# Squeezed light at 1550 nm with a quantum noise reduction of 12.3 dB

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**Abstract:** Continuous-wave squeezed states of light at the wavelength of 1550 nm have recently been demonstrated, but so far the obtained factors of noise suppression still lag behind today's best squeezing values demonstrated at 1064 nm. Here we report on the realization of a half-monolithic nonlinear resonator based on periodically-poled potassium titanyl phosphate which enabled the direct detection of up to 12.3 dB of squeezing at 5 MHz. Squeezing was observed down to a frequency of 2 kHz which is well within the detection band of gravitational wave interferometers. Our results suggest that a long-term stable 1550 nm squeezed light source can be realized with strong squeezing covering the entire detection band of a 3rd generation gravitational-wave detector such as the Einstein Telescope.

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**OCIS codes:** (270.0270) Quantum Optics; (270.6570) Squeezed states; (190.4970) Parametric oscillators and amplifiers.

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#### 1. Introduction

It has been shown by Caves [1] that squeezed light can be used to enhance the sensitivity of (quantum noise limited) interferometers as they pursue the first direct detection of gravitational waves (GWs). Caves' analysis revealed that the quantum noise contribution to the interferometer output signal was almost completely caused by the vacuum noise coupling into the interferometer through the open port of its 50/50 beam splitter. The replacement of this vacuum field by a field with less quantum noise in the measured quadrature, namely a squeezed vacuum state, would directly decrease the photon shot noise on the detector and hence increase the output signal to noise ratio.

All current GW interferometers are operated with lasers at 1064 nm. Accordingly, squeezed light research within the GW community has mainly been focused on the generation of continuous-wave (cw) squeezed light at that respective wavelength. Maximum squeezing values of 11.5 dB from a bulk lithium niobate (LiNbO<sub>3</sub>) crystal [2] and 12.7 dB from a periodicallypoled potassium titanyl phosphate (PPKTP) crystal [3] have been reported. These results were obtained in the MHz regime, and more importantly they used monolithic resonators to reduce intra-cavity optical loss. Monolithic resonators are not feasible as a GW detector squeezed light source, because a fast enough tuning of their resonance frequency to follow the detector's baseline laser has not been achieved so far. Active length/frequency stabilization can be realized by setting up the squeezed light source as a hemilithic (half-monolithic) resonator and feeding back a control signal to the piezo-driven coupling mirror. The implementation of the required control scheme usually introduces excess noise (typically technical laser noise) that masks the squeezing at frequencies below a few megahertz. In order to generate squeezing within the detection band of today's GW detectors, which ranges from about 10 Hz to 10 kHz, Vahlbruch et al. [4] proposed and demonstrated what they called a coherent control scheme. This control scheme facilitated the detection of squeezed light at frequencies of as low as 1 Hz [5]. A similar control scheme was used to construct the GEO 600 squeezed light source [6] that produced 8-9 dB of squeezing in a detection band from 10 Hz to 10 kHz. Just recently, this squeezed light source was successfully incorporated as an add-on into the km-scale gravitational wave detector GEO 600 [7, 8]. The injection of squeezed vacuum states into GEO 600 led to a broadband noise reduction of up to 3.5 dB in the detectors's shot-noise limited frequency range (above 700 Hz).

With the feasibility of squeezed light injection having been demonstrated, squeezing could contribute to achieving the envisaged sensitivities of the second generation of GW detectors

such as Advanced Virgo [9] and Advanced LIGO [10]. Here, the application of squeezed light allows for the reduction of the design laser power and thus the potentially critical thermal load on the interferometer's optical components [11].

Beyond these advanced detectors, plans for third-generation instruments already exist, e.g. those presented in the recent European design study for the so-called Einstein Telescope (ET) [12]. To improve the displacement sensitivity in the low-frequency range it is proposed to use cryogenically cooled interferometers with silicon test masses, which would reduce the thermal noise contribution to the detector sensitivity. Consequently, these detectors would need to be driven by 1550 nm lasers [13, 14]. As squeezing enhancement is indeed considered for ET, cw squeezed states at 1550 nm covering the frequencies from 1 Hz to 10 kHz are required to achieve a broad-band reduction of its quantum noise.

Squeezed states of light at a wavelength of 1550 nm have only recently been produced in the cw regime [15–17] with the highest value of 9.9 dB reported in [17]. So far, squeezing factors beyond 10 dB were reported from monolithic cavity designs and at megahertz frequencies only. Here, we report on the observation of 1550 nm squeezed light from an optical parametric amplifier that was designed as a hemilithic resonator and generated squeezing values exceeding 10 dB at frequencies of as low as 18 kHz. Squeezed vacuum states were generated using quasi phase-matched degenerate parametric down-conversion, also known as optical parametric amplification, in a crystal made of PPKTP. The crystal end face and a piezo-driven coupling mirror were used to realize the squeezing resonator in the desired hemilithic configuration. By means of balanced homodyne detection, a non-classical noise reduction of 12.3±0.2 dB was directly observed at a sideband frequency of 5 MHz. Furthermore, we extended our investigation to the sub megahertz-regime which revealed a squeezing factor of more than 10 dB from 80 kHz down to a frequency of 18 kHz. A maximum noise suppression of 11.4±0.5 dB was observed between 60 kHz and 80 kHz. Despite a considerable degradation of the squeezing level from 18 kHz downwards some degree of noise reduction expanded well into the detection band of GW detectors with a remaining 5 dB of squeezing measured at a frequency of 2 kHz.

## 2. Experimental setup

A schematic of our experimental setup is shown in Fig. 1. As the laser source we used a commercially available high power cw erbium microfiber laser with an output power of 1.5 W. The laser was transmitted through a three-mirror ring cavity (FC1) that provided spatio-temporal filtering of the beam for the downstream experiment. Approximately 20 mW of the transmitted light were reserved to be used as the local oscillator (LO) for balanced homodyne detection (BHD). Approximately 1 W of the remaining light was sent into a second-harmonic generator (SHG) to furnish the 775 nm pump field needed to drive the optical parametric amplifier (OPA). The SHG was a single-ended standing wave cavity built by two mirrors with 25 mm radius of curvature with a double anti-reflection (AR) coated, 10 mm long PPKTP crystal in between. The end mirror was highly reflective (HR) for both wavelengths; the piezo-driven coupling mirror had a 90 % power reflectivity for the fundamental and only a marginal reflectivity (< 0.2 %) for the second-harmonic field. Taking into account the refractive index of n = 1.816 for PPKTP at 1550 nm and the spacing of 20 mm between the crystal end faces and the mirrors, the cavity waist size and linewidth were  $w_0 = 60 \,\mu m$  and FWHM = 43 MHz, respectively. A second ring cavity (FC2) with specifications similar to FC1 was incorporated to reduce amplitude and phase fluctuations on the pump field. In order to servo-control the length of FC1, FC2 and the SHG to be resonant with their respective carrier fields a modulation-demodulation locking technique was used. The required phase modulations were imprinted onto the light using electro-optical modulators (not shown in Fig. 1) with frequencies (101.25 MHz for FC1 and FC2, 138 MHz for the SHG) chosen to be far outside the cavity linewidth such that unwanted sidebands on

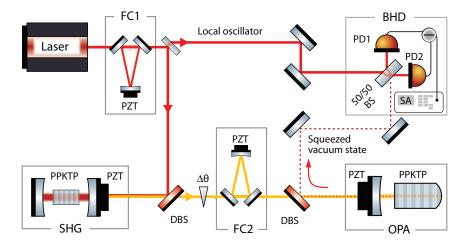


Fig. 1. Schematic of the experiment. Laser: 1550 nm fiber laser. FCs, filter cavities for spatio-temporal mode cleaning at both wavelengths. PZT, piezoelectric transducer; SHG, external second-harmonic generator to produce the 775 nm pump field; BS, beam splitter; DBS, dichroic beam splitter; PDs, photo diodes, SA, spectrum analyzer that converts the differential current of the two photo diodes into variances; BHD, balanced homodyne detector for the characterization of the squeezed field.

the transmitted light were kept small. The filtered pump beam was then mode matched to the  $TEM_{00}$  mode of the OPA with a mode matching efficiency of 95%.

Our OPA included a piezo-actuated coupling mirror and a PPKTP crystal of dimensions  $9.3 \, \text{mm} \times 2 \, \text{mm} \times 1 \, \text{mm}$ . The crystal end face had a radius of curvature of  $12 \, \text{mm}$  and was HR coated for  $1550 \, \text{nm}$  and  $775 \, \text{nm}$ , thus serving as the cavity end mirror. The PPKTP front side was AR coated for both wavelengths. An air gap of  $23 \, \text{mm}$  length was realized between the AR coated side of the crystal and the coupling mirror. As the input/output coupler we chose a half-inch substrate that had a power reflectivity of  $90 \, \%$  for the fundamental and  $20 \, \%$  for the second harmonic field and had a radius of curvature of  $25 \, \text{mm}$ . The intra-cavity waist size and linewidth were  $40 \, \mu \text{m}$  and  $63 \, \text{MHz}$ , respectively. A peltier element beneath the crystal was used to keep the phase matching temperature at around  $40 \, ^{\circ}\text{C}$ .

The squeezed states propagated in the opposite direction to the pump. By reflection at a dichroic beam splitter (DBS) the squeezed field was separated from the pump and was directed towards a balanced homodyne detector. The homodyne detector essentially consists of a 50/50 beam splitter and two photo detectors (PD1 and PD2) that detect the light in the output ports. The difference signal is then converted into a variance by spectrum analyzer (SA). The photo diodes we used for our homodyne detector were custom-made InGaAs PIN diodes with an active area of 300  $\mu$ m in diameter and a quantum efficiency of  $\sim$  99%.

In squeezing experiments the interference contrast between the local oscillator and the squeezed (signal) field on the 50/50 beam splitter (also known as the homodyne visibility) is crucial because any mode mismatch quadratically translates into optical loss which degrades the squeezing level. To adjust the homodyne visibility a bright beam was needed that resembled the squeezed vacuum output of the OPA. To this end an auxiliary beam (omitted in Fig.1) was matched to the TEM $_{00}$  mode through the HR rear surface of the OPA. With this control beam the OPA length could be locked and the transmitted light propagated congruent with the

mode to be squeezed. By carefully adjusting the overlap between auxiliary signal beam and LO a fringe visibility of 99.5% was achieved. During data taking the auxiliary field was blocked. This ensured true vacuum squeezing and avoided the degradation of the squeezing by additional noise from the control beam. The rigidity of the cavity construction allowed us to keep the squeezed light source on resonance by solely applying DC-voltage to the piezo.

#### 3. Experimental procedure and results

The two observables of interest were the amplitudes of the amplitude quadrature  $\hat{X}_1$  and the phase quadrature  $\hat{X}_2$  of the electromagnetic field. The homodyne detector measured their respective variances which obey an uncertainty relation,  $\Delta^2\hat{X}_1\cdot\Delta^2\hat{X}_2\geq 1/16$  [18]. The relative phase  $\theta$  between signal beam and local oscillator defines the quadrature under investigation, given by  $\hat{X}(\theta)=\hat{X}_1\cos\theta+\hat{X}_2\sin\theta$ . As depicted in Fig.1, in our setup a phase shifter (piezo driven mirror) in the pump path allowed us to vary the phase of the pump incident on the OPA. This led to a change of the phase with which the squeezing was produced and hence enabled us to adjust  $\theta$  to measure, e.g., the squeezed quadrature  $(X(0)=X_1)$  or the anti-squeezed quadrature  $(X(\pi/2)=X_2)$ , respectively. The pump power fluctuations due to beam pointing relative to the eigenmode of FC2 were below 1% and could be neglected. The output signal of the homodyne detector, i.e., the differential current of the two photo diodes, was converted into variances with a spectrum analyzer.

#### 3.1. Squeezing at 5 MHz sideband frequency

We performed measurements at a sideband frequency of 5 MHz and with a pump power of approximately 171 mW. Note that this value is already corrected for the 95% mode-matching efficiency of the pump field into the OPA and that this correction is also included in all other pump power values given below. The data as collected by the spectrum analyzer are shown in Fig. 2. Approximately 11.8 mW of LO power was used to obtain the vacuum (or shot noise) reference level with the signal input port of the 50/50 beam splitter blocked. When the input port was opened, the phase  $\theta$  was subsequently adjusted to measure the anti-squeezed and the squeezed quadrature. A squeezing value of  $12.3\pm0.2\,\mathrm{dB}$  below shot noise was directly measured. The corresponding anti-squeezing was  $19.3\pm0.2\,\mathrm{dB}$  above the shot noise level. The homodyne detector's electronic dark noise was 26 dB below the vacuum noise and was not subtracted from the data.

#### 3.2. Characterization of the OPA

For the below-threshold OPA the anticipated variances of the squeezed and anti-squeezed quadratures ( $V_1$  and  $V_2$ , respectively) can be modeled by [19]

$$V_{1,2} = 1 \pm \eta_{\text{det}} \eta_{\text{esc}} \frac{4\sqrt{P/P_{\text{thr}}}}{\left(1 \mp \sqrt{P/P_{\text{thr}}}\right)^2 + 4\left(2\pi f \kappa^{-1}\right)^2} , \tag{1}$$

where P is the second-harmonic pump power and  $P_{\rm thr}$  is the amount of pump power needed to reach the OPA threshold. The total detection efficiency  $\eta = \eta_{\rm det} \eta_{\rm esc}$ , where  $\eta_{\rm det}$  is the detection efficiency including propagation loss, the homodyne visibility (that is the quality of the mode overlap of the signal and LO on the 50/50 beam splitter), and the quantum efficiency of the photo diodes, and  $\eta_{\rm esc}$  is the escape efficiency of the OPA cavity defined as  $\eta_{\rm esc} = T/(T+L)$ , with the amplitude transmissivity T of the coupling mirror and the cavity round trip loss L. With the cavity round-trip length l and the speed of light c the decay rate of the cavity can be defined as  $\kappa = c(T+L)l^{-1}$ , and f is the measurement frequency.

The amount of detectable squeezing is not limited by optical loss alone. Fluctuations in the relative phase between signal and LO can likewise degrade the measured squeezing level. In an experiment, such phase noise might have numerous origins, for example unstable locking loops, residual phase modulation, or acoustically induced mirror motion. When assuming the standard deviation of the normally distributed phase fluctuations to be small, phase jitter with an rms of  $\theta_{\rm fluc}$  is equal to the homodyne detector measuring at a phase offset  $\theta_{\rm fluc}$ . The resulting variances can then be written as

$$V'_{1,2} = V_{1,2}\cos^2\theta_{\text{fluc}} + V_{2,1}\sin^2\theta_{\text{fluc}} . \tag{2}$$

At a Fourier frequency of 5 MHz, we repeatedly took zero-span measurements of squeezing and anti-squeezing at different pump powers. The collected data are shown in Fig. 3. All measurements were normalized to their respective vacuum level. Here, the contribution of the electronic detector dark noise was subtracted and hence the value of best (optimum) squeezing improved to  $-12.4 \pm 0.3$  dB. The horizontal error bars correspond to the fluctuation of the pump power P during data taking. For constant monitoring of P, a calibrated photo diode in transmission of a steering mirror in the pump path was used. The absolute error of a given pump power is  $\pm 3\%$  due to the measurement uncertainty of the power meter used for calibration. The vertical error bars are the standard deviation of 0.3 dB as given by the linear fit to each recorded trace.

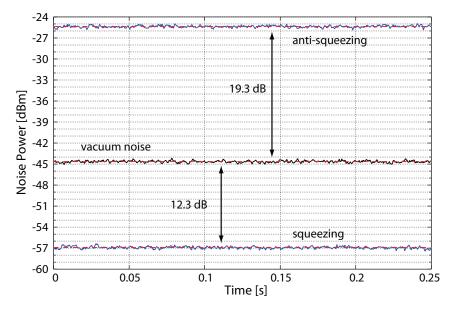


Fig. 2. Balanced homodyne measurements of the quadrature noise variances. The vacuum reference was recorded with a LO power of  $11.8\,\mathrm{mW}$  and a blocked signal port. The OPA was driven with a pump power of approximately  $171\,\mathrm{mW}$ . With an open signal port, the squeezed variance and the anti-squeezed variance were measured by choosing the corresponding relative phase between signal field and LO. The depicted measurements are averages of 2 traces that were recorded at a Fourier frequency of  $5\,\mathrm{MHz}$ , with a resolution bandwidth of  $200\,\mathrm{kHz}$  and a video bandwidth of  $200\,\mathrm{Hz}$ . No data postprocessing was applied, i.e., the data still include electronic dark noise, and thus represent direct observations. A linear fit to the linearized variances was used to determine the variance mean values and the associated standard deviation. The anti-squeezing was at  $+19.3\pm0.2\,\mathrm{dB}$  relative to the vacuum noise, whereas the squeezing was at  $-12.3\pm0.2\,\mathrm{dB}$ .

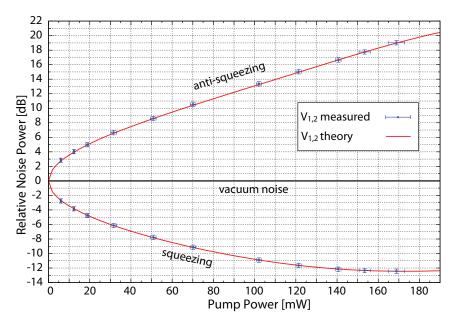


Fig. 3. Pump power dependence of anti-squeezed and squeezed quadrature variances. All values were obtained from zero-span measurements at 5 MHz. In order to fit the numerical model, all the data were dark-noise corrected and subsequently normalized to the vacuum reference.

Taking into account the parameters of our cavity, namely  $l=7.98\,\mathrm{cm}$ ,  $T=10\,\%$ ,  $L=0.1\,\%$ , and the measurement frequency  $f=5\,\mathrm{MHz}$ , we fitted for the total detection efficiency, the threshold power and the amount of phase noise using our model defined in Eqs. (1) and (2). This yields the following values:  $\eta=0.965\pm0.002$ ,  $P_{\mathrm{thr}}=221\pm3\,\mathrm{mW}$ ,  $\theta_{\mathrm{fluc}}=0.66\pm0.06^\circ$ . We confirmed these results by inserting the obtained values into Eq. (2) to model the frequency dependence of our squeezer and compared it to measured squeezing spectra. For that we took measurements from 2.5 MHz to 50 MHz at several pump powers between 6 mW and 180 mW. The collected data are depicted in Fig. 4. All spectra were averaged 10 times. As can be seen in Fig. 4 our theoretical model does indeed provide a good prediction of the experimental outcome. We especially note the quality of the fit with regards to the phase noise parameter  $\theta_{\mathrm{fluc}}$  since a considerable degradation of the squeezing level at frequencies below 5 MHz becomes apparent when approaching high pump powers. Assuming zero phase noise, the squeezing level would approach 14 dB as indicated by the bottom curve in Fig. 4.

## 3.3. Low frequency performance

For the observation of squeezing in the kHz regime, we used our homodyne detector together with a low-noise FFT-analyzer. This enabled us to measure the quantum noise from  $80\,\mathrm{kHz}$  downwards. For all measurements a power of  $4.8\,\mathrm{mW}$  for the LO was used. This yielded a vacuum reference level with a clearance from the electronic dark noise of approximately 15 to  $20\,\mathrm{dB}$  over the entire FFT window. Therefore, no data postprocessing to subtract the detector dark noise was applied. The resulting noise spectra are shown in Fig. 5. The measured antisqueezing [trace (b)] was at  $16.8\pm0.5\,\mathrm{dB}$  above the vacuum noise level [trace (c)]. The spectrum of the squeezed quadrature [trace (a)] showed a maximum non-classical noise suppression of  $-11.4\pm0.5\,\mathrm{dB}$  between  $60\,\mathrm{kHz}$  and  $80\,\mathrm{kHz}$ . Going down in frequency the squeezing

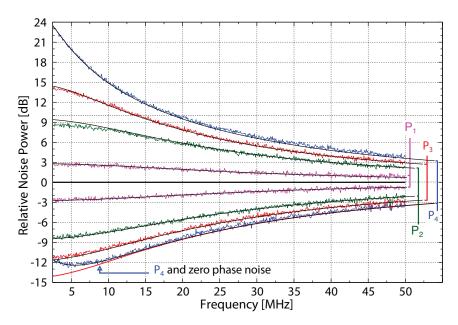


Fig. 4. Pump power dependence of the squeezing spectra, experiment and theory. All depicted traces are averages of 10 individual traces each recorded with a resolution bandwidth RBW =  $500\,\mathrm{kHz}$  and video bandwidth VBW =  $2\,\mathrm{kHz}$ . All traces were corrected for electronic detector dark noise and were normalized to the vacuum level. The theoretical predictions (solid lines) were obtained from Eq. (2) using  $\eta = 0.965$ ,  $P_{thr} = 221\,\mathrm{mW}$ , and  $\theta_{fluc} = 0.66^\circ$  with the respective pump power values of  $P_1 = 6\,\mathrm{mW}$ ,  $P_2 = 56\,\mathrm{mW}$ ,  $P_3 = 106\,\mathrm{mW}$ , and  $P_4 = 180\,\mathrm{mW}$ . The remaining cavity parameters were used as given in the text. The bottom curve shows the squeezing spectrum under the assumption of zero phase noise.

slightly decreased reaching  $-10.7\pm0.4\,\mathrm{dB}$  at  $20\,\mathrm{kHz}$ . From 18 kHz downwards the squeezing level degraded considerably. We attribute this mainly to two characteristics of our setup. First, no stabilization scheme was used to control the relative phase between LO and signal field. Hence, acoustically excited motion cannot be compensated for and together with the prolonged measurement times at smaller sideband frequencies this led to an averaging effect that decreased the observed squeezing level. Second, no Faraday isolator was incorporated between the squeezing resonator and homodyne detector to protect the OPA from back-scattered and reflected light. It is known that stray light can introduce excess noise [20, 21] and can cause parasitic interferences [5] within the system. Both effects can impair or even completely annihilate squeezing in the audio band. Despite the roll-up towards lower frequencies, squeezing of approximately  $-5\,\mathrm{dB}$  could still be observed at  $2\,\mathrm{kHz}$ .

#### 4. Conclusion

By means of balanced homodyne detection we directly observed 12.3 dB of squeezing of the vacuum fluctuations of a 1550 nm cw laser beam at a sideband frequency of 5 MHz. This non-classical noise reduction was achieved by degenerate parametric down-conversion below threshold in a standing wave resonator. High quality optics and the low absorption of the PP-KTP crystal made it possible to construct the squeezing resonator as a hemilithic cavity and still keep the optical loss small enough to detect such strong squeezing. Pump power depen-

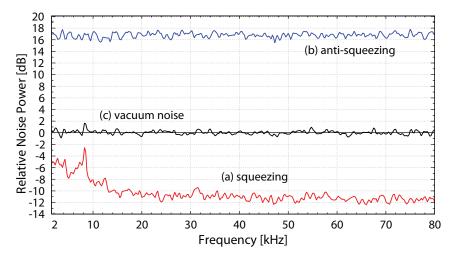


Fig. 5. Squeezing at frequencies between 1.5 kHz and 80 kHz. All traces were measured with RBW of 250 Hz and were normalized to the vacuum noise level corresponding to a LO power of 4.8 mW. Each measurement point is the averaged root mean square value of 20 [40 for trace(c)] measurements. Trace (a) shows the direct observation of more than 10 dB of squeezing down to a frequency of 18 kHz with a maximum noise suppression of  $-11.4\pm0.5$  dB between 60 kHz and 80 kHz. Below 18 kHz the squeezing level degraded, reaching approximately -5 dB at 2 kHz. The peak at 8 kHz was caused by a residual, non-stationary amplitude modulation from FC1. The anti-squeezing [trace (b)] was  $16.8\pm0.5$  dB above the vacuum noise level as measured by the homodyne detector [trace (c)]. Electronic dark noise was not subtracted from the measurement data.

dent squeezing values were used to characterize our squeezer in terms of optical loss and phase noise. By fitting a theoretical model to the data the overall optical loss and residual phase noise between signal and LO were determined to be 3.5% and 0.66°, respectively. Note that the value obtained for the optical loss includes the escape efficiency of the squeezing resonator, propagation loss and the subsequent homodyne detection. The amount of phase noise could most likely be reduced by the implementation of a stable control for the phase of the pump beam as well as the homodyne detection phase. Assuming zero residual phase noise, 14 dB of (dark noise corrected) squeezing would then be detectable in our setup. However, such control schemes are usually not easily realized without introducing excess noise from the participating light fields and hence were not pursued here. Although our overall loss value of 3.5% is already small, we believe that a further loss reduction is possible and that even higher values of squeezing should be feasible with current technology.

Squeezed vacuum states at frequencies within the detection band of GW interferometers can be used to enhance the sensitivity of the respective detector. These frequencies typically range from some Hertz up to  $10\,\mathrm{kHz}$ . Here, we were able to measure up to  $11.4\,\mathrm{dB}$  of squeezing below  $80\,\mathrm{kHz}$ . Even though from  $18\,\mathrm{kHz}$  downwards acoustically induced modulation and residual stray light degraded the level of squeezing, it extended into the detection band of a GW detector. Owing to the hemilithic layout of the squeezed light resonator, a coherent control scheme according to [4] is applicable. With such a control scheme the squeezing spectrum would presumably broaden to cover the entire range of frequencies down to a few hertz. Additionally, the required long-term stability would be obtained and an even higher squeezing factor can be expected since the aforementioned phase noise would be reduced.

We note that squeezed light at 1550 nm is also of interest in the field of fiber-based quantum communication because this wavelength lies in one of the telecommunication windows associated with low loss of silica fibers.

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