Mitigating Mode-Matching Loss in Nonclassical Laser Interferometry

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Strongly squeezed states of light are a key technology in boosting the sensitivity of interferometric setups, such as in gravitational-wave detectors. However, the practical use of squeezed states is limited by optical loss, which reduces the observable squeeze factor. Here, we experimentally demonstrate that introducing squeezed states in additional, higher-order spatial modes can significantly improve the observed nonclassical sensitivity improvement when the loss is due to mode-matching deficiencies. Our results could be directly applied to gravitational-wave detectors, where this type of loss is a major contribution.

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Nonclassical, squeezed states of light have progressed from being just peculiar quantum states to a quantum-mechanical technology that increases the sensitivity of interferometric measurements without the need for increasing laser power. This is a remarkable feature with application in several areas [1].

For example, gravitational-wave detectors already operate with extremely high laser power that is limited both by engineering difficulties of the laser sources as well as the induced thermal load on the interferometer mirrors [2,3]. While an increase in laser power by a factor of 10 (corresponding to a $10^{3/2} \approx 32$ increase in the observable Universe at shot-noise limited detection frequencies) seems extremely challenging, the same improvement could be achieved with the injection of squeezed light with a noise-reduction factor of 10 dB. Such strongly squeezed states are now routinely produced at near-infrared wavelengths [4–8]. In 2010, GEO 600 was the first gravitational-wave detector to employ squeezed-light input [9,10]. A test of squeezed light at the LIGO detector was successfully performed just before the upgrade to Advanced LIGO started [11], and an installation of squeezed-light sources at the Advanced LIGO and Advanced Virgo detectors is currently in progress [12,13].

Because squeezed states of light rely on quantum correlations between the individual photons, they are more sensitive to optical loss than coherent states: when photons are lost, these correlations are also destroyed. Tabletop experiments routinely achieve less than 10% total loss from production to detection of the squeezed states, allowing squeeze factors in excess of 10 dB and recently achieving 15 dB [8]. Yet, transferring these high values to quantum-metrology applications remains a challenge. For example, the best squeezing in the large-scale interferometer GEO 600 was measured to be 4.4 dB [14]. This stark contrast is due to a much higher optical and interferometric complexity, which brings the total loss to a value of $> 30\%$ [9,11,14]. Similarly, quantum enhancement in biological measurements [15] and magnetometry, using both atomic systems [16] or microresonators [17], has been limited by optical loss.

Some optical loss—such as absorption, scattering, and polarization mismatch—stems from imperfect optical elements and its impact can hopefully be reduced with additional engineering work. Another source of optical loss is imperfect matching between the wave fronts of the involved light fields, i.e., mode mismatch or axial misalignment. This loss channel is often difficult to control; e.g., in gravitational-wave detectors, sophisticated automatic alignment systems are in use [18,19], as well as adaptive mode matching with movable lenses [20] and/or thermal deformation of optical elements [21]. The latter two methods are, however, limited to quasistatic corrections and cannot adapt well to dynamically changing light fields.

An alternative way to alleviate the loss of squeezing due to mode mismatch is to additionally squeeze a small number of higher-order transverse modes of light. Töyrä *et al.* [22] theoretically analyzed the improvement that can be achieved for squeezing the Hermite-Gaussian HG_{20} and HG_{02} modes in addition to the fundamental mode HG_{00}. In their simulations, they are able to recover almost the full nonclassical sensitivity gain, for mode mismatching loss as high as 15%.

Here, we experimentally demonstrate the reduction of mode-matching loss in an interference experiment by additional squeezing of a higher-order transverse mode. Our proof-of-principle experiment almost fully compensates a

(7%) mode-mismatching loss between a squeezed field and the local-oscillator field of a balanced homodyne detector (BHD) [23]. Since the underlying theory of mode coupling is exactly the same, our results are also applicable to mode mismatch in cavity setups.

Conceptual description.—The idea behind squeezing of higher-order spatial modes for mode-mismatch compensation can be illustrated with the help of Fig. 1 in the following way. A BHD selectively amplifies and measures all components of a signal field that are contained in the spatial mode LO_{00}, which is defined by its so-called local oscillator (LO) beam. Usually, this mode is prepared in a well-defined HG_{00} state. Since all other HG_{mn} modes are orthogonal to HG_{00}, they do not interfere with the LO and do not contribute to the output of the BHD.

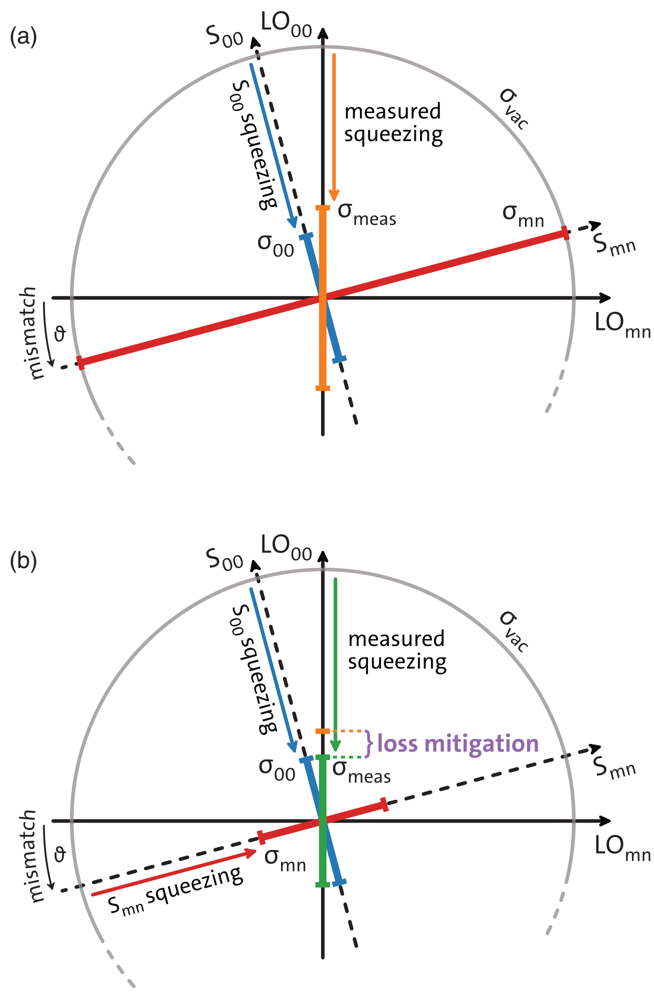

FIG. 1. Illustration of the concept behind mode-matching loss compensation with squeezed higher-order modes. Two orthogonal axes represent the electric fields in two orthogonal transverse spatial modes. The vacuum uncertainty of any combination of modes is represented by the outer circle σ_{vac}. Mode S_{00} corresponds to the mode carrying the signal of interest and should ideally be aligned with the mode LO_{00} of the local oscillator in balanced-homodyne detection, which defines the mode that is actually measured. Mode mismatch, represented by a rotation by angle ϑ, then couples quantum noise σ_{mn} from higher-order mode (s) into the measured quantum noise σ_{meas} in LO_{00}, as given by Eq. (1). (a) When only mode S_{00} is squeezed, and S_{mn} is in a vacuum state, the mode mismatch leads to a significant contribution of vacuum uncertainty to σ_{meas}. (b) When both S_{00} and S_{mn} are squeezed (here with identical squeeze factors), the optical loss due to mode mismatch is mitigated.

When the signal beam is mismatched with respect to the local-oscillator field, it needs to be described by its own set of transverse modes S_{mn}. For a small mismatch, the relation between the two sets of modes can be conceptually represented as a rotation by a mismatch angle ϑ. It connects the measured noise uncertainty σ_{meas} to the noise uncertainties σ_{00} and σ_{mn} in the signal field S_{00} and its higher-order modes S_{mn}, respectively, by the relation

$$\sigma_{\mathrm{meas}} = \sqrt{\sigma_{00}^2 \cos^2\vartheta + \sigma_{mn}^2 \sin^2\vartheta}, \tag{1}$$

where the noise in the individual modes is assumed to be uncorrelated.

When S_{mn} is in a vacuum state, $\sigma_{mn} = \sigma_{\mathrm{vac}}$, this relation implies that the mismatch is equivalent to an optical loss $\epsilon = \sin^2\vartheta$ acting on the (squeezed) mode S_{00}. Figure 1(a) visualizes this with the rotated, dashed coordinate system. The combined projection of the noise in the S_{00} and S_{mn} modes onto the LO_{00} mode results in a measurement noise σ_{meas} that exceeds the original squeezed noise σ_{00} in the signal beam by far. For more complex mismatches, the same considerations apply and extend to multiple mode dimensions.

From Eq. (1), the solution becomes obvious: if the noise in S_{mn} is also squeezed, then its contribution to the measurement noise can be significantly reduced. This is visualized in Fig. 1(b), where the squeezed σ_{mn} leads to a reduction of the noise components along the LO_{00} axis. With the exemplary squeeze factors chosen here for illustration, the initial squeezing is fully restored.

Generating squeezed states of light in higher-order spatial modes was investigated in the context of measuring lateral displacement and tilt of a laser beam [24]. More recently, applications of spatial squeezing in quantum imaging have been studied, see, e.g., [25]. Higher-order modes can also serve as additional (quantum) communication channels in quantum information networks, either increasing the channel capacity by the number of modes that are used, or representing individual modes of a multimode entangled state [26].

There are two main approaches to the production of squeezing in higher-order spatial modes: via reshaping or via direct squeezing [27]. In the first approach, squeezing is conventionally generated in the fundamental mode, and then converted into higher-order modes with the use of phase plates [24] or spatial-light modulators [27]. Especially the latter allows for a very flexible generation of almost arbitrary mode shapes; however, the overall efficiency and optical loss is limited by the resolution of the spatial-light modulator. In the direct approach, e.g., [28], the nonlinear parametric cavity is aligned such that it resonates on the desired higher-order mode. This approach yields very pure states that can in principle have the same amount of squeezing as the fundamental mode; however, it is only viable for low mode orders and does not support arbitrary mode shapes.

Experimental setup.—Our experiment followed the direct approach, with the setup depicted in Fig. 2. Two squeezed-light sources produced continuous-wave squeezed states of light at a wavelength of 1064 nm, using the same optical assembly as described in detail in [29]. Here, we label the two sources by the mode that they produced: while S_{00} was held resonant for a HG_{00} mode, the cavity of S_{mn} was held on resonance for a higher-order mode, specifically we chose the HG_{01} mode. This was achieved by intentionally introducing a vertical displacement in the control field at 1064 nm, which enters the cavity and is used both for locking and as an alignment reference. To obtain sufficient nonlinear gain inside the squeezing cavity, also the pump field at 532 nm had to be vertically adjusted. For both control field and pump field, the coupling to the cavity's HG_{01} mode was about 30%, which is about three quarters of the maximally achievable mode overlap between a HG_{01} mode and a displaced HG_{00} mode. In theory, this coupling could be as good as 43%.

The squeezed field S_{00} was first sent through a Faraday isolator, and then reflected off the S_{mn} cavity (as S_{mn} was not resonant for the S_{00} mode) [30]. A piezomounted mirror between the two squeezers served to adjust the relative phase of the two squeezed fields $\Delta\phi$. The combined fields S_{00} and S_{mn} then traveled through the Faraday isolator towards a balanced homodyne detector, where they were overlapped at a 50:50 beam splitter with a strong local-oscillator field. Both beam-splitter outputs were detected with photodetectors and the difference in photo currents was taken. After amplification, the output power spectrum was measured with a spectrum analyzer at a sideband frequency of 5 MHz. One of the beam-splitter outputs could be optionally sent towards a spatial-mode analyzer, which was a ring cavity specifically designed such that there was almost no mode degeneracy up to very high mode orders. This spatial-mode analyzer was used to investigate the mode content of all fields arriving at the BHD and additionally served as an alignment reference. The local-oscillator field came from a mode-filtering cavity as well, and could therefore be prepared in a very pure mode state. Figure 3 shows that our setup generated about 4.8 dB of squeezing in the HG_{01} mode, which to our knowledge is the highest amount of squeezing in a higher-order spatial mode reported so far.

Results.—In the first step, we activated only S_{mn} and prepared the local oscillator in the LO_{00} (HG_{00}) mode, with no vertical displacement Δy. In this configuration, we made sure that we were unable to detect squeezing from S_{mn}, due to the vanishing mode overlap, see the left panel of Fig. 4. We then turned on S_{00} as well. After reflection from S_{mn} and traveling twice through the Faraday isolator, we measured about 5.8 dB of squeezing.

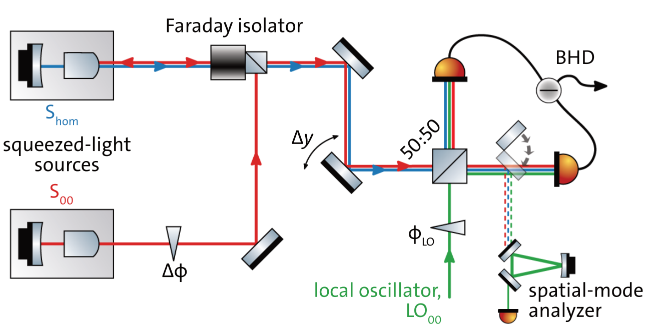

FIG. 2. Schematic of our proof of concept of using squeezed states of light in higher-order transverse modes to compensate for optical loss caused by mode mismatch. Squeezed-light source S_{00} produced output states in the fundamental HG_{00} mode, while squeezed-light source S_{mn} produces output states in the HG_{01} mode. The two fields were combined with a Faraday isolator and then sent towards a balanced homodyne detector (BHD). The BHD's local oscillator LO_{00} was contained in the HG_{00} fundamental mode. Mode-matching loss was intentionally introduced by a vertical misalignment of one of the steering mirrors by Δy. The resulting mode content could be examined with a spatial-mode analyzing cavity in one of the paths of the BHD, when the two squeezing resonators were operated with a strong carrier field but without pumping.

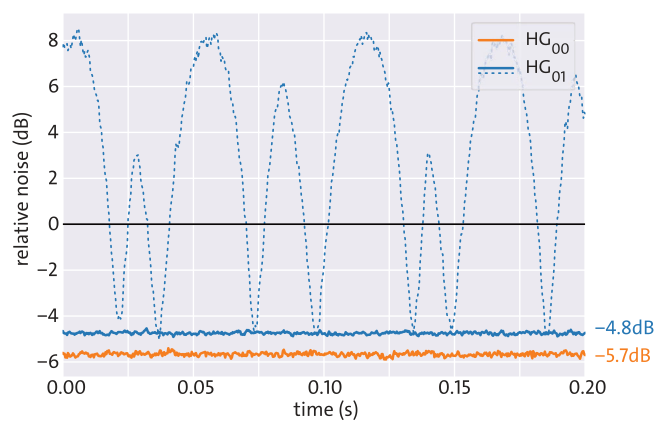

FIG. 3. Characterization of squeezed states of light from squeezing resonator S_{mn}, when resonating in the HG_{01} transverse mode, compared to resonating in the HG_{00} mode. In each case, the local oscillator was provided in the corresponding mode to achieve an optimal mode overlap at the balanced homodyne detector. The dashed blue curve was produced by scanning the local-oscillator phase ϕ_{LO}, thus showing the oscillation between squeezing and antisqueezing. All traces were acquired with a resolution bandwidth of 300 kHz and a video bandwidth of 300 Hz, at a zero-span frequency of 5 MHz and with the local-oscillator power set to 2.25 mW. Except for the scanning trace, an averaging filter of 5 was active.

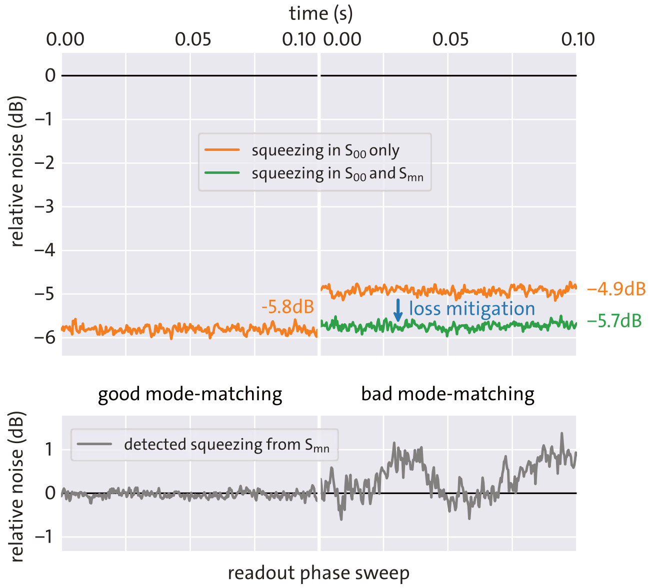

FIG. 4. Confirmation of mitigating mode-matching loss via squeezed higher-order modes. Top left, 5.8 dB of squeezing can be detected for the case where there is no vertical displacement introduced in the squeezing path, $\Delta y = 0$ and thus $S_{00} = \mathrm{LO}_{00}$. Top right, a small vertical misalignment Δy is introduced and the detected S_{00} squeezing drops to 4.9 dB. Introducing the additional squeezed-light field in S_{mn}, almost the full initial squeezing is recovered (5.7 dB, green trace). Bottom, detected noise during a sweep of the readout phase when only S_{mn} is squeezed. This measurement confirms that there is negligible contribution from the squeezed field in S_{mn} for the good mode-matching case, while it becomes visible in the bad mode-matching case.

In the next step, we intentionally introduced a vertical displacement Δy in the path between the Faraday isolator and the BHD by slightly misaligning a steering mirror in that path. The effect on the detected squeezing from S_{00} and S_{mn}, when looked at individually, can be seen in the right part of Fig. 4. First, the squeezing from S_{mn} became visible again, although only with very low squeezing values (the figure shows a sweep of the LO phase ϕ_{LO} of the BHD for this curve, which then also shows the antisqueezing, making it more visible). Second, the detected squeezing from S_{00} dropped from 5.8 dB down to 4.9 dB. From the measured squeezing to antisqueezing for S_{00}, we were able to estimate an additional $(7 \pm 1)\%$ of loss that was introduced by the misalignment. This was also independently verified via the spatial-mode analyzer, which showed an increase in higher-order modes (mostly HG_{01} as expected) by the same 7%. We then switched on both squeezed-light sources at the same time and carefully adjusted the relative phase between the two until we obtained the green trace in Fig. 4. This curve reached a squeezing level of 5.7 dB, i.e., by combining the misaligned S_{00} squeezing with a squeezed S_{mn} beam, we were able to recover almost all squeezing that was lost because of the misalignment. The remaining 0.1 dB can be explained by the small amount of additional modes with $m + n > 1$, which were introduced by the misalignment, but not compensated by the single additional squeezed field.

Summary and conclusion.—We have shown that mitigating optical loss from mode mismatch between a mode carrying squeezed states and a bright local oscillator is indeed experimentally feasible by introducing additional squeezed fields in higher-order modes. Our setup used two squeezed fields in a HG_{00} and HG_{01} mode, respectively, and was able to almost completely compensate for incurred loss due to mode misalignment and brought the measured squeezing level back to within 0.1 dB of the initial value. Although misalignment can usually be compensated quite well with autoalignment methods, our scheme can be extended and applied to a compensation of, e.g., wave-front–curvature mismatch by chaining together additional squeezed-light sources operating in the HG_{20} and HG_{02} modes.

In measurement applications where squeezed states of light are used to increase the shot-noise limited sensitivity, a precise matching of the optical transversal mode to the instrument can be very challenging. In these situations, the setup shown here could be adapted to provide a squeezed field in a specifically tailored transversal-mode configuration, to compensate for encountered loss due to mode mismatch. It is straightforward, although costly, to extend our setup to more higher-order modes, by cascading additional squeezed-light sources via Faraday isolators. Our scheme could enable much higher enhancement factors in quantum metrology, such as in squeezed-light enhanced gravitational-wave detection, where strong squeeze factors are produced but are severely degraded because of optical loss.

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[30] This arrangement was chosen because of constraints of a preexisting setup. To keep propagation loss for the S_{00} mode as low as possible, the roles of the two squeezed-light sources should be reversed.