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Demonstrating Quantum-Enhanced Interferometric Telescopy

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Abstract: We emulate quantum-enhanced telescopy through interconnected interferometers and demonstrate experimental progress toward optimally recovering the visibility amplitude of a source and displaying an advantage of using distributed single photons over a weak coherent source.

1. Introduction

Interferometric telescopy is used to increase the effective coherent aperture of a telescopic system, increasing the angular resolution. A massive coherent aperture can be created by separating detectors over long distances, a method known as very long baseline interferometry (VLBI). However, direct detection VLBI has greater difficulty for photons of higher frequency due to increased transmission losses in optical fibers, and the inability to directly record the optical field (in contrast with radio telescopes, whose signals can be recorded electronically and subsequently 'interfered', as with the Event Horizon Telescope [1]). Gottesman, Jennewein and Croke proposed to circumvent this limitation by detecting correlations across telescopes, each fed by a superposition of an astronomical photon and a terrestrial one (with a controllable relative phase between the telescopes) [2]. In essence, there is a quantum mechanical two-photon interference between the two processes in which the astronomical photon enters one telescope and the terrestrial photon goes to the other, and vice versa. The variation in the interference visibility as a function of telescope baseline separation determines the mutual coherence of the source at the two telescopes, which in turn, via the Van Cittert-Zernike theorem, allows one to determine the intensity distribution of the light source [3]. Here we present a proof-of-principle demonstration using photons from spontaneous parametric down-conversion (SPDC).

2. Experimental Design

The "terrestrial" and "astronomical" photons in our experiment are produced via non-collinear type-I phase-matched SPDC using a 0.6-mm-long beta barium borate (BBO) crystal. The pump consists of a doubled TiSa

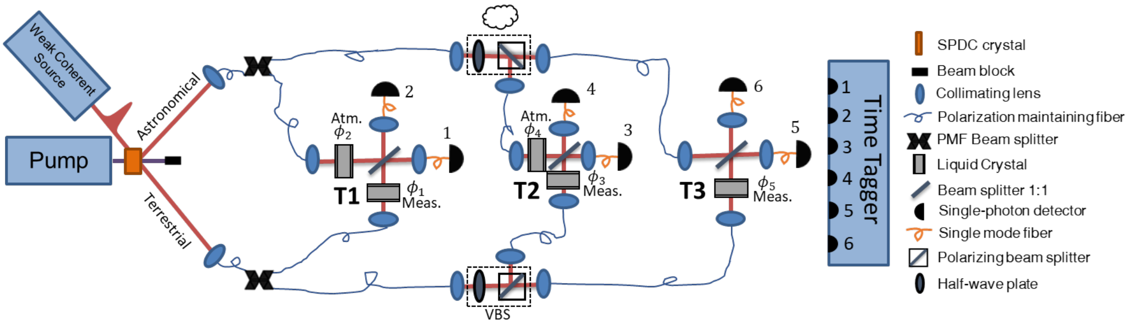

Fig. 1. Three-telescope experimental design. The "terrestrial" and "astronomical" photons are produced via SPDC of a single beta-barium borate (BBO) crystal. The photons from each path are collected into polarization-maintaining fiber (PMF) and distributed to three "telescopes" via half-wave plates, polarization beam splitters and fiber beam splitters. The telescopes contain liquid crystals to simulate atmospheric turbulence and apply controlled phases $\{\phi_1, \phi_2, \phi_3, \phi_4\}$, where the last telescope is set as a reference phase. For some measurements a weak coherent source is allowed into the terrestrial arm for comparison between classical and single-photon sources. The single-photon detectors (1-6) are connected to a time-tagger to measure single and coincidence counts.

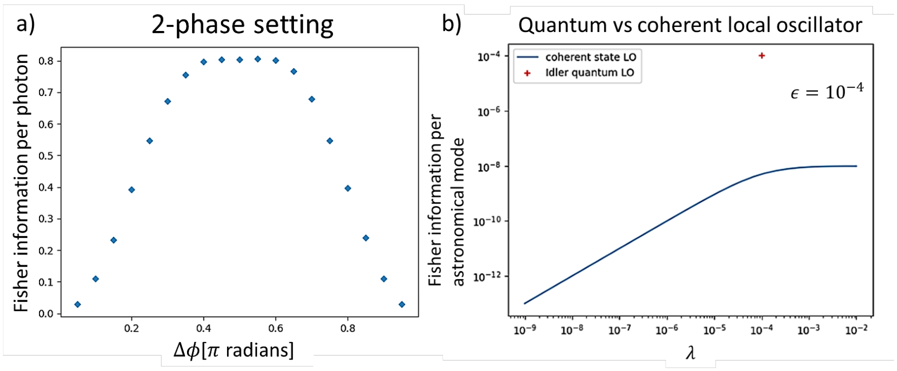

Fig. 2. Both figures represent the theoretical curves appropriate for our experimental setup. a) The Fisher information per astronomical photon when applying 2 discrete phases onto the measurement liquid crystals. b) Assuming an astronomical photon rate of $\varepsilon = 10^{-4}$, the Fisher information per astronomical mode when using different intensities for our weak coherent source, compared to a single-photon source (indicated by the red cross).

laser centered at 810 nm with a 62-fs pulse width to produce 405-nm light by using a 0.6-mm-long bismuth borate (BiBO) crystal. The signal/idler arms represent the astronomical/terrestrial sources. The photons are collected into polarization maintaining fibers; a combination of half-wave plates, polarizing beam splitters and fiber beam splitters is then used to direct the photons to the various ”telescopes” (see Fig. 1). The variable beam splitters before telescopes 2 and 3 mimic cloud cover over one telescope (in the astronomical arm) and amplitude matching of the transmitted photons (in the terrestrial arm). The photons are then subjected to a phase change via liquid crystal variable retarders (LCVR) as they arrive to the telescopes. The astronomical arm has LCVRs in its path to simulate turbulence, whereas the terrestrial path’s LCVRs are used to impose discrete phase settings.

Simulations for the applied discrete phase settings were conducted to optimize the recovery of the visibility amplitude of the source. Two discrete phase settings were shown to be sufficient and optimal, where the Fisher information per photon is maximized when applying a phase difference of $\pi/2$ radians for the two settings (see Fig. 2a). Another simulation was conducted to show the advantage of using distributed single photons in comparison to a coherent source (see Fig. 2b); this shows that the Fisher information per astronomical mode (defined by the atmospheric coherence window) for a single-photon source is higher than that of a coherent source with a minimum of $1/\varepsilon$ enhancement, where ε is the astronomical photon rate. We are investigating regimes for which $\lambda \ll \varepsilon$, $\lambda \approx \varepsilon$, and $\lambda \gg \varepsilon$, where $\lambda \equiv |\alpha|^2$ is the intensity of the coherent light source.

3. Discussion

For this proof-of-principle experiment our “astronomical” photons were generated to be coincident with and identical to our terrestrial photons. This allows us to simulate a strong enough “terrestrial” single-photon source that meets the requirements made by Gottesman, Jennewein and Croke [2] of having exactly one photon per field mode. Our testbed also allows us to explore other methods relevant to the quantum telescopy problem. For example, the measured fringe visibility will be reduced if there are different coupling losses into the various telescopes; however, using the waveplate and polarizing beamsplitter, we can match this imbalance on the terrestrial photon, recovering full interference visibility (up to the coherence of the telescope input modes). We also investigate the use of > 2 telescopes to implement “closure phase” methods, allowing not only the magnitude of the mutual coherence (the interference visibility) to be extracted but the *phase* information as well.

References

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