Ultra-low phase noise squeezed vacuum source for gravitational wave detectors: supplementary material

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1. LOSS BUDGET

Here, we provide additional details about the loss measurements presented in Table 1 of the main text, which is reproduced here as Table S1. With the exception of the OPO escape efficiency, all sources of loss are due to the readout system. The homodyne photodiode quantum efficiency was determined by measuring the power incident on the photodiode with a power meter, measuring the generated photocurrent using a transimpedance stage with known gain, and calculating the efficiency of conversion from power to current. The dominant source of uncertainty is due to the calibration of the power meter which is specified to be accurate to $\pm 3\%$. The OPO escape efficiency was measured using a method detailed in Section 7.1.3 of [1]. A beam at the fundamental wavelength is injected into the cavity while the cavity length is scanned. By measuring the reflection dip for the TEM(0,0) mode when the cavity scans through resonance, one can infer the level of intra-cavity losses and compute the escape efficiency. Escape efficiencies as high as 99% were measured, though the exact value varies depending on the crystal alignment and the beam spot position on the cavity mirrors. The propagation losses and homodyne visibility are straightforward to determine with reasonably high precision.

2. PHASE NOISE BUDGET

When working with squeezed vacuum, one has no direct way to control the relative phase between the squeezed and Local Oscillator (LO) fields. As a result, there is no single error signal which one can calibrate to estimate the level of relative fluctuations between the two fields.

Table S1. Loss and phase noise budget

Source of Loss	Value (%)
OPO Escape Efficiency	2 ± 1
Propagation Losses	1 ± 0.2
95% Homodyne Visibility	10 ± 0.5
Photodiode quantum efficiency	5 ± 3
Total Efficiency	$\eta = 0.83 \pm 0.03$
Source of Phase noise	Value (mrad)
OPO Detuning Noise	0.35 ± 0.1
OPO Control Sidebands	0.35 ± 0.1
SHG length noise	1 ± 0.3
CLF shot noise	0.9 ± 0.3
Total Phase Noise	$\theta_{rms} = 1.4 \pm 0.5$

The coherent control technique described in the main text uses two servos to stabilize the squeezed quadrature angle. The first servo, the coherent locking field (CLF) loop, phase locks the CLF to the pump field. Since the phase of the pump field determines the orientation of the squeezing ellipse, this effectively stabilizes the phase of the CLF relative to the squeezed field. The second servo, which we will refer to as the LO loop, phase locks the LO field to the CLF. The aggregate effect of these two loops is to stabilize the phase of the LO relative to that of the squeezed field. Therefore one may use the quadrature sum of the two calibrated error signals as an estimate of the phase noise.

Fig. S1. CLF loop calibrated error spectrum. The dashed line represents the shot noise level. When operated with a bandwidth of 20kHz, this servo is completely shot noise limited. Fluctuations on the pump field due to SHG length noise appear in this error signal as well and are the second largest contributor after shot noise. The orange curve shows an estimate of the SHG length noise contribution.

In practice, using the CLF and LO error signals to determine the phase noise can be difficult, as the coherent control technique is susceptible to lock-point errors. When lock-point errors are present, the coherent control error signals are no longer a reliable measure of the total phase noise. Both the LIGO and GEO 600 squeezing experiments suffered from lock-point errors, and their quadrature control error signals vastly underestimated the level of phase noise as a result [2, 3]. In such cases, the most reliable way to measure phase noise is to operate the squeezed vacuum source with high linear gain, as described in the main text. Due to the extensive efforts to minimize OPO Detuning noise, we believe that our apparatus is not significantly impacted by lock-point errors. To verify this we compared the direct measurement of the phase noise with the total predicted by the quadrature control error signals and found the two to be in agreement.

Calibrated error signals are shown in Figures S1 and S2. We see that the CLF loop has achieved broadband shot noise limited performance. As shown in Figure S2, the shot noise fluctuations imposed on the CLF by the CLF servo show up in the LO loop error signal, though this contribution is well suppressed within the control bandwidth. The bulk of the RMS for the LO loop is caused by length noise on the SHG cavity. The SHG length noise contribution to both error signals was estimated by multiplying the error signal spectrum for the SHG length servo by a transfer function from the error point on the SHG servo to the error points on both quadrature control loops. This estimate is only plotted in regions where the transfer function had good coherence. The total phase noise due to SHG length noise (1 ± 0.3 mrad) and CLF shot noise (0.9 ± 0.3 mrad) listed in Table S1 represent the quadrature sum of their contributions to both error signals.

Some additional phase fluctuations in the LO loop are present below 2 kHz, but they do not significantly alter our estimate of the total phase noise. These fluctuations have not been rigorously characterized, though we did observe a significant decrease in noise at these frequencies when we acoustically isolated the optical fibers. The remaining detuning noise on the OPO cavity also contributes some phase fluctuations. Since OPO detuning noise gives rise to lock-point errors, this term cannot

Fig. S2. LO loop calibrated error signal spectrum. The contribution from SHG length noise dominates the spectrum between 2 kHz and 20 kHz. The contribution from the shot noise level on the CLF photodiode is a limiting noise source above 20 kHz, but is well suppressed within the control bandwidth (10 kHz). The spectrum below 2 kHz is not well understood, but its contribution to the total RMS is relatively small (< 0.1 mrad). Since this error signal is sensed at the homodyne along with the squeezed field, the shot noise level depends on the measurement quadrature angle. Here, the anti-squeezed quadrature is being measured. The shot noise level, depicted by a dashed line, is elevated in this case and begins to dominate the spectrum around 100kHz.

be reliably inferred from the quadrature control error signals. Instead, we measured a calibrated error signal for the OPO length servo and computed the resulting squeezing angle fluctuations using Equation 3 in the main text as done in [3]. Due to our intrinsically low cavity length noise and high servo bandwidth, this error signal is completely shot noise limited. Using this method, we calculated a contribution of 0.35 ± 0.1 mrad due to OPO detuning noise.

Additionally, a small portion of the 86 MHz control sidebands on the pump field used to lock the OPO cavity are converted into phase fluctuations on the squeezed field via parametric down-conversion. Based on a measurement of the modulation depth of these control sidebands, their contribution to the total phase noise is 0.35 ± 0.1 mrad.

All major sources of phase noise are listed in Table S1. The quoted uncertainties for the OPO Detuning noise, SHG Length noise, and CLF shot noise contributions represent the uncertainties in calibrating the relevant error signals in each case. The total phase noise level listed at the bottom of the table is computed by taking the quadrature sum of all of the individual noise terms.

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