Loss-tolerant all-optical distributed sensing

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OCIS codes: 270.5585,270.6570, 270.5290

Abstract: We investigate a resource-efficient distributed quantum sensing (DQS) scheme using phase-sensitive optical parametric amplifiers and linear optics, achieving sensitivity levels close to the optimal limit determined by the quantum Fisher information of the resource state.

Quantum metrology estimates an unknown physical quantity using quantum resources such as quantum coherence and entanglement beyond the classical limitations [1]. Since the first proposal of using quantum resources to enhance the gravitational wave detection by squeezed states, there have been numerous theoretical proposals and proof-of-principle experiments, including quantum-enhanced interferometer and quantum-enhanced clock [2,3]. Displacement sensing has gained significant interest for its applications in fundamental sciences and advanced sensing technology development [4]. Conventional displacement sensing estimates an input state's displacement, assuming a displacement axis. In single-mode and distributed sensing cases, balanced homodyne detection (BHD) is the optimal measurement for measuring phase-space quadratures along this axis. However, while quantum-enhanced, these implementations fall short of their full potential due to BHD's overall detection inefficiencies and limited bandwidth in the mega- to gigahertz range.

In this work, we introduce a novel approach that overcomes the limitations of traditional BHD-based distributed sensors. Our method uses phase-sensitive optical parametric amplifiers (OPAs), linear interferometers, and displacement operations to achieve optimal performance allowed by the quantum Fisher information (QFI). We show its high tolerance to overall detection loss, which is crucial to attain full quantum advantages. Moreover, our method significantly expands the accessible bandwidth of quantum fields to tens of terahertz, offering significant scalability advantages with frequency-multiplexed architectures. Our proposed scheme is displayed in Fig. 1a,

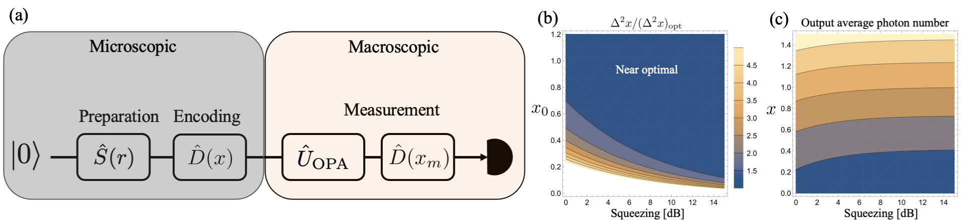

Fig. 1. (a) Single-mode displacement estimation of an unknown parameter x. The high-gain OPA (i.e., $G \gg 1$), $\hat{U}_{\text{OPA}}$, transforms the microscopic quadrature to a macroscopic levels. Introducing an additional displacement x_m breaks the symmetry and allows one to discriminate x and $-x$ via direct power detection. (b) Error ratio ($\Delta^2 x/(\Delta^2 x)$opt) with respect to the optimal error at high-gain OPA gain G = 50 dB and an unknown displacement x = 0.01. (b) The average photon number in the displacement-encoded amplified signal at G = 50 dB and $x_0 = 1$, showing the macroscopic average photon number detectable by a classical detector.

where the grey and beige shaded regions depict the probe and encoding and measurement procedures, respectively. We first consider the single-mode displacement sensing with a squeezed vacuum as a probe state, and the unknown sensing parameter is encoded via displacement. The encoded microscopic quadrature $\hat{x}_{\phi=0}$ first amplified to a macroscopic level with a high-gain OPA. Subsequently, the amplified quadrature undergoes a known displacement x_m, followed by power detection using a classical photodiode. The role of the known displacement operation is to discriminate the quadrature x and $-x$ unambiguously via direct power measurements. Note that the displacement operation is applied to a macroscopic quadrature; thereby, the approximated all-optical implementation of the displacement via an unbalanced beam splitter does not lead to severe degradation in the performance. Mathematically, the probe state is $\hat{S}(r)|0\rangle = |r\rangle \to \hat{D}(x)|r\rangle \equiv |\psi_{\text{out}}\rangle$, where $\hat{S}(r) \equiv e^{r(\hat{a}^2 - \hat{a}^{\dagger 2})/2}$ is the squeezing operation with parameter r and $\hat{D}(x) \equiv e^{-i\hat{p}x}$ is the displacement operator, both along the x axis. The resulting state $|\psi_{\text{out}}\rangle$ contains the encoded information of x, which can be extracted through our proposed measurement. We first analyze the performance of the OPA-assisted all-optical quadrature power detection as a substitute for conventional homodyne detection. By incorporating the additional known displacement, the total displacement is given by $\sqrt{G}x + x_m$, where $G = e^{2r_m}$ is the OPA gain. This allows us to differentiate between x and $-x$, corresponding to distinct values before the power measurement when $x_m \gg \sqrt{G}|x|$. As a result, the photon-number operator, which we use as an estimator, is $\hat{O} = \hat{U}^\dagger_{\text{OPA}}(\sqrt{G})\hat{D}^\dagger(x_m)\hat{n}\hat{D}(x_m)\hat{U}_{\text{OPA}}(\sqrt{G})$. We then use the error propagation $\Delta^2 x = \Delta^2\hat{O}/|\partial\langle\hat{O}\rangle/\partial x|^2$ to analyze the sensitivity of the proposed scheme. We can determine the estimation error by calculating the first and second moments of the estimator for the output state. In the high-gain limit, $r_m \gg 1$, the estimation error simplifies to

$$\Delta^2 x \to \frac{1}{2e^{2r}} + \frac{e^{-4r}}{8(x+x_0)^2}. \tag{1}$$

For sufficiently large initial squeezing r and effective displacement $(x+x_0)^2$, the sensitivity $\Delta^2 x \to 1/2e^{2r}$ attains the Heisenberg scaling in the input photon number and reaches its optimum value determined by QFI. In Fig. 1 (b), we illustrate the impact $x_0 = x_m/\sqrt{G}$ on estimating the unknown displacement $x = 0.01$ under different levels of input probe squeezing with a given $G = 50$ dB. We use the ratio $\Delta^2 x/(\Delta^2 x)$opt to evaluate the performance. We chose $G = 50$ dB to ensure that the displacement-encoded OPA-amplified signal possesses a macroscopic level of photons (Fig. 1c), enabling direct detection by simply measuring the power using classical detection. Our scheme achieves nearly optimal performance by carefully selecting the known displacement for a given input squeezing over various parameters.

Next, we extend our scheme to two distributed displaced sensing protocols with different measurement settings (Fig. 2). Both schemes first create a multipartite entangled state by distributing a single-mode squeezed state over M modes using a programmable beamsplitter array (BSA) characterized by $\hat{U}_{BSA}$. This is followed by the identical displacement operations $\hat{D}(x)$ for encoding the unknown displacement. The first scheme (Fig. 2a) involves applying $\hat{U}^\dagger_{\text{BSA}}$ to transfer the information of multimode displacement to a single mode, which is subsequently measured with our proposed method while disregarding the remaining modes. On the other hand, the second scheme (Fig. 2b) considers using M high-gain OPAs and displacement operations for each mode, followed by total power detection. We find that both schemes achieve near-optimal performance $\Delta^2 x \to 1/2Me^{2r}$ (Fig. 2a,

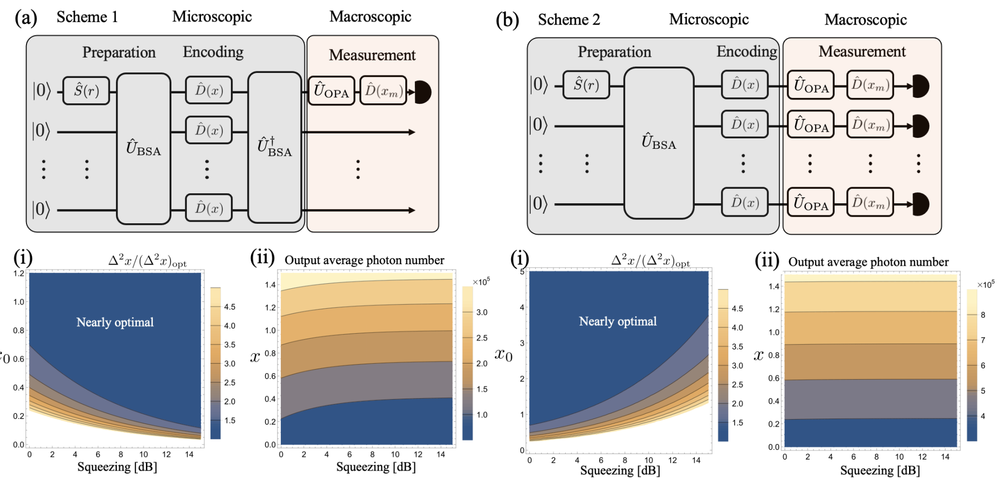

Fig. 2. Multimode displacement sensing scenarios. (a) Encodes multimode displacements onto a single mode using a BSA, followed by a single high-gain OPA and known displacement for extracting the displacement parameter. (b) Each mode is directly measured using our proposed scheme without BSA. We set M = 10, x = 0.01, and G = 50 dB for numerical simulations.

b (i)) in both the number of modes and average photon number while offering the macroscopic optical signal detectable by a classical photodetector (Fig. 2a, b (ii)). Furthermore, we perform the loss analysis by accounting for two distinct types of loss. The first occurs right after encoding, and the second just before photodetection. Our approach shows high resilience to losses that occur post the high-gain OPA amplification, enabling one to fully harness the advantages offered in DQS systems. This work is supported by National Science Foundation Grant No. 1846273 and No. 1918549, ARO Grant W911NF-23-1-0048, and NASA Jet Propulsion Laboratory.

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