Distributed phase sensing using two-mode squeezed states in a truncated SU(1,1) interferometer

Seongjin Hong,[1,*] Matthew A. Feldman,[1] Claire E. Marvinney,[1] Michael Febbraro,[1] Alberto M. Marino,[1] and Raphael C. Pooser,[1]

[1] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*

**seongjinhong90@gmail.com*

Abstract: We demonstrate distributed phase sensing with a truncated SU(1,1) interferometer through the measurement of a linear combination of two phases distributed between the two beams of a two-mode squeezed state. We theoretically analyze the sensitivity enhancement with respect to the corresponding classical strategy and experimentally demonstrate a 2 dB quantum noise reduction in the measurement of a linear combination of two phases.

1. Introduction

Quantum metrology has drawn increasing interest, as it allows us to estimate an unknown parameter with enhanced sensitivity over classical approaches by exploiting quantum resources [1]. Recently, there has been a push toward multi-parameter sensing for various applications [1]. In particular, distributed quantum sensing provides a measure of a linear combination of spatially distributed independent parameters, which can be a useful tool in various sensor network applications such as dark matter search, local beam tracking, and global-scale clock synchronization [2]. A notable way to achieve a quantum enhanced sensitivity is through the use of squeezed states via a nonlinear interferometer called a SU(1,1) interferometer, in which the beam splitters of a traditional interferometer are replaced with nonlinear parametric amplifiers [3].

The phase sensitivity of the measurements in the SU(1,1) can be maintained in a truncated version of the interferometer (tSU(1,1)), in which the second nonlinear parametric amplifier is replaced with homodyne detection [3]. The advantage is that homodyne detection can be performed locally as it only requires additional reference beams, which provide an external reference phase. Due to these features, the tSU(1,1) can be used as a distributed quantum sensor. However, the study of the tSU(1,1) for distributed sensing has not been done yet.

In this work, we theoretically characterize the improvement in sensitivity for the measurement of a linear combination of two phases in a tSU(1,1) interferometer and experimentally demonstrate a 2 dB quantum noise reduction for distributed phase sensing.

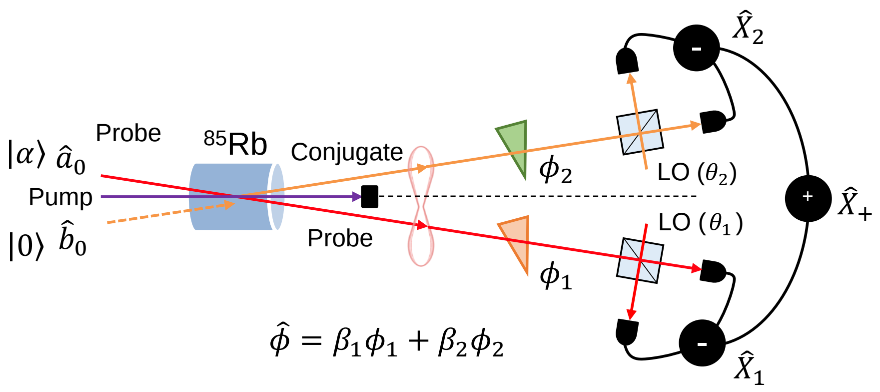

Fig. 1. Schematic of a distributed quantum sensor to estimate the linear combination of two phases in a tSU(1,1) interferometer. Two-mode squeezed states are generated in a ^{85}Rb vapor cell and experience phase shifts of ϕ_1 and ϕ_2, respectively. Then they are measured by two homodyne detectors to perform a joint measurement to estimate $\hat{\phi} = \beta_1\phi_1 + \beta_2\phi_2$. LO; local oscillator.

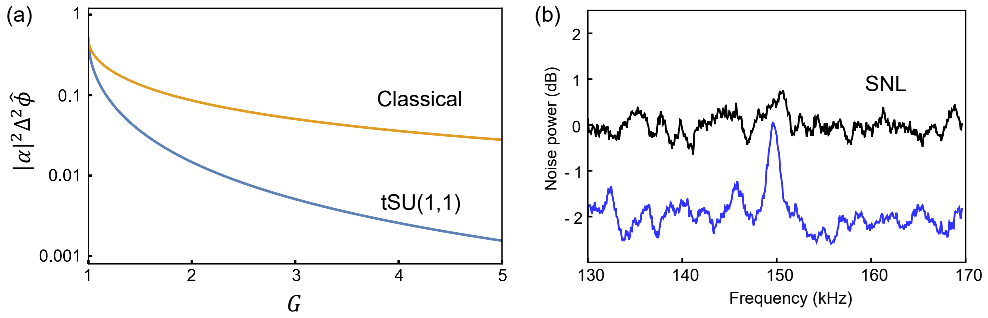

Fig. 2. (a) Theoretical limit of detection sensitivity of the linear combination of phases multiplied by the optical intensity $|\alpha|^2$ as a function of gain G. The orange solid line is the sensitivity of the classical approach and the blue solid line denotes the sensitivity of the tSU(1,1) interferometer. (b) Measured spectrum analyzer traces of the modulation of $\hat{\phi}$ at a 150 kHz analysis frequency. The black line is the shot noise limit (SNL) and the blue line represents the signal from the tSU(1,1) interferometer.

2. Theory and experiment

Figure 1 is our experimental setup for estimating a linear combination of two phases. There are two distributed unknown phases ϕ_1 and ϕ_2, and our goal is to estimate the linear combination of $\hat{\phi} = \beta_1\phi_1 + \beta_2\phi_2$ satisfying the normalizing condition $\beta_1 + \beta_2 = 1$. The two-mode squeezed states experience phase shifts of ϕ_1 and ϕ_2, respectively, and are jointly measured with a balanced dual homodyne detection system. To calculate the expected sensitivity, one can obtain the observable of $\hat{X}_+(\hat{\phi}) = \hat{X}_1(\phi_1) + \hat{X}_2(\phi_2)$, where $\hat{X}_1(\phi_1)$ ($\hat{X}_2(\phi_2)$) is the quadrature from the homodyne detection signal of probe (conjugate). Here, we assume that the phases of the LOs used as phase references are fixed to $\pi/2$. Then, the minimum detectable phase is defined by the limit of detection (LOD) as

$$\Delta^2\hat{\phi} = \frac{\Delta^2\hat{X}_+}{(\partial_{\hat{\phi}}\hat{X}_+)^2}, \tag{1}$$

where $\Delta^2\hat{X}_+$ is the variance of measurement [3]. Figure 2(a) shows the theoretical LOD for both the tSU(1,1) and the classical approach with the same total optical power, as a function of gain G, which is related to the squeezing parameter $r = \cosh^{-1}(\sqrt{G})$. As can be seen, a sensitivity enhancement can be obtained and increases as the gain increases.

Next, we experimentally realize the tSU(1,1) interferometer using a ^{85}Rb vapor cell [4]. A small phase shift is imparted on $\hat{\phi}$ with a photo-elastic modulator at a frequency of 150 kHz. The signal appears on the spectrum analyzer as a peak as shown in Fig. 2(b), where the signal is normalized to the shot noise limit. A quantum noise reduction of 2 dB was achieved in our experiments, which enables the measurement of smaller phase modulations in the tSU(1,1) interferometer than with the classical approach. We theoretically and experimentally study a quantum enhanced sensitivity for measuring two distributed phases in a tSU(1,1) interferometer. Distributed quantum sensors based on a nonlinear amplifier can provide a practical platform to investigate various sensing applications.

3. Acknowledgement

This work was performed in part at Oak Ridge National Laboratory, operated by UT-Battelle for the U.S. Department of Energy under contract no.DE-AC05-00OR22725. Support for this work came from the U.S. DOE, Office of Science, Office of High Energy Physics and from the U.S. DOE, Office of Science National Quantum Information Science Research Centers, Quantum Science Center.

References

1. S. Pirandola, B. R. Bardhan, T. Gehring, C. Weedbrook, and S. Lloyd, “Advances in photonic quantum sensing,” Nat. Photon. **12**, 724 (2018).
2. W. Ge, K. Jacobs, Z. Eldredge, A. V. Gorshkov, and M. Foss-Feig, “Distributed quantum metrology with linear networks and separable inputs,” Phys. Rev. Lett. **121**, 043604 (2018).
3. B. E. Anderson, et al., “Phase sensing beyond the standard quantum limit with a variation on the SU(1,1) interferometer,” Optica **4**, 752 (2017).
4. R. Pooser, N. Savino, E. Batson, J. Beckey, J. Garcia, and B. Lawrie, “Truncated nonlinear interferometry for quantum-enhanced atomic force microscopy,” Phys. Rev. Lett. **124**, 230504 (2020).