

Squeezed States of Light for Future Gravitational Wave Detectors at a Wavelength of 1550 nm

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The generation of strongly squeezed vacuum states of light is a key technology for future ground-based gravitational wave detectors (GWDs) to reach sensitivities beyond their quantum noise limit. For some proposed observatory designs, an operating laser wavelength of 1550 nm or around $2\ \mu\text{m}$ is required to enable the use of cryogenically cooled silicon test masses for thermal noise reduction. Here, we present for the first time the direct measurement of up to 11.5 dB squeezing at 1550 nm over the complete detection bandwidth of future ground-based GWDs ranging from 10 kHz down to below 1 Hz. Furthermore, we directly observe a quantum shot-noise reduction of up to (13.5 ± 0.1) dB at megahertz frequencies. This allows us to derive a precise constraint on the absolute quantum efficiency of the photodiode used for balanced homodyne detection. These results hold important insight regarding the quantum noise reduction efficiency in future GWDs, as well as for quantum information and cryptography, where low decoherence of nonclassical states of light is also of high relevance.

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Since the first detection of gravitational waves in 2015 [1], a network of ground-based gravitational wave detectors (GWDs) [2] has opened a new view into our Universe [3]. In the last gravitational wave observation run (O3) the advanced LIGO [4,5], advanced Virgo [6], and GEO600 [7] detectors used squeezed states (SQZ) of light to extend their astrophysical reach. The LIGO and Virgo detectors reached a shot-noise reduction of about 3 dB [8,9], and at GEO600 recently a quantum shot-noise reduction of 6 dB was demonstrated [10]. The quantum noise limitation of GWDs is composed of the shot noise at higher detection frequencies and the quantum radiation pressure noise at lower frequencies. For a quantum noise reduction over the full detection band, the frequency-independent squeezed light can be converted into frequency-dependent states with optical filter cavities [11]. This was demonstrated at GWD detection frequencies [12,13], and intense research activities for integration at the advanced detectors are ongoing.

Two design concepts of the optical parametric amplifier (OPA), which generates the squeezed states via the process of parametric down-conversion, are implemented in the current GWDs operating at a laser wavelength of 1064 nm. Linear, half monolithic OPA cavities are used at GEO600

and Virgo [14,15]. With this kind of OPA the highest squeezing factors have been demonstrated: 15 dB in the megahertz range [16] and 12.0 dB in the audio band [17], the latter of which is relevant for current GWDs. The LIGO GWDs use a bowtie OPA design [18,19]. One important difference between the two OPA topologies is that the bowtie configuration is less sensitive to backscattered light because of the two distinct traveling wave directions inside the cavity. This leads to an intrinsic suppression, comparable to a conventional Faraday isolator, but without introducing additional optical loss [18]. In a separate experiment 11.6 dB squeezed light in the audio band was demonstrated using this OPA design [20].

The application of squeezed light is a key technology in the design of all next generation GWDs, demanding an effective quantum noise reduction of 10 dB in the gravitational wave detection channel [21,22]. Some of the future GWDs aim to reduce mirror thermal noise via cryogenic cooling combined with appropriate mirror materials like silicon. This requires a change in the operating wavelength from 1064 to 1550 nm or $2\ \mu\text{m}$ [21–23] and the development of high-efficiency squeezed light sources at these wavelengths. So far, squeezing levels of 13.1 dB [24] and 7.2 dB [25] have been demonstrated in the megahertz regime at 1550 and 2128 nm, respectively. At audio-band frequencies, 11.4 dB [26] and 4 dB [27] were achieved at 1550 and 1984 nm without the stabilization of the squeezed light phase. With a phase stabilization, 8.2 dB [28] and 3.9 dB [29] were reported. None of the demonstrated squeezed light sources was able to generate and detect

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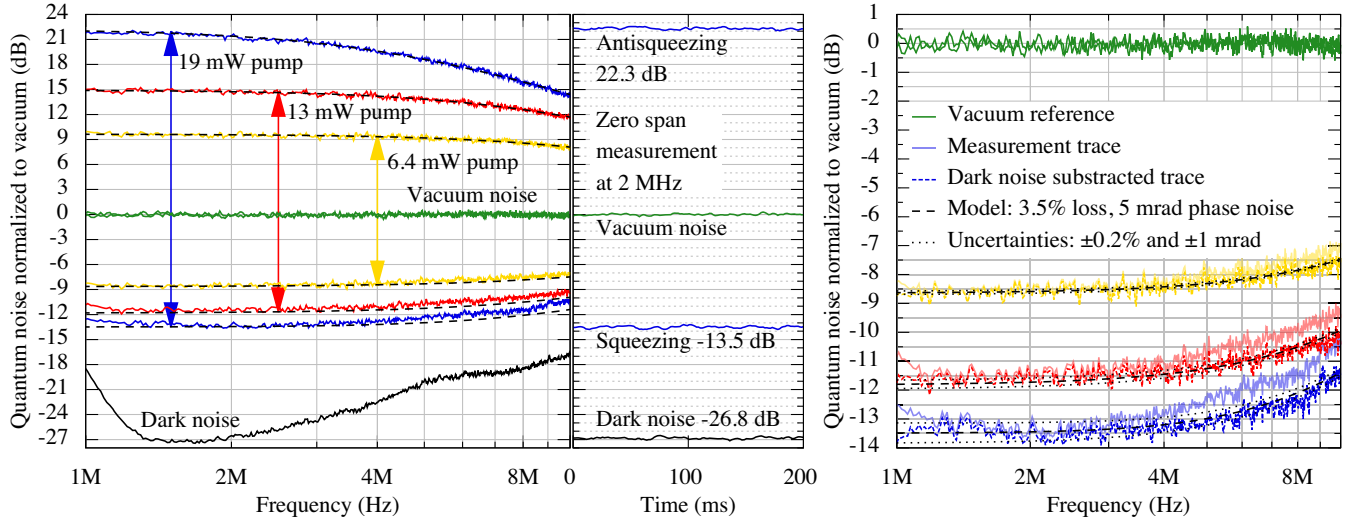


FIG. 2. Homodyne measurements with the signal input from the linear OPA. Left: noise spectra of the (anti)squeezing using three different OPA pump powers normalized to the vacuum noise reference for 20 mW local oscillator power at frequencies between 1 and 10 MHz. The measurements were modeled to estimate the optical loss and phase noise for the squeezed states. The best fits (see black dashed curves) were obtained with an optical loss of $(3.5 \pm 0.2)\%$ and a phase noise of (5 ± 1) mrad. All spectra are captured with a resolution bandwidth (RBW) of 300 kHz and a video bandwidth (VBW) of 100 Hz (left and right). Center: a zero span measurement at 2 MHz over 200 ms time confirms the detection of (13.5 ± 0.1) dB squeezing (RBW 100 kHz, VBW 30 Hz). Right: enlargement of the measured quantum noise reduction of the left-hand graph. The uncertainties of our model fits are illustrated with dotted black lines.

homodyne contrast was measured to $(99.5 \pm 0.05)\%$, which corresponds to an optical loss of $(1.0 \pm 0.1)\%$. Second, we determined the transmission loss through three lenses and the antireflection coating of the beam splitter back side to $(0.05 \pm 0.02)\%$ in an independent measurement. Third, we calculated the OPA escape efficiency to be $(99.0 \pm 0.4)\%$ based on our measurements of the free spectral range (FSR) (3443.0 ± 0.2) MHz, the cavity full width at half maximum frequency (FWHM) (59.2 ± 0.2) MHz, and the transmission of the coupling mirror $(10.15 \pm 0.02)\%$ at a wavelength of 1550 nm. The FSR and FWHM were measured with a bright laser beam at 1550 nm wavelength with strong phase modulation sidebands imprinted for calibration. The power transmission of the coupling mirror was measured with a power stabilized laser. Furthermore, we characterized in an independent measurement the highly reflective (HR) coating of the PPKTP crystal by determining the reduction of the reflected power at 1550 nm of the light, which is coupled into the OPA via the back side of the crystal, when the OPA is on resonance. The measured depletion of $(1.25 \pm 0.13)\%$ implies a residual transmission of the HR coating of (340 ± 40) ppm. To explain the escape efficiency, (280 ± 180) ppm single path loss through the PPKTP crystal remains, which includes the absorption in the crystal, scattering, and reflection of the AR coating of the crystal.

From all these measurements one can conclude that, in order to be in agreement with the model parameters as derived from the measurements shown in Fig. 2, the absolute quantum efficiency of the homodyne detector

PDs has to be $(98.5 \pm 0.7)\%$ including the enhancement in sensitivity of 0.5% gained with the retroreflectors.

Based on the precise characterization of the detection efficiency and given the above loss estimation for the PPKTP crystal material, we can now study the bowtie OPA in more detail. This OPA design aimed for minimal astigmatism of the squeezed field mode in order to obtain a high contrast with any nonastigmatic Gaussian beam as it is used, e.g., for the BHD local oscillator beam or in GWDs. To this end, two concave mirrors ($r = -100$ mm) focus the beam into the double-sided 0.5° wedged and AR coated 11.5-mm-long PPKTP crystal. The focus radius inside the crystal is $47 \mu\text{m}$, which requires a higher pump power compared to the linear cavity, where the waist size is $40 \mu\text{m}$ in radius. The two coupling mirrors are convex, $r = +1000$ mm, to reduce astigmatism, which is introduced by the bowtie geometry and spherical curved mirrors, and to provide an OPA output field with a low beam divergence. All cavity mirrors are clamped under 5° angle of incidence on a rigid aluminum spacer with one PZT per coupling mirror for cavity length actuation, as shown in Fig. 1.

A BHD contrast measurement of $(99.85 \pm 0.05)\%$ experimentally confirms the low level of astigmatism: a squeezing detection loss of only $(0.3 \pm 0.1)\%$ is introduced by the nonperfect mode overlap at this stage. Similar to the linear OPA, we determined the bowtie OPA escape efficiency to $(98.7 \pm 0.6)\%$, calculated from individual measurements of the FSR (464.74 ± 0.04) MHz, the FWHM (8.14 ± 0.04) MHz, and the 1550 nm coupler transmission

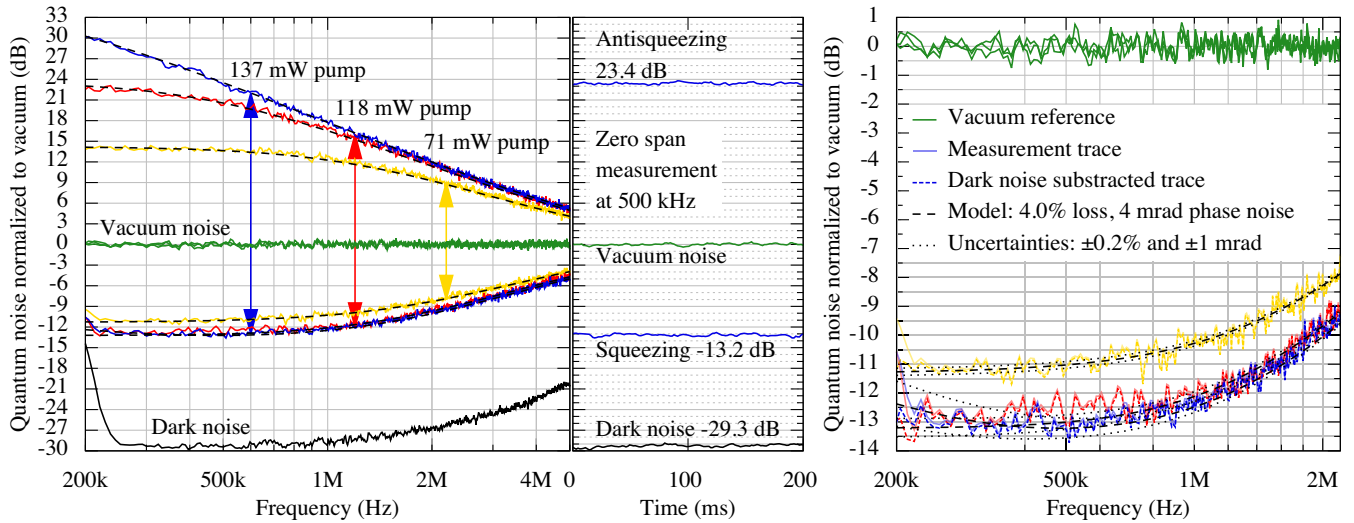


FIG. 3. Homodyne measurements with the signal input from the bowtie OPA. Left: noise spectra of the (anti)squeezing using three different OPA pump powers normalized to the vacuum noise reference for 20 mW local oscillator power at frequencies between 200 kHz and 5 MHz. Given the high electronic dark noise clearance a noise subtraction has only minor impact on the model (black dashed curves), which was found to fit best with $(4.0 \pm 0.2)\%$ optical loss and (4 ± 1) mrad phase noise. All spectra are captured with a RBW 100 kHz and VBW 100 Hz (left and right). Center: zero span measurement at 500 kHz over 200 ms time confirms the detection of (13.2 ± 0.1) dB squeezing (RBW 50 kHz, VBW 30 Hz). Right: enlargement of the measured quantum noise reduction of the left-hand graph. The uncertainties of our model fit are illustrated with the dotted black lines.

of $(10.303 \pm 0.012)\%$. Compared to the linear OPA, the bowtie OPA shows a slightly lower escape efficiency. This can be explained by the higher transmission of the 775 nm coupling mirror at 1550 nm wavelength of (3340 ± 120) ppm. With the above estimation of the homodyne detector PD quantum efficiency, the total optical loss budget for the bowtie squeezing path adds up to $(3.1 \pm 1.4)\%$, which is in agreement with the expected optical loss taken from the fits of the measurements as presented in Fig. 3 of $(4.0 \pm 0.2)\%$. The highest squeezing level we could measure with the bowtie OPA is (13.2 ± 0.1) dB at a harmonic pump power of 137 mW and is thus comparable in squeezing strength to the results we achieved with the linear OPA.

In contrast to the relatively short measurement times required at megahertz frequencies, where no active phase control scheme was necessary to capture the presented measurements, the phase of the (anti)squeezed state has to be stabilized to the readout quadrature of the BHD to demonstrate the performance below 10 kHz. Following the coherent control scheme [35], we therefore injected a frequency shifted auxiliary control field into the bowtie OPA. A beat signal between the auxiliary laser field and the main laser field is used for an offset phase lock loop (PLL) that stabilize the laser frequency difference to 7.15 MHz (not shown in Fig. 1). This optical beat frequency readout f_{beat} also serves as the electronic local oscillator input source for the error signal generation required for phase stabilization, which circumvents a very high bandwidth PLL. The beat frequency is doubled with an electronic mixer for the pump phase error signal generation.

In this configuration we performed squeezing measurements from 10 kHz down to below 1 Hz, and the noise spectra are shown in Fig. 4. Each trace is computed from a 120-s-long time series, sampled with 22 kS/s. The averaging factor varies between 38 for frequencies below 1.7 Hz and 377 000 for the frequencies between 1.7 kHz and 10 kHz. The measurement time was limited

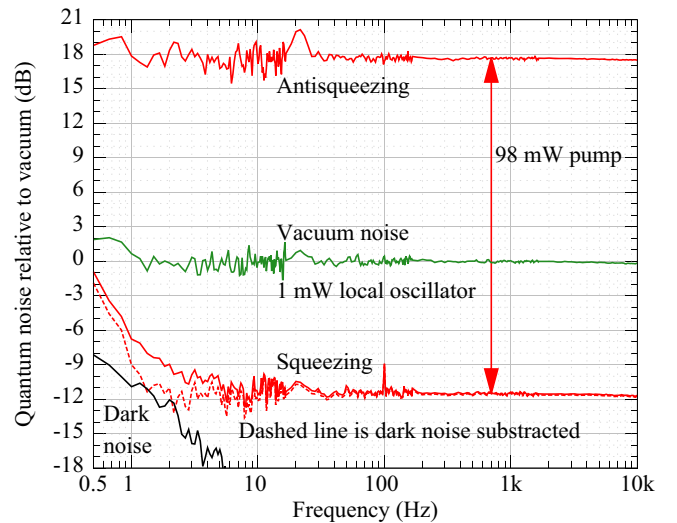


FIG. 4. Quantum noise measurements from 10 kHz down to 0.5 Hz obtained with the bowtie OPA. The results correspond to a harmonic OPA pump power of 98 mW and are plotted relative to the vacuum noise reference. The dashed curve illustrates the squeezing level after the electronic dark noise was subtracted.

to about 120 s due to noise transients, occurring approximately every few 100 s. We suspect that single dust particles, passing the beam in one arm of the BHD, might be the origin of these events [20]. Time traces with at least one of these events lead to noise spectra with a noise shoulder below a few 10 Hz.

Nevertheless, a quantum noise reduction of up to 11.5 dB is detected at audio-band frequencies with as little as 17.5 dB antisqueezing. Below a few hertz the residual electronic dark noise contribution limits the direct squeezing measurement, but the dark noise subtraction reveals the full potential of our squeezed light source, leading to a squeezing level of 9 dB at 1 Hz frequency.

At these low measurement frequencies we observed several increased noise couplings in the squeezing setup. For example, the laser power noise shows up at the homodyne detector stage below 2 Hz, probably due to air flow and particles passing the beams. For the measurements we show here, we therefore optimized the local oscillator power and carefully checked the linearity of the BHD. Above 2 Hz the measurement is mostly limited by the technical noise of the coherent control field beating with the local oscillator field. This white noise source is at about -18 dB relative to the vacuum noise and led to about 0.5 dB squeezing degradation.

In conclusion, we reported on the first demonstration of strongly squeezed vacuum states of light at a wavelength of 1550 nm at detection frequencies spanning the complete range of current [4,6,7,36] and future ground-based GWDs [21,37]. We measured squeezing at frequencies from 10 kHz down to 0.5 Hz with a quantum noise reduction of up to 11.5 dB, which highlights the potential of the proposed quantum noise reduction schemes for future GWDs with silicon test masses, e.g., the low frequency interferometers of the Einstein Telescope GWD [21]. Without the special technical difficulties for squeezing measurements that arise from the long measurement time in the audio band, we were able to demonstrate more than 13 dB quantum noise reduction at megahertz frequencies, for both the linear and the bowtie OPA configuration. However, the bowtie design might be beneficial for the application in GWDs as the intrinsic immunity to back-scattering [18,20], but requires further optimization of the cavity mirror coatings to reach an escape efficiency as high as the one we achieved with the linear OPA. Finally, we demonstrated that a careful design of the bowtie cavity geometry allows for very low astigmatism competitive to linear designs. The gained knowledge on the 2 mm photodiode quantum efficiency, the optical loss of current PPKTP crystal material, and the investigation of limitations for the audio-band and sub-audio-band squeezing pave the way for the design of squeezed light sources and photodetectors for future GWDs operating at 1550 nm.

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