Snowmass2021 - Letter of Interest

Opportunities for Optical Quantum Noise Reduction

Thematic Areas:

■ (IF1) Quantum Sensors

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Abstract: Optical quantum noise reduction (QNR), or squeezing, has a long history in the search for gravitational waves[1]. In recent years the quantum effect has achieved demonstrated utlity in important experiments such as LIGO[2]. In such demonstrations, the advantages of optical sensing techniques (such as the extremely high precision afforded by fringe counting in interferometry, for example) have been enhanced with reduced noise floors, allowing for even higher precision than is available with semi-classical (coherent) sensing probes. Additional experiments which use optical probes, such as table-top gravitational wave detection experiments or accelerometry for detection of fundamental particles coupling to gravity (see related LOI by D. Carney *et al.*: "Mechanical sensors as particle detectors: Snowmass LOI") stand to benefit from similar noise reduction techniques. To date, most sensors which exploit squeezing have demonstrated a reduced noise floor over a single mode of the optical field. That is, the signal transduction occurred in a single mode, where noise reduction over only a single mode was required. Here, we consider the natural generalization of signals and noise to multi-mode detection and discuss the advantages of multi-mode quantum noise reduction in such scenarios. In particular, we consider quantum-networked sensors (see related LOI by N. Peters *et al.: "Quantum Networks for High Energy Physics"*) for certain physical phenomena which would benefit from this generalization.

Motivation: Optical quantum noise reduction (QNR), or squeezing, has a long history in the search for gravitational waves[1]. In recent years the quantum effect has achieved demonstrated utility in important experiments such as LIGO[2]. In such demonstrations, the advantages of optical sensing techniques (such as the extremely high precision afforded by fringe counting in interferometry, for example) have been enhanced with reduced noise floors, allowing for even higher precision than is available with semi-classical (coherent) sensing probes. Additional experiments which use optical probes, such as table-top gravitational wave detection experiments or accelerometry for detection of fundamental particles coupling to gravity (see related LOI by D. Carney *et al.*: "Mechanical sensors as particle detectors: Snowmass LOI") stand to benefit from similar noise reduction techniques. To date, most sensors which exploit squeezing have demonstrated a reduced noise floor over a single mode of the optical field. That is, the signal transduction occurred in a single mode, where noise reduction over only a single mode was required. Here, we consider the natural generalization of signals and noise to multi-mode detection and discuss the advantages of multi-mode quantum noise reduction in such scenarios. In particular, we consider quantum-networked sensors (see related LOI by N. Peters *et al.*: "Quantum Networks for High Energy Physics") for certain physical phenomena which would benefit from this generalization.

Notably, both microwave regime and atomic fields have obtained quantum noise reduction. In general, these media can outpace the rate of QNR obtained optically, although the current record for optical squeezing (15 dB) is close to both of these categories[3]. On the other hand, under certain conditions, optical fields may be used to transduce and transmit signals over long distances with very low loss, and under those same conditions they may facilitate quantum networks of sensors which obtain sensitivity scaling at the Heisenberg limit.

Squeezing in Optical Fields: Squeezing of a single mode of the optical spectrum of the electromagnetic field is often obtained from optical parametric amplifiers. Such systems have interaction Hamiltonians of the form (in the interaction frame of the Heisenberg picture) $H = i\hbar\kappa(a^2 - a^{\dagger 2})$, where $\chi^{(2)}$ is a material property related to the nonlinear polarizability of the interaction medium, a is the quantum annihilation operator for an optical field which interacts with a second field a_p, which provides energy for the interaction, and $H.C.$ is the Hermitian conjugate of the preceding term. In general the field a_p is large and can be taken classically, such that $\kappa = \chi^{(2)}\alpha_p$. Obtaining the equations of motion and solving for the time-dependent quadrature operators $X = a + a^\dagger$ and $P = i(a - a^\dagger)$, one obtains the variances

$$\left\langle \Delta P(t)^2 \right\rangle = e^{2\kappa t} \left\langle \Delta P(0)^2 \right\rangle, \tag{1}$$

$$\left\langle \Delta X(t)^2 \right\rangle = e^{-2\kappa t} \left\langle \Delta X(0)^2 \right\rangle. \tag{2}$$

That is, the amplitude operator, X is squeezed while the phase operator P is antisqueezed. In general, the squeezing angle may be oriented in the phase space such that a combination of X and P is squeezed. This leads to the basic idea that signals can be transduced into the quadratures which obtain QNR, and through measurements of the quadratures one may obtain signals with higher SNR than one could obtain with ordinary optical fields. For example, the X quadrature can be measured via balanced homodyne detection (BHD). Therefore, one may use a local oscillator (LO) in BHD which is itself a squeezed field in order to observe signals consisting of modulation of the X quadrature with noise floors below the standard quantum limit (SQL). Interferometry is required to observe amplitude or phase squeezing of optical fields, but squeezing of the intensity, or photon number, is observable with direct detection.

Consider the case of a beam deflection measurement. Such a measurement could be useful in observing the deflection of a micro-electro-mechanical system (MEMS) cantilever. Such a device can be used as an accelerometer, for example. Acting as a mirror, a MEMS cantilever can deflect light and impart a pure phase shift to an optical field. By orienting the squeezing angle in phase space to coincide with phase detection, one can obtain phase measurements with noise below the SQL, and thereby infer accelerometer displacement with precision beyond that available with the SQL. A key advantage of this technique is that squeezed LOs may be superimposed upon the signal fields to reduce the SQL at the BHD[4;5].

Multi-mode Squeezed Fields: While most sensors which exploit squeezing to date have utilized single modes of the electromagnetic field, in general nondegenerate interactions can result sharing of quantum correlations between readily distinguishable modes. In this case, $H = i\hbar\chi^{(2)}a_i a_j a_p^\dagger + H.C.$, and one obtains joint quadrature operators which are squeezed: $P_+(t) = P_i + P_j = e^{-\kappa t}P_+(0)$; $X_-(t) = X_i - X_j = e^{-\kappa t}X_-(0)$. Obtaining such measurements with dual BHDs when the signal field's phase is squeezed relative to the phase of a reference field is known as truncated nonlinear interferometry[6]. Notably, the presence of squeezing in these two operators simultaneously is evidence of the Einstein Podolsky Rosen (EPR) paradox[7;8]. In other words, one may construct quantum sensors that transduce signals onto a probe field and measure signals with respect to a reference field by generating entangled beams of light and then performing joint quadrature measurements. Alternatively, one may perform joint intensity measurements and demonstrate QNR below the shot noise limit in signals transduced to the intensity of an optical field. Consider two accelerometers which transduce an impulse, such that the displacements of the accelerometers are correlated. The signals can be obtained via the joint P_+ measurement, for example, after reflecting one half of an entangled state from each accelerometer. Such a system may be thought of as a two-node quantum sensor network.

Squeezed Networks: Consider the case of more than two accelerometers, such that one has a network of such devices in which each node on the network denotes the location of an accelerometer. In fact, one may obtain the generalization of the two-mode EPR state by considering a generalization interaction Hamiltonian among $N > 2$ optical modes, where each mode interacts equally with all of the others. This special case is known as a Greenberger-Horne-Zeilinger (GHZ) state.

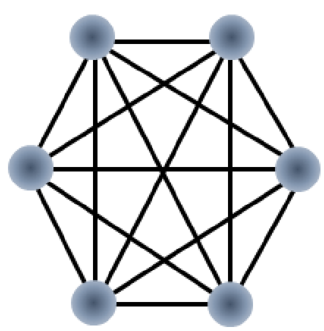

Figure 1: The connectivity-graph that represents the entangling interactions required to prepare a GHZ state, with nodes representing optical fields and lines representing entangling interactions.

One can easily show that the squeezed operators for this network are

$$(N-1)X_1 - \sum_{i=2}^{N} X_i, \tag{3}$$

$$\sum_{i=1}^{N} P_i. \tag{4}$$

Figure 1 shows a graphical representation of a network with these squeezed operators. Considering that at every node or at a subset such as half of the nodes, one may locate an accelerometer, one may detect impulses below the SQL whose force correlates all of the accelerometers by measuring the joint quadratures above.

The network here is a special case, and more complex state preparation tailored to specific signals is possible. For example, one may imagine preparing the network of optical modes in any stabilizer code that can be reached with the entangling Hamiltonian and linear optics transformations. One could then consider detecting impulses of arbitrary spatial extent across the network with sub-SQL accuracy.

Because accelerometers can be used as impulse detectors, one can aspire to use them as sensors for trajectories of particles which couple to gravitational fields. Squeezed networks of these sensors could be used to study such particles or to study the nature of gravity itself.

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