Entanglement-Enhanced Interferometry in Optical Fiber

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Abstract: Fiber-based interferometry with entangled states of photons can provide sub-shot-noise resolution, providing an ideal measurement for photon-starved applications. Simulations demonstrate that measurements with realistic losses and other imperfections show quantum-enhanced phase resolution for practical measurements.

Quantum states of light are able to exceed the shot noise limit. This was famously demonstrated with squeezed light in the detection of gravitational waves [1]. For applications that require a low photon flux, like biochemical sensing, quantum computing and quantum communication, entangled photons could be the optimal probe [2]. Additionally, the flexibility and low optical attenuation of optical fiber may provide a more robust platform to bring these techniques into a wider application space.

More specifically, entangled photon states can exceed the shot noise limit by a factor of $\sqrt{N}$, where N is the number of photons in the state. This is achieved with a maximally entangled N00N state [3], but the related Holland-Burnett states are both more easily generated and more robust against loss [4]. While previous models have shown how the measurement capability of these states are affected by loss, noise, and other imperfections separately [3–5], we present the first, to our knowledge, scalable model integrating all imperfections at once. We use this model to analyze the feasibility of fiber-based, entanglement-enhanced interferometry. Under realistic experimental conditions (10% internal loss, 90% detector efficiency, 2 mrad of phase noise, and 5% photon distinguishability), the model shows a quantum advantage between 14% and 28% beyond the shot noise limit, depending on the number of photons in the entangled state. Additionally, using a superposition of 2, 4, and 6-photon states, as generated from a two-mode squeezed-vacuum state, we see measurement resolution 14% beyond the shot noise limit, while also having up to 30 times the photon flux for faster measurements.

A model entanglement-enhanced Mach-Zehnder interferometer in polarization-maintaining fiber is shown in Figure 1(a). A phase change can be induced by thermal expansion or strain in the fiber, or if using a photonic crystal fiber, a change in concentration of a diffuse gas in the fiber holes. Because the phase resolution is a function of the phase, a portion of the top fiber can vary in strain to add a feedback element $\theta_feedback$ to keep the interferometer near its most sensitive operating point.

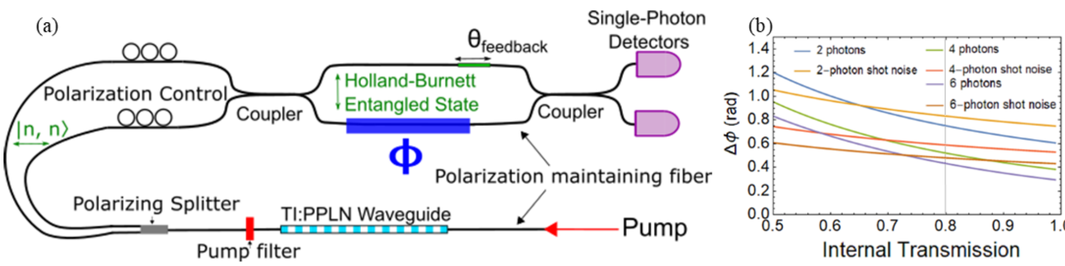

Fig. 1. Conceptual design for a fiber-based Mach-Zehnder interferometer with entangled photons. The TI:PPLN waveguide acts as a degenerate photon pair source using type-II spontaneous parametric downconverison, while the polarizing splitter and 50:50 directional fiber coupler act to create a Holland-Burnett path-entangled state. The state interferes with itself at another 50:50 directional coupler, and the photon counting statistics are recorded with number-resolving photon detectors. (b) Plot of the phase resolution for 2, 4, and 6-photon entangled states, compared with the equivalent shot noise, as a function of internal transmission in the interferometer.

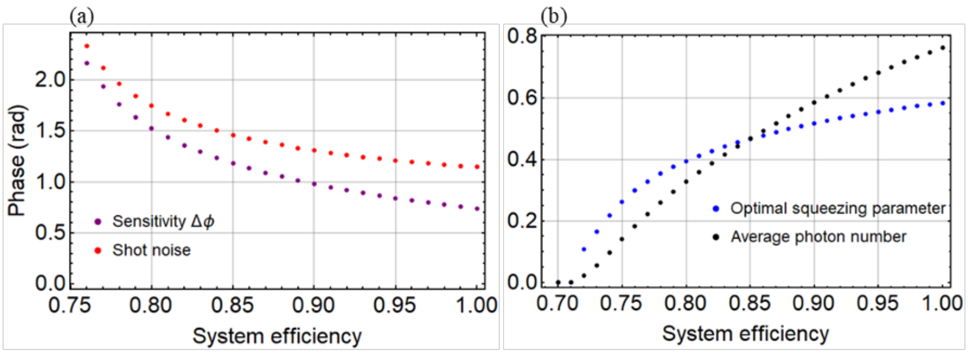

Fig. 2. Results from inputting a two-mode squeezed vacuum state, optimized for sensitivity as a function of system efficiency. (a) Phase resolution for the state compared to shot noise, and (b) the optimal squeezing parameter and corresponding average photon number of the input state, as a function of system efficiency.

Mathematically, the model is represented by transformations of photon creation operators $\hat{a}^\dagger$ and $\hat{b}^\dagger$ [6]. To represent losses and detector inefficiencies, the model adds beamsplitters in both paths of the interferometer and in front of the detectors, respectively, that output into unmeasured 'vacuum' modes [4]. Additionally, a finite degree of entanglement is considered by sometimes outputting the result of classical interferometry for each photon, with probability $(1-V)$ where V is the Hong-Ou-Mandel visibility of the input photon state. Other sources of phase noise are also modeled in a similar fashion to ref. [5]. Once probabilities of each detection event are calculated, the quantum Fisher Information and quantum Cramer-Rao bound give a lower bound on the phase sensitivity of the setup. Our analysis focuses on analyzing 2, 4, and 6-photon Holland-Burnett states in varying lossy conditions, given finite noise and visibility.

Figure 1(b) shows the phase resolution of the 2, 4, and 6-photon Holland-Burnett states as a function of internal loss in both arms, in comparison to the state's shot noise. This plot uses a Hong-Ou-Mandel visibility of 0.95, detector efficiency of 0.9, and 2 mrad of phase noise, which we believe are realistic experimental parameters in optical fiber. What is most notable here is that, despite increased sensitivity to loss, the 4 and 6-photon states still maintain a quantum advantage in sensitivity for transmissions above around 0.7. Additionally, the minimum sensitivities still follow the scaling $\Delta\phi \propto N^{-1}$, so they still have Heisenberg scaling.

We also consider the two-mode squeezed-vacuum state as an input, which after entanglement is taken as a superposition of HB(N) states with a thermal distribution in N. Photon number resolution for detection is limited, and so only 2, 4, and 6-photon states are considered for measurements, while any higher states are lost. Using this input state, we calculate the optimal squeezing parameter to maximize the phase information per photon and the corresponding phase resolution.2 shows the optimal squeezing parameter and the resulting net phase resolution for the state as a function of system efficiency. A quantum advantage of 14% beyond shot noise is still experimentally achievable, with the additional benefit of increased photon flux. Compared to producing a single photon pair with a 1% chance of a second pair, the optimal squeezed state here can have up to 30 times the photon flux. We expect that this method will scale very well with advances in number resolution and flux rating for single-photon detectors, since higher-number states have higher sensitivity.

We have presented a model for entanglement-enhanced interferometry that shows that with realistic parameters, a practical measurement with a quantum advantage is possible, and that more photon flux is possible with a more generalized two-mode squeezed vacuum state. Accounting for multiple imperfections into the model allow for accurate comparison to future experiments.

References

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