previous quantum interference experiments.<sup>6,7</sup> However, doing so inherently results in the sampling rate being constrained by the brightness of the photon pair source. To exceed the Hz-scale sampling rates previously reported, we have developed an analysis protocol based on a “flux probing” technique<sup>8</sup> that draws on recent advances in single-photon imaging.<sup>9</sup> Figure 1 outlines our measurement procedure with this new protocol. We start with the sensing step, which involves the two inputs of the interference beamsplitter, labeled “reference” and “probe”. Each input path contains one photon from the energy-entangled photon pair, and the probe path is subject to some time-varying delay  $\tau(t)$ , e.g., introduced by a vibrating mirror. The two paths then meet at a balanced beamsplitter, where the photons undergo interference. After interference, energy-resolved detection (via SNSPDs and dichroic mirrors) monitors for both coincidences (photons exiting in separate ports) and anti-coincidences (photons exiting in the same port). Timestamps for both types of coincident detections are then used to reconstruct the original signal via flux probing.

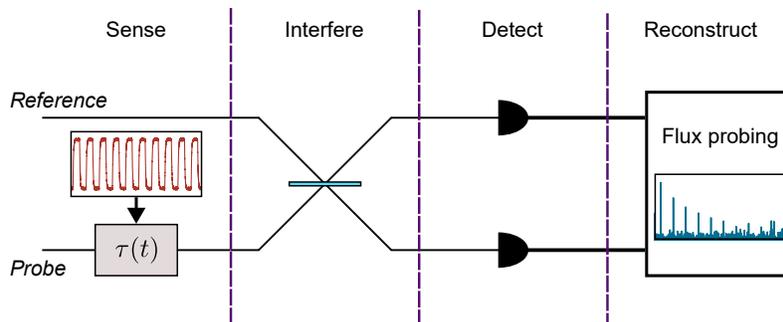


Figure 1. Schematic outlining our process for observing time-varying signals with two-photon interference. There are four stages: Sense, interfere, detect, and reconstruct.

To perform flux probing, we model the detection timestamps via the flux functions

$$\begin{aligned}\varphi_C(t) &= R_C P_C[\tau(t)] \\ \varphi_A(t) &= R_A \{1 - P_C[\tau(t)]\},\end{aligned}\tag{3}$$

where the  $C, A$  subscripts denote coincidences and anti-coincidences, respectively, and  $R_{C,A}$  are scalars related to the photon-pair generation rate. By projecting the detection timestamps onto windowed Fourier basis functions, we can estimate  $\varphi_{C,A}(t)$  and, from there,  $\tau(t)$ . An advantage of this method is that the timestamp resolution—currently 100 ps for our experiment—sets the sensing bandwidth to a theoretical maximum frequency of 5 GHz.

### 3. RESULTS

To illustrate the ability of our technique to accurately estimate the frequency and amplitude of multi-component signals, we present the results of detecting a 10-Hz square wave vibration with a nominal peak-to-peak amplitude of 50 nm. We introduce the signal by using a piezoelectric nano-positioning stage to vibrate a retro-reflecting mirror in the probe path. Figure 2(a) shows the coincidence counts (in 1-ms bins) as a function of time; the corresponding anti-coincidences are not shown. While the square waveform is visible, the low number of counts in each bin results in a noisy signal. Figure 2(b) shows the frequency spectrum we obtain after performing flux probing on the collected pair-detection time stamps ( $\sim 2$  million over 10 seconds). The harmonics associated with the square wave are clearly visible. A threshold derived from a probability of false alarm (0.1%) allows us to separate the frequency components with high energy from noise. From these components, we reconstruct the flux functions and obtain the signal shown in Fig. 2(c), with a peak-to-peak amplitude of  $\sim 60$  nm. This recovered signal is significantly less noisy than the raw version shown in Fig. 2(a), and compares favorably to the original signal from the stage position encoder shown in Fig. 2(d), which yields a peak-to-peak amplitude of  $\sim 54$  nm.

The slight amplitude overestimation appears to be a consequence of the fluctuations present in the quantum data, which we primarily attribute to finite harmonic recovery. In some cases, this may be addressed by utilizing

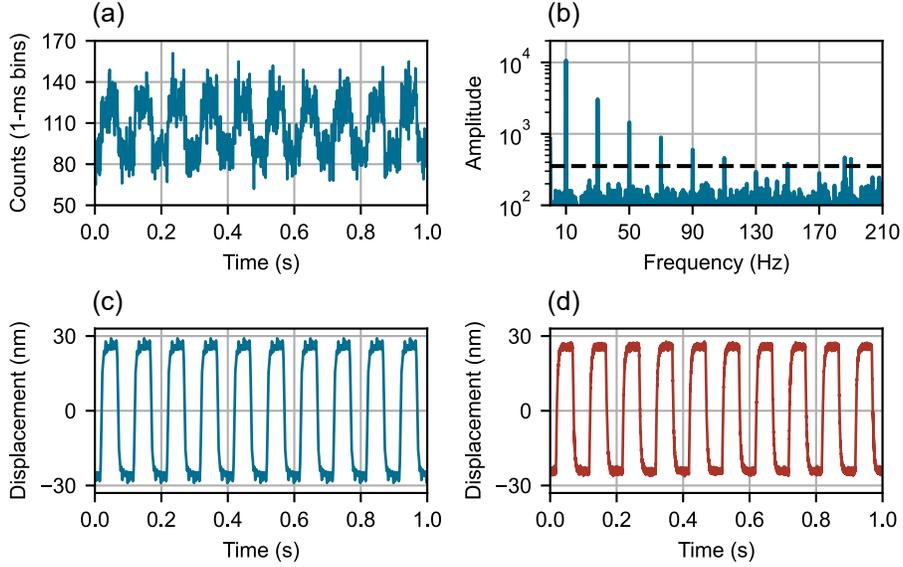


Figure 2. Measurement of a 10-Hz square wave vibration. (a) The raw pair-detection counts as a function of time (coincidences only). (b) The frequency spectrum recovered by our flux probing procedure; the dashed line indicates the threshold used to separate the signal from the noise. The spurious 186-Hz component (visible near the 190-Hz harmonic) was determined to be background and therefore removed from subsequent analysis steps. (c) The reconstructed signal showing the measured mirror displacement as a function of time; our analysis takes into account a factor of 2 arising from retro-reflection. (d) The mirror displacement according to the internal position encoder of the piezoelectric stage.

an alternative technique for extracting the peak-to-peak amplitude. For example, instead of taking the difference of the highest and lowest points (as was done for the values given above), one could average points near the peaks and troughs. Averaging over 0.03 s for the first peak and trough in each of Figs. 2(c) and 2(d) yields peak-to-peak amplitudes of  $\sim 52$  and  $\sim 50$  nm, respectively.

#### 4. CONCLUSIONS

The results presented in Fig. 2 illustrate how our flux probing analysis technique significantly increases the versatility of our energy-entangled two-photon interferometer in probing time-varying signals. We are able to recover a clean time-varying signal from relatively sparse detection timestamps without being subject to trade-offs between the sampling rate and measurement resolution. While our method is currently only suitable for periodic signals, future work may result in extensions to non-periodic signals. As discussed in Ref. 8, we have observed nanometer-scale precision and accuracy using our method. We have also successfully recovered vibrational frequencies as high as 21 kHz, which exceeds the nominal upper bound of human hearing (20 kHz). Crucially, we also showed that the significant quantum advantage associated with two-photon interference (loss and background resilience) continues to be present when detecting vibrations with our flux probing method; a head-to-head comparison between quantum and classical interference revealed that only the quantum case resulted in signal recovery largely unaffected by loss and background. The quantum-enhanced ability to accurately recover nanometer-scale vibrational signals despite the presence of loss and background has important implications for novel studies, such as the long-range detection of faint acoustic vibrations.

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