Alignment sensing and control for squeezed vacuum states of light

E. Schreiber,1,∗ K. L. Dooley,1 H. Vahlbruch,1 C. Affeldt,1 A. Bisht,1 J. R. Leong,1 J. Lough,1 M. Prijatelj,2 J. Slutsky,3 M. Was,4 H. Wittel,1 K. Danzmann,1 and H. Grote1

1Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and Leibniz Universität Hannover, Callinstr. 38, 30167 Hannover, Germany
2European Gravitational Observatory (EGO), I-56021 Cascina (Pt), Italy
3CRESST and Gravitational Astrophysics Laboratory NASA/GSFC, Greenbelt, MD 20771, USA
4Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France

Beam alignment is an important practical aspect of the application of squeezed states of light. Misalignments in the detection of squeezed light result in a reduction of the observable squeezing level. In the case of squeezed vacuum fields that contain only very few photons, special measures must be taken in order to sense and control the alignment of the essentially dark beam. The GEO 600 gravitational wave detector employs a squeezed vacuum source to improve its detection sensitivity beyond the limits set by classical quantum shot noise. Here, we present our design and implementation of an alignment sensing and control scheme that ensures continuous optimal alignment of the squeezed vacuum field at GEO 600 on long time scales in the presence of free-swinging optics. This first demonstration of a squeezed light automatic alignment system will be of particular interest for future long-term applications of squeezed vacuum states of light.

Fig. 1. The effect of misalignment on the observed squeezing level. Here the squeezed beam is misaligned by rotating one of the mirrors in the input path and the squeezing level is recorded. With 0.4 mrad of misalignment, nearly all squeezing is lost. The measurements are compared to a numerical model [9]. The small remaining difference along the x-axis between measurements and model is consistent with the uncertainty of the actuator calibration.

One of the first practical applications of squeezed states of light is in interferometric gravitational wave detection. Injecting a squeezed vacuum state into the dark output port of a Michelson interferometer can reduce the quantum noise in the observed light field quadrature and thereby improve the sensitivity of the detector at frequencies where quantum noise is a limiting factor [1, 2]. This scheme has been successfully demonstrated at the GEO 600 and LIGO gravitational wave detectors [3, 4] and it is in constant use at GEO 600 since 2011 [5, 6].

To observe the full benefit of squeezing, the squeezed light field must be well overlapped with the interferometer’s output beam. The two fields have to match in their alignment axes, beam parameters, and relative phase. While phase control has been treated in [7], this letter reports on the first design and implementation of an alignment sensing and control scheme for the squeezed vacuum field in the context of GEO 600.

Misalignments need to be compensated because a reduced overlap of the squeezed field with the interferometer beam will lead to effective optical losses [8], thus degrading the observed squeezing level and the corresponding improvement of sensitivity (see Figure[1]). Additionally, alignment fluctuations can introduce lock-point errors in the phase control [7, 8].

While short-term tabletop experiments are typically stable enough that one-off manual alignment is sufficient, in a large-scale optical system, such as GEO 600, drifts of the individual components will occur and have to be ac-
The squeezed vacuum field is injected via a Faraday isolator, enters the interferometer through the output port, and is reflected back. It then travels together with the interferometer output beam through the output mode cleaner (OMC) to the detection photodiode. A pair of 3-axis piezo-actuated mirrors in the in-air path serves to steer the squeezed light field. Sets of differential wavefront sensors (DWSs) at two possible locations can be used for alignment sensing.

For the control we need alignment error signals that give a measure of how well the axis of the squeezed field overlaps with the interferometer beam axis. To generate these error signals we use differential wavefront sensing, in which the beat of two light fields with different frequencies is detected on a quadrant photodiode and demodulated to give a signal proportional to the relative misalignments of the two beams. With a set of two differential wavefront sensors (DWSs) at different positions along the beam (with a different Gouy phase), the full set of four alignment DOFs (angular and lateral offsets of the beam axis in horizontal and vertical direction) can be sensed.

Since the squeezed vacuum field contains only very few photons, it cannot directly be detected by the DWSs. Instead, the axis of the squeezed vacuum beam is marked by coherent control sidebands (CCSBs). These are auxiliary light fields with a frequency offset of ±15.2 MHz with respect to the carrier frequency. They are generated inside the squeezed light source and are also used for the longitudinal phase control of the squeezed vacuum. The CCSBs resonate inside the cavity of the optical parametric amplifier (OPA). This ensures that they share the same spatial mode as the squeezed light field that originates from within the interferometer's output mode cleaner (OMC) to the detection photodiode. A pair of 3-axis piezo-actuated mirrors in the in-air path serves to steer the squeezed light field. Sets of differential wavefront sensors (DWSs) at two possible locations can be used for alignment sensing.

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We can now either detect the beat of the CCSBs with the interferometer’s carrier light, or alternatively with existing control sidebands at ±14.9 MHz (called Michelson sidebands) co-travelling with the interferometer beam. The carrier light at the output port, before it is filtered by the OMC, is not a perfect Gaussian beam but is composed largely of higher order modes (HOMs). The distribution of the HOMs is not static in time and introduces varying offsets in the DWS signals which show up as false misalignment signals. The Michelson sidebands, on the other hand, are spatially much cleaner and thus can provide alignment signals that are less contaminated by HOMs. Both variants have been implemented at GEO 600 using the same hardware. The field used for generating the DWS error signals can be selected by choosing the demodulation frequency for the respective optical beat (15.2 MHz for CCSBs vs. carrier light, 0.3 MHz for CCSBs vs. Michelson sidebands). As expected, using the Michelson sidebands rather than the carrier yields significantly more accurate alignment signals. The effect of HOMs in the carrier-derived signals dominates in a way such that using them for feedback control leads to a strongly fluctuating squeezing level as shown in Figure 3. No such effects are present when aligning the squeezed field to the Michelson sidebands, so this proved to be the better method and it was adopted for permanent operation.
Fig. 3. Squeezing level stability with different alignment signals. The plot shows spectra of the detector’s shot-noise level calculated as a band-limited RMS (BLRMS) in the frequency band from 4 to 5 kHz. When locking the alignment of the squeezed beam to the carrier, the contamination of HOMs leads to excess fluctuations within the bandwidth of the alignment loops, which was 4 Hz in this example. When locking to the Michelson sidebands instead, no degradation occurs. There is no measurable improvement with respect to the case without any alignment actuation because alignment fluctuations beyond very slow drifts are currently not a limiting source of squeezing losses.

The DWSs can be placed at two different points in the output chain (see Figure 2): One of the steering mirrors in front of the OMC has a transmission of 1% to provide a pick-off of all relevant fields. Alternatively, the CCSBs and Michelson sidebands are also available in reflection of the OMC. The latter variant has the benefit of higher light powers, allowing a better signal-to-noise ratio. Also, it opens up the possibility of altogether avoiding the loss-inducing pick-off. Sets of DWSs at both positions have been set up and are currently used interchangeably.

Using the error signals, the aim is to actively control the alignment of the squeezed beam with feedback loops. A set of two 3-axis piezo-actuated mirrors in the in-air part of the squeezing injection path (see Figure 2) serve as alignment actuators. They can shift the angle of the beam axis at their respective positions horizontally and vertically and each provide a total range of about 2.5 mrad in the current setup. Like the sensors, the two actuators are spaced apart along the beam path at different Gouy phases to ensure accessibility of all four alignment DOFs.

The feedback control loops are implemented in GEO 600’s digital control and data system (CDS). The demodulated DWS signals are digitized, filtered digitally, and then sent back to analog high-voltage amplifiers that drive the piezo actuators. Figure 4 is a simple demonstration of the positive effect of the alignment control when starting from a misaligned state. Figure 5 shows the resulting error-point suppression of the control loop for two DOFs. Unity-gain frequencies of up to 4 Hz are easily achieved.

The alignment control system for the squeezed field has been in operation for most of the time since squeezing was implemented at GEO 600. The typical state of operation is to control two DOFs using one DWS and one actuator. This is currently sufficient for suppressing almost all relevant misalignments over long periods of time. The remaining two uncontrolled DOFs have to be tuned manually every few months. Full automatic control of all four DOFs has also been successfully demonstrated and is currently being fully commissioned for
future permanent use.

In conclusion, we have designed and implemented a system for sensing and controlling the relative alignment of a squeezed vacuum field to a given interferometer light field. Since there are virtually no photons in the squeezed vacuum state itself, we have resorted to aligning a sideband field to our interferometer. The system we have implemented uses digital control loops which are relatively fast, having a unity gain frequency of a few hertz. It has been running at the gravitational wave detector GEO 600 over a long period of time, demonstrating its reliability. Having automatic control of the alignment proved to be a valuable asset for upkeeping optimal squeezing performance, both during commissioning work as well as during science operation of GEO 600. Because upcoming applications of squeezed light in gravitational wave interferometers will aim for higher levels of squeezing and have lower optical losses, the demands on alignment will be more stringent than those seen in GEO 600 at the time of writing this letter. However, since the control loops we have implemented are fast enough to suppress most occurring alignment fluctuations, they are already well-equipped to fulfill these stronger alignment needs. Furthermore, as the challenge of achieving good alignment will exist in any long-term squeezing experiments, this system may also find applications outside the realm of gravitational wave interferometry.

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