Quantum Multiparameter Estimation Model of Cascaded Phases in Optical Fiber

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Abstract: We present a new architecture for quantum-enhanced multiparameter estimation, where measured phases are cascaded along a single optical fiber. Embedded reflectors separate these phases, enabling novel fiber-based quantum distributed sensing of temperature and strain.

Quantum states of light enable measurements that surpass the shot-noise limit [1]. Recent work in the field has extended quantum-enhanced measurements to sense multiple parameters at once, such as phase imaging [2–4]. These demonstrations exclusively consider the measured parameters to be in parallel, limiting the application space. Instead, we present an innovative architecture with a single optical fiber interferometer measuring phases cascaded in series, which is a concept largely unexplored. Simulations show that the sensor can nearly achieve the maximum possible quantum advantage for phase sensing, and has enormous potential in scalability. Our work represents a new paradigm in photonic quantum metrology wherein multiple parameters share an optical path. It also has direct potential to enhance a variety of optical fiber sensors, since the technique is similar to that of classical distributed fiber sensing [5]

The overall architecture is illustrated in Figure 1(a). The sensing arm is partitioned into N independent phases with $N-1$ reflectors, and two 50:50 couplers form a bidirectional Mach-Zehnder interferometer. Circulators ensure that the detectors are isolated from the inputs. Pulses of squeezed light are input from both sides at intervals equal to the propagation time between reflectors, so that separate pulses hit reflectors simultaneously. Interfering squeezed pulses generated at different times on the reflectors effectively multiplexes the number of squeezed sources. Detectors perform ideal homodyne detection in each time interval, so that distinguishing information is obtained on each phase depending on the time of arrival.

Methods from continuous-variable quantum computing were used to model the sensor and evaluate performance. Input pulses are represented as Gaussian states, and the interferometer by a Gaussian operation [6]. The output state is used to calculate the classical Fisher information matrix F [7], which quantifies the sensitivity of the output state to changes in each measurable phase. F^{-1} is then the multiparameter Cramér-Rao bound [8], containing a lower bound on the measurement variance $\Delta^2\phi_i$ on each phase ϕ_i. Thus:

$$\Delta^2\phi_i \geq (F^{-1})_{ii} \tag{1}$$

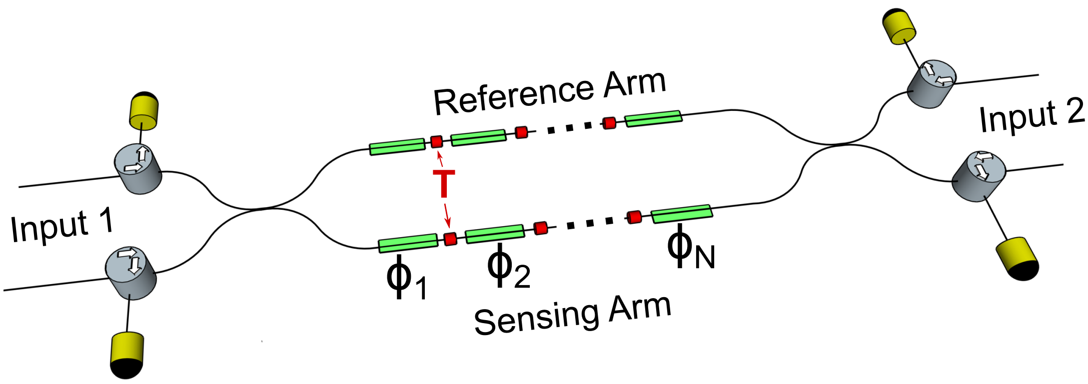

Fig. 1. (a) Cascaded phase sensing architecture. Evenly spaced reflectors separate N cascaded phase delays in the sensing arm of a fiber-based Mach-Zehnder interferometer. Circulators separate the sensor's bidirectional input from its output. Squeezed light is injected from both input directions to show quantum-enhanced multiparameter estimation.

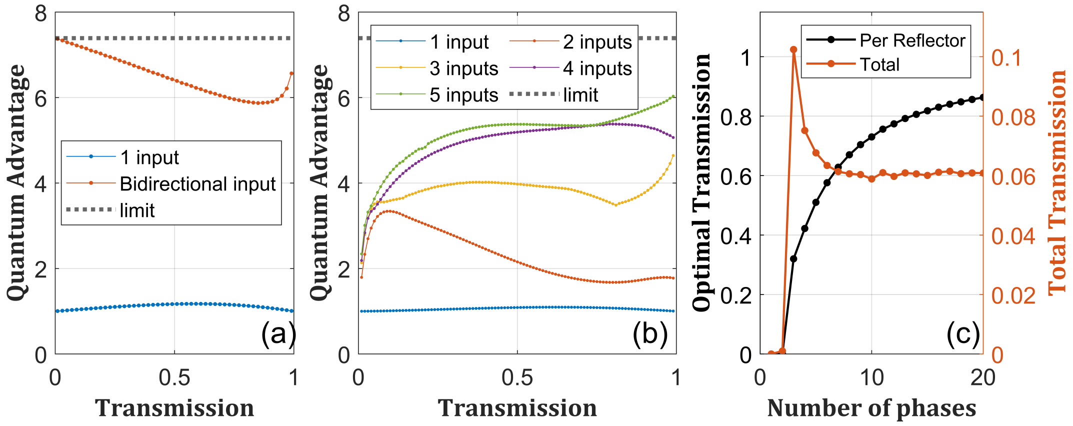

Fig. 2. Enhancement factor in phase estimation by using squeezed light. (a) A two-phase, one-reflector interferometer, with either a single input or bidirectional input. (b) A three-phase, two-reflector interferometer, with traces showing the enhancement given up to 5 input pulses. (c) Optimal transmission coefficients of the reflectors as the sensor scales to include more phases. Total transmission stabilizes to 6% for high N.

To assess the enhancement in sensitivity from squeezed light, F^{-1} was computed with both classical and squeezed light with the same intensity. The input parameters were optimized to minimize the cost function $Tr[F^{-1}]$, or the sum of each phase's measurement variance. We define the quantum advantage as the ratio of that cost function's value with classical light over that of the cost function with squeezed light.

Figure 2(a) plots the quantum advantage as a function of reflector transmission T for a two-phase, one-reflector interferometer. With input from one side, the maximum achievable quantum advantage is only 17%. This limitation is because the reflector is essentially a beamsplitter, with an empty input port. The empty port introduces vacuum noise back into the system, effectively reducing the squeezing strength of the probe. In contrast, with inputs from both sides, the reflector has no empty input port. With squeezed light from both sides, no vacuum noise is introduced. The result is a much higher quantum advantage than using a single input, nearly the maximum achievable with the given squeezing strength (e^{2r}, where the squeezing strength $r = 1$). The bidirectional design is essential to achieving a substantial quantum advantage because of its ability to eliminate vacuum noise at reflectors. Moreover, the high quantum advantage is possible even when information between the two phases are nearly inseparable ($T \approx 1$).

As a more complex example, Figure 2(b) plots the quantum advantage as a function of reflector transmission T for a three-phase, two-reflector interferometer. The additional reflector introduces the possibility of multiple reflections as well as multiple inputs at different times. It also means some amount of vacuum noise will always enter the system, but can be compensated by sequentially interfering many squeezed pulses. Traces of the quantum advantage using up to 5 pulses are shown, demonstrating greater quantum advantage with each added pulse. Thus, with a sufficient number of input pulses, a quantum advantage near its maximum possible value is achievable. Moreover, the three-phase interferometer is representative of the behavior of an N-phase interferometer, and so the same methods can be used for quantum-enhanced sensing in much larger structures. As shown in Figure 2(c), larger interferometers will optimally have weaker reflectors, such that the total transmitted power remains 6%.

In summary, we present a novel architecture for performing quantum-enhanced multiparameter metrology, where measurable phases are cascaded in series. We show that such a sensor can achieve a high quantum advantage in phase sensitivity with squeezed light in both a simple two-phase and more complex three-phase structure. This work shows the potential in using squeezed light and quantum metrology for practical sensors in optical fiber.

References

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