

Bright squeezed light generation via nonclassical power stabilizationJasper R. Venneberg¹,* Henning Vahlbruch², Marina Trad Nery², and Benno Willke²*Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) und Institut für Gravitationsphysik, Leibniz Universität Hannover, Callinstraße 38, 30167 Hannover, Germany*

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Low-power-noise lasers are essential for many high-precision experiments. Shot noise imposes a fundamental limit on the power stability achievable with classical light sources. In this Letter, we report the generation of bright squeezed light in the audio band, which can improve the sensitivity of otherwise shot-noise-limited measurements. The bright squeezed light source is experimentally realized via the use of squeezed vacuum in a power stabilization scheme. We demonstrate a laser beam at a power of 9.9 mW with a broadband power noise suppression below the classical stabilization limit by up to $8.7^{+0.3}_{-0.4}$ dB in the audio band, resulting in a bright squeezed beam with a power noise of $5.7^{+0.3}_{-0.4}$ dB below shot noise for frequencies from 6 kHz to 20 kHz. We further conceptually outline a method to surpass this result in the future.

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The quantum nature of light gives rise to random fluctuations of its power called shot noise, which poses a challenge to many state-of-the-art laser experiments. Increasing the mean laser power can improve the signal-to-shot-noise ratio. However, there are limits to the amount of power that can be used. Some applications impose technical limitations, for example, due to the finite power handling capabilities of components such as photodiodes. Other experiments, e.g., in biospectroscopy, limit the usable power fundamentally, as extensive laser power can disturb the observed processes or induce damage [1,2]. In power-limited measurements, the shot noise imposes an inherent limit to the achievable sensitivity if classical light sources are used. Nonclassical techniques can surpass the shot noise limit. In particular, states of light with some (non-negligible) power and subshot noise power fluctuations are of interest to many such applications. These states will be referred to as bright squeezed light in this letter. Past experiments have demonstrated bright squeezing in the megahertz regime, for example, in a pulsed laser system to improve the sensitivity of Raman spectroscopy [1], and the generation of bright squeezed light in a continuous wave system via a brightly seeded optical parametric amplifier [3]. For kHz frequencies, where lasers are typically not shot-noise-limited but exhibit technical noise, Buchler *et al.* [4] proposed a bright squeezing scheme with active power stabilization using a beamsplitter in combination with a squeezed vacuum source. Classically, the power noise reduction achievable with similar stabilization schemes is limited by vacuum fluctuations that couple via the open beamsplitter port to the power

noise sensing and are imprinted onto the laser beam. However, injecting squeezed vacuum can surpass this classical limitation, as demonstrated in [5]. The work presented here expands this idea and experimentally investigates the bright squeezing concept developed in [4]. It complements previous experimental results by demonstrating a bright squeezed light source for the kilohertz regime. After explaining the theoretical background, this letter illustrates the bright squeezing setup. The experimental results are presented and discussed. Finally, possible future advancements are considered. Figure 1 shows a sketch of the nonclassical power stabilization setup. A beamsplitter (BS) reflects some light toward the in-loop photodetector (PD) to measure power fluctuations. The in-loop PD's signal is amplified by the complex open-loop feedback transfer function G and sent to a power actuator upstream of the BS. For a large feedback gain, this control loop counteracts power fluctuations and thus stabilizes the power. The beam transmitted through the BS is the stabilized output field for a downstream application in which high power stability is required. The output can optionally be sent to an independent out-of-loop PD to analyze the performance of the power stabilization scheme. In classical power stabilization setups, vacuum fluctuations enter the second BS input. They are detected by the in-loop PD and imprinted on the light by the control loop. This effect limits the achievable power stability. Our nonclassical power stabilization replaces this vacuum field with an amplitude-quadrature-squeezed vacuum state.

Generally, modulations and fluctuations of an optical field $\hat{a}$ can be described via its two-photon amplitude and phase quadrature operators $\hat{a}_c$ and $\hat{a}_s$, following [6]. The amplitude quadrature (subscript “c”) is conventionally defined as the quadrature of the carrier field, which can effectively be described as a classical field with the real-valued amplitude A_c . For small amplitude fluctuations compared to the carrier amplitude, power fluctuations with the Fourier frequency f can be linearly expressed via the amplitude quadrature

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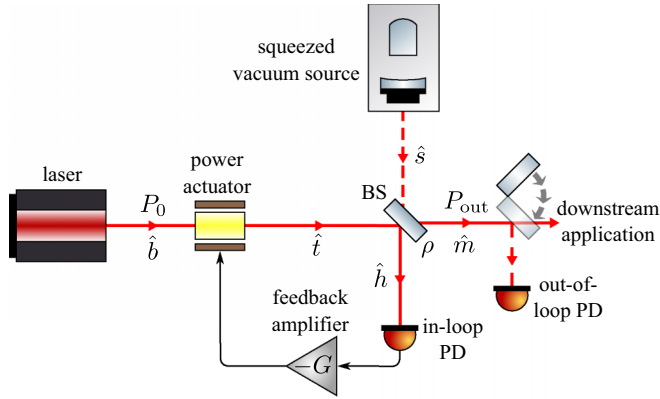


FIG. 1. Concept of the nonclassical power stabilization. The laser field $\hat{b}$ (power P_0) passes a power actuator. A beamsplitter (BS) splits off a fraction ρ of the resulting field $\hat{t}$ into the field $\hat{h}$, whose power is sensed by the in-loop photodetector (PD). The PD's signal is amplified and fed back to the actuator to counteract any measured fluctuations. The transmitted field $\hat{m}$ (power P_{out}) is the stabilized output, sent to the application or optionally an out-of-loop PD. The field $\hat{s}$ of a squeezed vacuum source is injected into the second input port of the BS, which allows power stabilization beyond the classical limit.

operator:

$$\delta\hat{P}(f) \approx h f_0 A_c \hat{a}_c(f) = \sqrt{2h f_0 P_0} \hat{a}_c(f), \quad (1)$$

where h is the Planck constant, f_0 is the optical carrier frequency, and $P_0 = h f_0 A_c^2 / 2$ is the optical mean power. One can define the relative power noise (RPN) as the amplitude spectral density of the power fluctuations normalized by the mean power:

$$\text{RPN}(f) = \sqrt{\frac{S_{\hat{P},\hat{P}}(f)}{P_0}} = \sqrt{\frac{2h f_0}{P_0}} S_{\hat{a}_c}(f), \quad (2)$$

where $S_{\hat{a}_c}$ is the power spectral density of $\hat{a}_c$. The explicit frequency dependence will be omitted in the following. For a coherent state, $S_{\hat{a}_c} = 1$, and Eq. (2) becomes the shot-noise limited RPN or relative shot noise (RSN):

$$\text{RSN}_{P_0} = \sqrt{\frac{2h f_0}{P_0}}. \quad (3)$$

This formalism can be applied to the stabilization scheme in Fig. 1. One finds for the in-loop field $\hat{h} = \rho \hat{t} + \sqrt{1 - \rho^2} \hat{s}$, where $\rho \in [0, 1]$ is the amplitude reflectivity coefficient and the BS is assumed to be lossless. Behind the power actuator, $\hat{t}_c = \hat{b}_c - G \hat{h}_c$ is obtained, which yields

$$\hat{m}_c = \sqrt{1 - \rho^2} \hat{t}_c - \rho \hat{s}_c = \frac{\sqrt{1 - \rho^2}}{1 + \rho G} \hat{b}_c - \frac{\rho + G}{1 + \rho G} \hat{s}_c, \quad (4)$$

where an antisymmetric BS convention with a phase shift of 180° upon reflection of $\hat{s}$ was used. For large feedback gains, the control loop imprints the amplitude fluctuations measured by the in-loop detector with opposing sign onto $\hat{t}_c$ so they cancel in $\hat{h}_c$. As a result, noise contributions of $\hat{b}_c$ to $\hat{m}_c$ are suppressed, but at the same time, a fraction of $\hat{s}_c$ is imprinted onto $\hat{t}_c$, which constructively interferes with the reflected part

of $\hat{s}_c$ and propagates to the output. With $|G| \rightarrow \infty$ follows $\hat{m}_c \rightarrow -\hat{s}_c/\rho$, and since $\rho \in [0, 1]$, the contributions of $\hat{s}_c$ to the output field's amplitude quadrature $\hat{m}_c$ are effectively magnified. Thus, the field $\hat{s}$ and the BS ratio define the scheme's fundamental limit. Power fluctuations in the output can be quantified via the RPN of $\hat{m}$ [via Eqs. (2) and (4)]:

$$\begin{aligned} \text{RPN}_{out} &= \sqrt{\frac{1 - \rho^2}{|1 + \rho G|^2} \text{RPN}_{in}^2 + \frac{|\rho + G|^2}{|1 + \rho G|^2} \frac{\zeta}{1 - \rho^2} \text{RSN}_{P_0}^2} \\ &\xrightarrow{|G| \rightarrow \infty} \frac{\sqrt{\zeta}}{\rho \sqrt{1 - \rho^2}} \text{RSN}_{P_0}. \end{aligned} \quad (5)$$

RPN_{in} is the RPN of the input field $\hat{b}$. ζ is the power spectral density of $\hat{s}_c$ and represents the injected quantum noise in the amplitude quadrature. $\zeta = 1$ corresponds to a vacuum state, while $\zeta < 1$ represents amplitude quadrature squeezed vacuum. In the high-feedback-gain regime, the output RPN depends only on the input RSN (defined by the input power), the injected vacuum squeezing level, and the BS ratio. The factor $(\rho \sqrt{1 - \rho^2})^{-1}$ can be considered as a quantum noise penalty, which contains two opposing effects: for a higher ρ , the magnification of the contribution of $\hat{s}_c$ to the output due to the control loop is lower but the laser beam in the transmission of the BS is also more attenuated, leading to a larger RSN, and vice versa. The minimum of the quantum noise penalty is 2 for $\rho = 1/\sqrt{2}$, i.e., for a 50:50 BS, when these effects are balanced. Furthermore, the output RPN depends on the squeezing factor $\sqrt{\zeta}$. For a 50:50 BS and high feedback gain, $\text{RPN}_{out} \rightarrow \sqrt{2\zeta} \text{RSN}_{P_{out}}$. So for $\zeta < 1/2$, the output beam has power fluctuations below shot noise, i.e., it is bright squeezed light. The following presents our realization of this bright squeezing regime using a 50:50 BS. Figure 2 shows the bright squeezing experiment sketch. A 500 mW laser with an infrared wavelength of 1064 nm is used (model Mephisto by the company Coherent). The beam passes through an electro-optic modulator to imprint a 122 MHz phase modulation for Pound-Drever-Hall locking of the downstream cavities. Then, it is split into three parts: The first is the “bright” beam (i), which propagates to the 50:50 BS and to the in-loop and out-of-loop PDs. To stabilize the laser power, the in-loop PD signal is amplified and sent to two actuation paths: the laser pump-diode current modulator and an electro-optic amplitude modulator. For the power stabilization loop, a unity gain frequency of 2.4 MHz was achieved with a gain of up to 650 from 1 kHz to 10 kHz. The out-of-loop PD is connected to a spectrum analyzer to independently measure the power noise of the output beam, i.e., RPN_{out} from Eq. (5). Both PDs use high-quantum-efficiency ($\geq 99\%$) photodiodes [8] to reduce detection losses. The power on both PDs is adjusted to 9.9 mW to avoid saturation or damage to the photodiodes. By subtracting their signals, the two PDs can operate as a balanced homodyne detector to characterize the squeezed vacuum source with the power stabilization disabled. The second beam (ii) is sent to the second harmonic generator (SHG). In the SHG (stabilized to the infrared frequency via the SHG PD), the light interacts with a nonlinear crystal (magnesium-oxide-doped lithium niobate), which converts the infrared beam into its second harmonic field: a green beam at a wavelength of 532 nm. This green beam is injected into

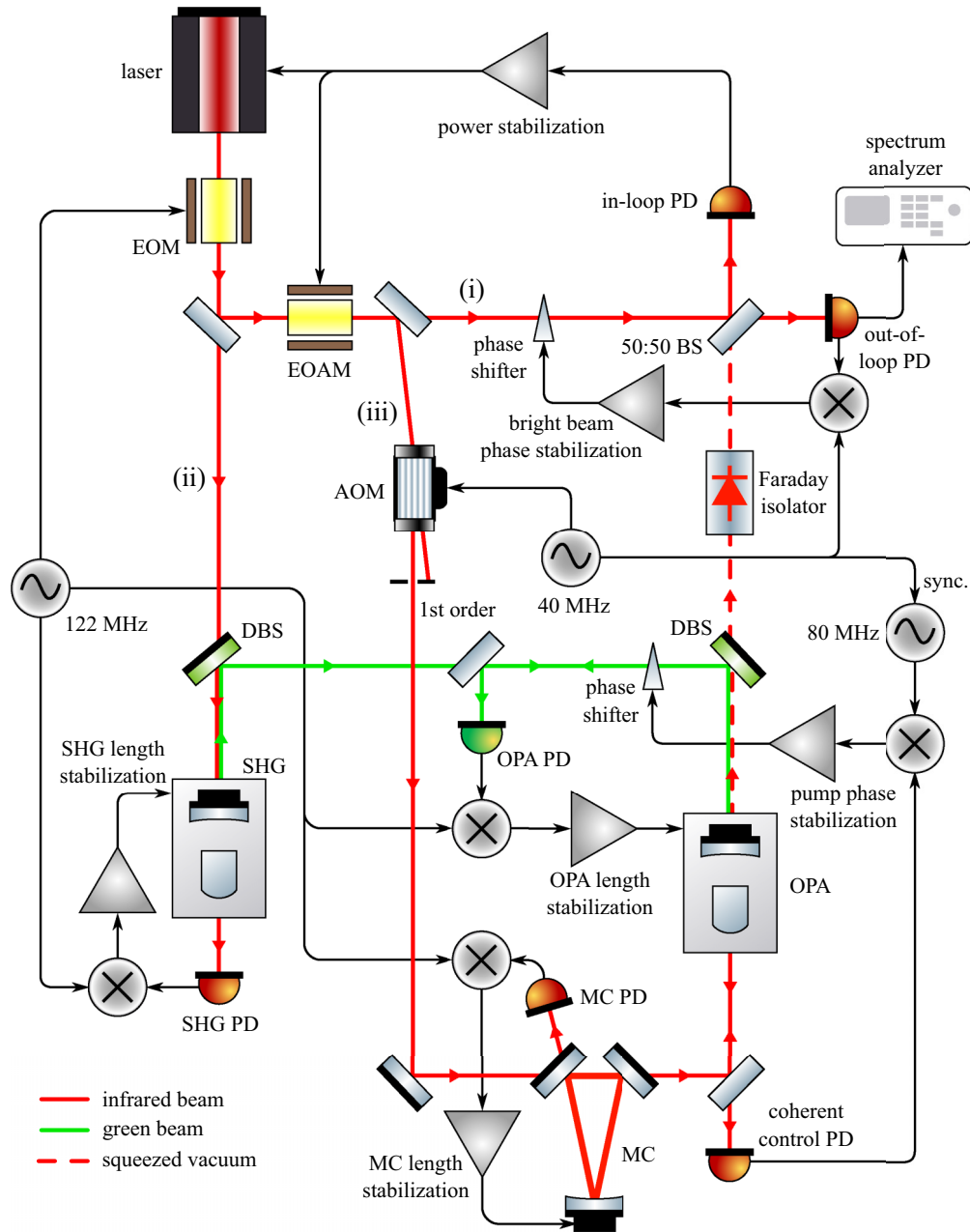


FIG. 2. Schematic of the bright squeezing experiment. The bright beam (i) is incident on the 50:50 BS, which splits it between the in-loop PD, used for the power stabilization via the laser pump diode current and an electro-optic amplitude modulator (EOAM), and the out-of-loop PD, used to measure the output RPN. Another beam (ii) is sent to the second harmonic generator (SHG), whose green output beam is used in the optical parametric amplifier (OPA) to generate squeezed vacuum at the infrared frequency. An acousto-optic modulator (AOM) frequency shifts a pick-off beam (iii), which is then used as a coherent control field for squeezing angle stabilization [7]. All cavities are stabilized via a Pound-Drever-Hall scheme. More details are given in the text. Legend: DBS, dichroic beamsplitter; EOM, electro-optic modulator; MC, mode-cleaner.

the OPA, which is stabilized to the second harmonic frequency via the OPA PD. In the OPA, the green beam is the pump field for squeezed vacuum generation at the fundamental frequency via parametric down-conversion in another nonlinear crystal (periodically polarized potassium titanyl phosphate). The cavity is doubly resonant for both the fundamental and second harmonic fields, where a precise tuning of the crystal temperature yields coresonance. The squeezed vacuum output is sent to the 50:50 BS through a Faraday isolator to suppress

scattering of the bright beam into the OPA cavity, which could degrade the squeezing performance [9,10]. The third beam (iii) is an auxiliary field for the coherent control of the squeezing angle [7]. It is frequency-shifted by 40 MHz via an acousto-optic modulator to avoid extraneous noise at the fundamental frequency. To suppress any residual contamination with non-frequency-shifted light, a mode-cleaner (MC) cavity (locked via a PDH loop using the MC PD) with a pole frequency of about 1 MHz was used as a frequency

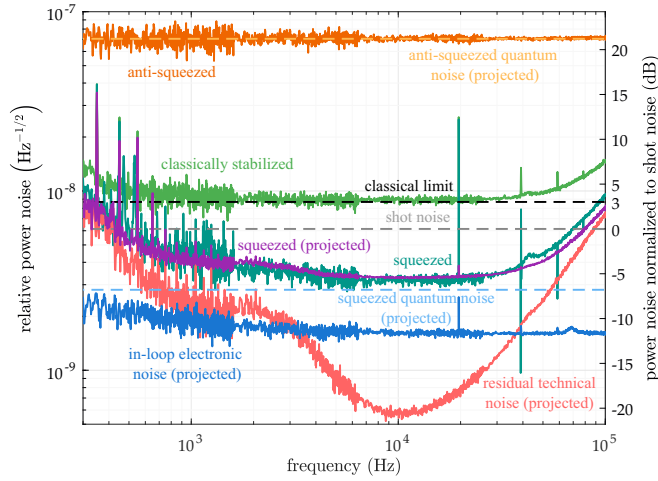


FIG. 3. Double logarithmic plot of the output RPN. The green curve shows the classically stabilized RPN. The teal and orange curves show the squeezed and antisqueezed measurements, respectively. The out-of-loop PD dark noise was subtracted (not shown, 13 dB below the classical limit at 10 kHz). The peaks at 19.6 kHz and its harmonics stem from the power supply of the used network analyzer, and the corresponding dips in the teal curve are an artifact of the dark noise subtraction. The dashed lines give the calculated quantum noise levels of the classical stabilization (black), the shot noise (gray), and squeezed (light blue) and antisqueezed (light orange) operations. The in-loop electronic noise (blue) and residual technical noise (red) in uncorrelated sum with the squeezed quantum noise yield the expected squeezed RPN (purple). The free-running technical RPN was $3 \times 10^{-7} \text{ Hz}^{-1/2}$ (36 dB above classical limit) or more in the depicted frequency range (not shown) and only decreases below shot noise above several MHz, which is outside the control bandwidth.

discriminator. The MC's output is injected into the back of the OPA. Locking the bright beam and the OPA pump field phases to the coherent control field stabilizes the squeezing angle. For this, error signals are obtained via the out-of-loop PD and the coherent control PD, demodulated at 40 MHz and 80 MHz, respectively. Phase shifters are placed in both beams as actuators for the respective phase control loops. Figure 3 displays the amplitude spectral density of the output RPN [cf. RPN_{out} in Eq. (5)] from 300 Hz to 100 kHz with the out-of-loop PD's electronic dark noise subtracted. The green curve shows the measurement for a blocked squeezed vacuum beam (i.e., the classical result), which settles on the dashed black line representing the classical stabilization limit at a factor $\sqrt{2}$ above the RSN of the output power of 9.9 mW (dashed gray line). The excess noise below 500 Hz and above 30 kHz can be explained by a gain limitation of the power stabilization loop, which does not allow full technical laser noise suppression at these frequencies. This is supported by the red curve, which shows the free-running noise multiplied by the control loop's noise suppression function. The dark blue curve shows the in-loop electronic noise (comprising the in-loop PD and feedback amplifier noise) projected to the output RPN. The dashed light blue line at a factor of 3.1 (or 9.8 dB) below the classical limit depicts the projected quantum noise limited RPN for amplitude quadrature squeezed vacuum

injection. It corresponds to the classical limit multiplied with the vacuum squeezing level, which was measured with balanced homodyne readout via the in-loop and out-of-loop PDs (with the power stabilization disabled). The measured RPN of the nonclassical power stabilization is shown in teal. The curve shows a broadband improvement over the classical stabilization. Aside from a number of peaks (some of which are simply power line harmonics), the measured RPN surpasses the classical stabilization limit from about 350 Hz to 94 kHz, and particularly is below the RSN from about 550 Hz to 70 kHz. At an RPN of $3.2^{+0.13}_{-0.13} \times 10^{-9} \text{ Hz}^{-1/2}$ from about 6 kHz to 20 kHz it is a factor $2.71^{+0.11}_{-0.11}$ (or $8.7^{+0.3}_{-0.4}$ dB) below the classical limit and conversely $1.92^{+0.08}_{-0.08}$ (or $5.7^{+0.3}_{-0.4}$ dB) below the shot noise of the output power of 9.9 mW. As such, the output beam distinctly classifies as bright squeezed light. Computing the uncorrelated sum of the projected quantum noise (dashed light blue), the residual technical noise (red), and the in-loop electronic noise (dark blue) results in the purple curve, representing the expected squeezed output RPN. This curve closely matches the measurement. The minor deviation of measurement and projection above 40 kHz is insignificant, as it can be explained by an observed nonstationary power noise behavior of the laser source. In the time between measuring the free-running noise for the residual technical noise projection and the squeezed RPN, the power noise likely changed slightly, which results in the deviation as the setup is gain limited for these frequencies. The origin of the extraneous noise in form of peaks below 1.6 kHz is unknown, but is likely scattered light. The main limitation for frequencies around 10 kHz was the achievable squeezing. It was limited by optical losses, which were determined to be $10.4^{+1}_{-1} \%$ by fitting the squeezing and antisqueezing levels measured at different OPA pump powers to a theoretical model [8,11]. Within the error margin, this matched the estimated loss budget of $8.8^{+3}_{-2.5} \%$. The corresponding antisqueezed RPN is shown in orange. At a factor of $8.19^{+0.43}_{-0.43}$ (or $18.3^{+0.4}_{-0.5}$ dB) above the classical limit it closely matches the expectation from balanced homodyne readout at 18.2 dB (dashed light orange line).

The demonstrated performance shows the nonclassical power stabilization scheme's capabilities as a bright squeezed light source. In this scheme, however, there is a tradeoff between the achievable output power and squeezing level due to the quantum noise penalty. Even for the minimum quantum noise penalty configuration (50:50 BS), the output RPN is a factor of two above the input RSN [see Eq. (5)], diminishing the squeezed vacuum source's full potential. Furthermore, for a fixed BS ratio the bright squeezed beam's maximal power is determined by the in-loop PD's power handling capability. For the minimal penalty, it has to be as high as the bright beam's power in the downstream application. To circumvent this power limitation issue and enable higher squeezing levels, we investigated an alternative concept using an optical AC coupling topology [12], as shown in Fig. 4. A beam's power noise is sensed in reflection of a cavity instead of a BS. For a close-to-impedance-matched cavity, a resonant carrier field is almost entirely transmitted, and conversely strongly attenuated in reflection. Power noise contributions at frequencies above the cavity pole frequency are effectively reflected and

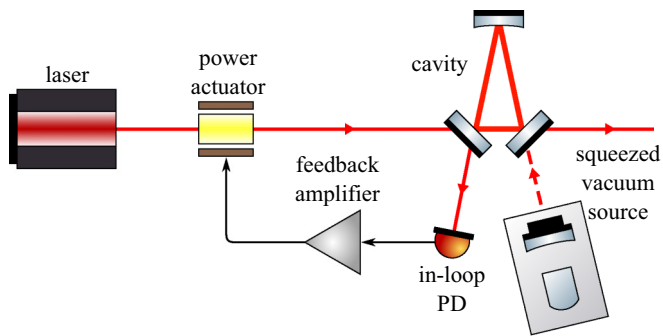


FIG. 4. Optical AC coupling [12] assisted bright squeezing. The power noise of a laser is measured in reflection of a cavity. The resonant carrier field is mostly transmitted and only a small fraction of its power has to be detected in reflection. Power fluctuations with frequencies above the cavity pole frequency are mostly reflected and sensed by the in-loop PD for feedback stabilization. Squeezed vacuum injection in the output port (dashed red line) can yield bright squeezing without quantum noise penalty at effectively the full beam power.

measured by an in-loop PD to stabilize the power. The field entering the cavity output port is equivalent to the field $\hat{s}$ in Fig. 1, causing a quantum limit. For large feedback gain and frequencies sufficiently above the cavity pole frequency, all technical noise is suppressed, so that the output power noise is given solely by the reflected quantum noise. Thus, an output RPN equal to the output power's RSN is achievable [13], and for a certain power stability significantly less power has to be detected by the in-loop PD compared to the conventional scheme discussed above. Injecting amplitude quadrature squeezed vacuum in the cavity output port could yield a bright squeezed output beam for frequencies sufficiently above the cavity pole frequency in principle without any quantum noise penalty. For a low enough pole frequency, as demonstrated in [14], audio band bright squeezing could be

achieved. As only a fraction of the full power must be detected by the PD, this technique is scalable to high power levels, e.g., several hundred watts as used in gravitational wave detectors (GWDs) [15]. This makes it applicable as a laser source for a heterodyne readout of a GWD, which might require a bright squeezed input beam [16,17]. Another potential application is in future GWDs, where laser power noise can couple to frequency noise via radiation pressure in the input mode cleaner cavities, which limits the achievable frequency stability [18]. Due to this mechanism even a shot-noise-limited high-power laser beam could impose a relevant limit to the GWD's sensitivity, which could be surpassed by a bright squeezed light source via the nonclassical optical AC coupling topology.

In conclusion, we reported the first experimental realization of bright squeezed light generation via nonclassical power stabilization. At an optical power of 9.9 mW, the output beam exhibited an RPN below the classical power stabilization limit and a broadband reduction below its shot noise in the kHz frequencies of up to $5.7^{+0.3}_{-0.4}$ dB. Our measurements agree well with simulations that allow us to predict the subshot noise behavior of our power stabilization scheme for different injected vacuum squeezing levels and BS ratios. The demonstrated scheme is highly relevant for experiments that only allow for low light levels in the application. Furthermore, we discussed an alternative bright squeezing topology via optical AC coupling, which could enable higher squeezing levels and brighter squeezed beams.

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The authors declare no conflicts of interest.

Data underlying the results presented in this paper are not publicly available but may be obtained from the authors upon reasonable request.

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