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Long-baseline interferometry using single photon states as a non-local oscillator

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ABSTRACT

Recent proposals suggest that distributed single photons serving as a 'non-local oscillator' can outperform coherent states as a phase reference for long-baseline interferometric imaging of weak sources [1,2]. Such nonlocal quantum states distributed between telescopes can, in-principle, surpass the limitations of conventional interferometric-based astronomical imaging approaches for very-long baselines such as: signal-to-noise, shot noise, signal loss, and faintness of the imaged objects. Here we demonstrate in a table-top experiment, interference between a nonlocal oscillator generated by equal-path splitting of an idler photon from a pulsed, separable, parametric down conversion process and a spectrally single-mode, quasi-thermal source. We compare the single-photon nonlocal oscillator to a more conventional local oscillator with uncertain photon number. Both methods enabled reconstruction of the source's Gaussian spatial distribution by measurement of the interference visibility as a function of baseline separation and then applying the van Cittert-Zernike theorem [3,4]. In both cases, good qualitative agreement was found with the reconstructed source width and the known source width as measured using a camera. We also report an increase of signal-to-noise per 'faux' stellar photon detected when heralding the idler photon. 1593 heralded (non-local oscillator) detection events led to a maximum visibility of ~17% compared to the 10412 unheralded (classical local oscillator) detection events, which gave rise to a maximum visibility of ~10% – the first instance of quantum-enhanced sensing in this context.

Keywords: Very-Long-Baseline Interferometry, Quantum Sensing, Nonlocal Oscillator

1. INTRODUCTION

While applying interferometry to conduct astronomical imaging has its inception rooted in Europe, the first implementation of such imaging was done over 100 years ago by Michelson and Pease [5]. By coherently combining the light from two telescopes separated by a baseline, b, one can increase the angular resolution $\theta \approx \lambda/b$, where λ is the wavelength of the observed radiation (called direct detection). Since the first experiment, there have been a wide range of applications spanning not only astronomy, but also geodesy: including imaging the black hole at the center of a galaxy [6], the tectonic motion of the earth [7], and the local upheaval [8]. Interestingly, even though the original experiment was done in the visible spectrum, it has taken a back seat to experiments in the radio regime. In particular, the radio regime has one main advantage over the visible spectrum: the ability to measure both the phase and amplitude of the electric field directly. This allows many radio receivers to be placed on the earth and not require more than a computer memory and an accurate clock at each site. However, no such detectors exist in the visible band; so, most visible-band very-long-baseline interferometric (VLBI) telescope arrays have not had a conceptual implementation shift from Michelson and Pease's first demonstration.

In the last decade, multiple proposals have been raised to aid in the goal of making visible-band VLBI telescope arrays more sensitive or surpass the technical limits that are fundamental to their operation (shot noise, signal loss, or the need of bright objects) with the goal of extending the baseline to longer distances for increased angular resolution. Some proposals take advantage of the quantum nature of light [1,9], quantum memories [2], or local two-photon interference [10]. In a proof-of-principal experiment, our group has demonstrated source reconstruction (imaging) and increased signal-to-noise ratio per photon from a single spectral-temporal mode, quasi-thermal source detected in coincidence with a single-photon non-local oscillator (NLO), compared to an equivalent setup using a weak source with uncertain photon number -similar to heterodyne VLBI where a coherent laser source is shared between the telescopes. This, we believe, is the first instance of quantum-enhanced sensing in this context. The long-range goal of this project is to find the optimal quantum protocol to achieve the best possible visible-band telescope resolution of faint astronomical objects.

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2. EXPERIMENTAL DETAILS

2.1 Experiment Proposal

VLBI works on the basis of the van Cittert-Zernike theorem [3,4], which states that light from a spatially incoherent source becomes coherent through propagation and, further, that the complex degree of coherence in the imaging plane is the Fourier transform of the intensity distribution in the object plane. To measure the coherence in the visible-band, the collected light from each telescope pair is brought together to be interfered spatially where the visibility of the interference is then directly related to the coherence of the light. However, this process is lossy when transmitting long distances over optical fibers. To get around this specific problem, Gottesman et al. proposed sending a single-photon reference state from a single source to be split into individual paths -one with a controllable phase, represented by δ- to each telescope where the photons collected at each telescope are then interfered with the distributed photon at each telescope via a 50:50 beam splitter [1]. All outputs of the beam splitters are monitored with single-photon detectors as seen in Figure 1. In the two-telescope case, the probability of detecting a coincidence between two detectors, one at each telescope -assuming the light from the star has less than one photon per mode- is

$$P(|\mathrm{v}|, \delta, \phi) = \frac{1}{2}(1 \pm |\mathrm{v}| \cos(\delta - \phi)), \tag{1}$$

where |v| and ϕ are the magnitude and phase of the complex visibility respectively, and the plus or minus is due to the phase gained from transmission or reflection at the beam splitters. Tsang showed that this method is half as efficient as direct detection (because cases in which both the astronomical and NLO photon are detected at the same telescope beam splitter, no information about the source is gained) when losses in fiber transmission are negligible [11]. Since optical fibers are lossy in the visible spectrum, it is possible that a quantum network to distribute the path entanglement of the NLO over long distances would overcome this obstacle and possibly be one of the first applications of quantum distributed sensing.

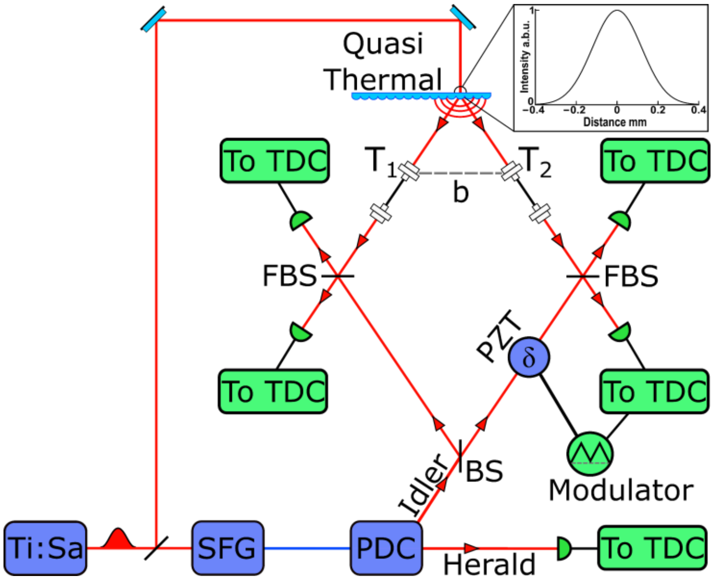

Figure 1. Simplified experimental setup. A herald and an idler photon at 830 nm are created simultaneously from a PDC crystal pumped by an upconverted 10 nm wide pulse at 830 nm. The heralded idler photon is used as the nonlocal oscillator. A PZT modulates the path length in one of the arms of the interferometer. A weak single spectral-temporal mode quasi-thermal source created by a synchronized laser pulse at 830 nm scattered from a diffuser simulates a 'faux' star with fibers (T_1 and T_2) placed far away to collect the incoming light as mock telescopes separated by a variable baseline (b). The collected light is interfered with the nonlocal single-photon state at two fiber beam splitters (FBS). All signals including the voltage that modulates the PZT are routed to a time tagger to measure visibility and phase.

2.2 Experiment Details

The NLO is created by first frequency doubling an 830 nm pulse with a bandwidth of 10 nm from a titanium sapphire (Ti:Sa) laser in a BBO crystal; this pump pulse is subsequently parametric downconverted via type-II phasematching in a KDP crystal yielding spectrally factorable photon-pair states. One photon is split from the other via polarization and sent to a superconducting nanowire single-photon detector (SNSPD) acting as a herald. The other photon is then split into two paths with a 50:50 beam splitter. In one of the arms, a piezoelectric translator (PZT) is added as a variable delay line to change the relative phase between the two paths. The PZT is driven with a 600 Hz triangle wave with amplitude corresponding to roughly 4π of phase. The two paths are then collected into separate single-mode fibers each of which is directed to a fiber beam splitter.

To create a star-like object in the lab, a pickoff beam splitter is used to direct a fraction of the main Ti:Sa pulse to a rotating diffuser where the transverse profile of the beam is Gaussian with a width of 0.24 mm. The rotating diffuser creates a single temporal-spectral mode, quasi-thermal field ($g^{(2)}(0)=1.929\pm0.028$) with a near-Lorentzian scattering distribution. The light from the diffuser propagates 1 m to a beam splitter. One of the outputs of the beam splitter is spatially sampled in 10 μm transverse steps over a total range of 2 mm parallel to the optical table with a bare, movable, ~5 μm core, single-mode fiber (T1) using an automated stage. The other output is monitored with an identical, stationary fiber (T2) situated such that it samples the equivalent transverse mode from the table-top stellar source as T1 at the center of its travel. These fibers act as 'faux' telescopes and measure an average photon number of 0.0038 per pulse.

The four output fibers (two from the pseudo-thermal source, two from the heralded NLO source) are paired up and each pair is mated into a 50:50 fiber beam splitter, where one pair contains one fiber from the NLO paths and the other from one of the telescope fibers. The outputs of the fiber beam splitters are then monitored with SNSPDs. All of the SNSPDs' electrical signals are sent to a time tagger along with a 600 Hz square voltage pulse that is phase locked to the triangle wave that modulates the PZT. To ensure timing overlap from the pulses, the two outputs from a single fiber beam splitter are monitored while an internal delay is scanned to measure the decrease in coincidences indicative of photon bunching due to Hong-Ou-Mandel interference [12]. Finally, the signals are post processed to find the coincidences between detectors monitoring one output from each fiber beam splitter, but never from the same fiber beam splitter (from a common 'telescope') as required by the protocol. This can be done using either heralded or unheralded coincidences. Each coincidence is then measured relative to the rising edge of the last acquired square pulse. From this, a relative phase -ϕ_n- is determined and the collected phasors -$e^{i\phi_n}$- are averaged to infer the magnitude of the visibility. In this case, since the source is symmetric, only the magnitude is needed for source reconstruction [13].

3. DATA & RESULTS

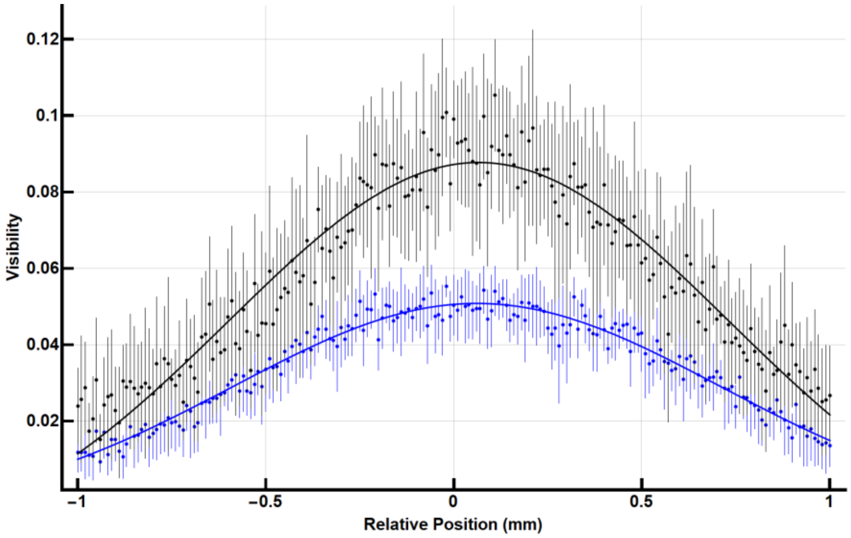

Figure 2. Representative data of a typical measurement. Heralded (black) and unheralded (blue) data is the average over 10 trials and the error bars are the standard deviation of the data sets. Each plot shows the measured visibility as a function of the relative distance (baseline) between the two "telescope" fibers. The curves show the Gaussian best fits to the data.

The average visibility was measured ten times for each baseline position and the average and standard deviation are plotted in Figure 2. There we see that the signal-to-noise ratio for heralded and unheralded data is roughly equal; however, the number of unheralded events compared to heralded events is almost a factor of 7 different (1 593 heralded, 10 412 unheralded). This implies that for every stellar photon interfered and detected in coincidence, more information is obtained in the heralded single-photon NLO case than in the unheralded case when the NLO may contain more than one photon. It should be noted that for small average photon number, thermal states and coherent states have the same photon statistics, so we are justified is using the unheralded idler beam as a quasi-coherent state with random phase.

The data shown in Figure 2, allowed us to reconstruct the source. The measured visibility from both the heralded and unheralded data has a Gaussian shape, and the Fourier transform recovers the width of the intensity distribution at the diffuser to be 0.2 mm for the unheralded data and 0.19 mm for the heralded data; this is close to the value of 0.24 mm measured directly via a camera.

4. CONCLUSION

In conclusion, we have used the protocol put forward by Gottesman et al. to reconstruct a single temporal-spectral mode, quasi-thermal source using a distributed single photon acting as a nonlocal oscillator. Further, we have made the comparison to traditional heterodyne very-long-baseline interferometers and showed that the single-photon NLO provided better signal-to-noise ratio per stellar photon, compared to a weak coherent state, for very dim sources. This opens further avenues of study such as using a true blackbody source for the thermal state as well as using quantum repeaters or memories to extend the baseline for distributing a nonlocal oscillator to compete with direct detection for very-long-baseline interferometers. If these methods are successful, very-long baseline interferometric astronomy could be a prime application for a high-rate quantum network link.

5. ACKNOWLEDGEMENTS

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