

Reservoir-Engineered Squeezed Lasing through the Parametric Coupling

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We report the first experimental demonstration of squeezed lasing in a reservoir-engineered optical parametric oscillator (OPO). The OPO provides a basis of squeezed states and parametric amplification in lasing emission, whose vacuum reservoir is coupled to a squeezed vacuum generated by a second OPO. With a precisely controlled squeezing angle and strong squeezing injection, the parametric interaction in the first OPO is exponentially enhanced. It successfully circumvents the decoherence in the system, and eliminates the undesired noise of spontaneous photon emission in the OPO. As a result, the amplified parametric process simultaneously reserves the coherence and quantum properties in the first OPO, and yields a -6.1 dB squeezed laser in optical domain with a narrow linewidth and high brightness. Our work sheds light on potential applications of squeezed lasing in quantum metrology and quantum optics.

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A squeezed laser retains both lasing coherence and photon correlations of squeezed states. It has potential applications that go beyond standard lasers or squeezed vacuum states. To improve the performance of coherent coupling between squeezed lasers and atomic transitions, squeezed states should have a narrow linewidth to drive superior applications of atomic quantum metrology [1,2], quantum memory, etc. [3,4]. A squeezed laser with lower noise and long coherence time also offers a possibility to improve the detection sensitivity, resolution, and distance in coherent detection scenarios, etc. [5–10], while it is also advanced for quantum key distribution maintaining a laserlike coherent amplitude [11,12]. In optical interferometry, a squeezed laser is free of squeezed vacuum state injection from the dark port of the interferometer [7,13,14], which is expected to simplify the implementation of precision measurement. These broad prospective applications generate great interest in researching squeezed lasing [15,16].

Conventionally, the subthreshold optical parametric oscillator (OPO) belongs to the most successful approaches for squeezed state generation [17–26], in which spontaneous parametric coupling induces a coherence deterioration [27,28]. When above threshold, the stimulated parametric coupling induces lasing radiation with excellent coherence [27,28]. However, two-photon damping and thermal noise

emerge to induce an undesired noise [16,29–33], along with a phase transition to turn the squeezed state into a mixture of two coherent states [34]. In this regard, the coherence and quantum properties herein are mutually incompatible. Additionally, the output frequency spectrum of an OPO always has a frequency comb property with a frequency separation of its free spectral range [19,35–37], which forms a multimode optical field output with multiple frequency components to cause a mode competition in lasing emission. Hence, in order to prepare a squeezed laser with an OPO, we should eliminate the undesired noise under single mode operation. A detuned parametric driven cavity with an external squeezed vacuum reservoir and an intracavity atom gain medium is proposed to prepare a squeezed laser [16]. Profiting from the squeezed vacuum reservoir, the undesired noise is removed, and the photon-atom interaction is simultaneously enhanced by a factor of $\cosh 2r$ (r is the squeezing parameter) [16,29,30,38,39]. Finally, a single squeezed laser mode corresponding to the transition of the atom energy levels can be directly generated. However, the proposal is confronted with a great challenge in experimental implementation. Strikingly, an open quantum system with assistance of squeezed vacuum not only can be parametrically driven to generate a desired quantum state with undesired noise removed, but also can enhance the interaction in the system to become a strong coupling one and preserve longer coherence time [15,16,29,30,38–40]. The regime provides a feasible route for squeezed lasing generation.

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Here, we report on the first experimental demonstration of squeezed lasing in an optical domain, resorting to a low-loss OPO engineered by a broadband squeezed vacuum. In contrast to the above threshold OPO, the reservoir-engineered OPO enables to enhance the parametric interaction and reduce the noise coupling with environment simultaneously, which drives the spontaneous parametric coupling into a stimulated parametric one, and reserves the quantum property of the output field. Because of the difference in cavity length design of the two OPOs for squeezed vacuum and squeezed laser generation, only the single cavity mode at the carrier frequency can be amplified to form a lasing. As its origin from a subthreshold OPO, the process simultaneously preserves the squeezing and laser-like coherence properties. This experiment points toward the potential applications of squeezed lasing in quantum metrology and quantum optics.

Optical parametric coupling with engineered reservoir— Let us consider a $\chi^{(2)}$ parametric coupling process with subthreshold OPO for single mode squeezed state generation in Figs. 1(c) and 1(d), which is validly demonstrated in Sec. 3 of Supplemental Material [41]. A pump photon with a carrier frequency of ω_p spontaneously down-converts into a signal photon ω_s and an idle photon ω_i [Fig. 1(c)], with coherence deterioration [Fig. 1(d)] [27,28]. When the OPO operates above threshold, the stimulated down-conversion dominates the interaction with perfect coherence [Figs. 1(a) and 1(b)] [27,28]. However, due to the stimulated intense signal and idler fields, two-photon damping [Fig. 1(a)] occurs to cause a phase transition at threshold, accompanied by spontaneous symmetry breaking of the discrete phase above threshold [34]. It turns the squeezed vacuum state into a mixture of two coherent states

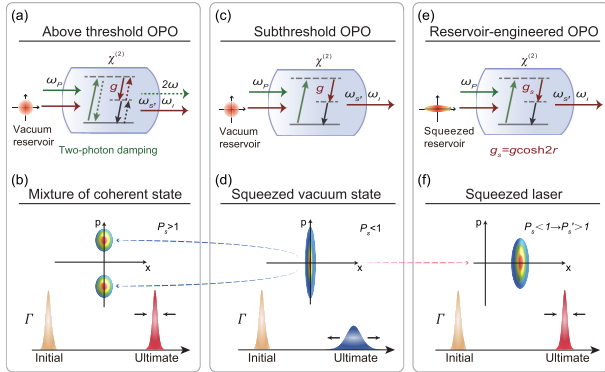


FIG. 1. Physical mechanism of the parametric coupling with vacuum or squeezed vacuum reservoir. (a) Parametric down-conversion (PDC) in an above threshold OPO. (b) Mixture of two coherent states with coherence preservation and quantum characteristic deterioration. (c) PDC in a subthreshold OPO. (d) Squeezed vacuum state with quantum characteristic preservation and coherence deterioration. (e) PDC in a subthreshold OPO with squeezing vacuum reservoir. (f) Squeezed lasing with coherence and quantum characteristic preservation.

[Fig. 1(b)] [16,34]. The influence of the damping can be also treated as an undesired noise coupling to submerge the squeezed property, as a consequence of the vacuum input [16,29,30,38,39]. Hence, the conventional OPO cannot be directly applied to generate a squeezed lasing.

Recently, a parametrically driven OPO with squeezed vacuum reservoir had been theoretically proposed to eliminate the two-photon damping induced undesired noise, and exponentially enhance the light-matter interactions at the same time in the atom [16,29,39] and optomechanical resonators systems [30,38]. Inspired by these ideologies, we propose a squeezed vacuum reservoir-engineered OPO to prepare a squeezed laser [Figs. 1(e) and 1(f)]. Differing from Ref. [16], the parametric interaction in our system is reserved without cavity detuning. With assistance of squeezed vacuum reservoir, the intracavity parametric coupling is exponentially enhanced with undesired noise removed. Then, the Hamiltonian of the system can be written as $\hat{H} = \Delta_c \hat{a}^+ \hat{a} + g(e^{-i\theta_p} \hat{a}^2 + \text{H.c.})/2$, where θ_p is the phase of the pump field, Δ_c is the detuning of the cavity, and \hat{a} represents the annihilation operator. By changing the basis with squeezing unitary transformation $\hat{S}(\xi) = \exp[1/2(\xi^* \hat{a}^2 - \xi \hat{a}^{\dagger 2})]$, where $\xi = r e^{-i\theta}$, we substitute $\hat{a} \rightarrow \hat{a}_s \cosh r - \hat{a}_s^+ e^{-i\theta} \sinh r$, in which \hat{a}_s is the annihilation operator in the new squeezed basis, and θ is the squeezing angle in squeezing unitary transformation. Then, the Hamiltonian in the new basis can be deduced as [16,29,41]

$$\begin{aligned} \hat{H}_s = & \left\{ \hat{a}_s^2 \left[\frac{g}{2} (e^{i\theta_p} \cosh^2 r + \sinh^2 r e^{-i(\theta_p - 2\theta)}) \right. \right. \\ & \left. \left. - \Delta_c e^{i\theta} \cosh r \sinh r \right] + \text{H.c.} \right\} \\ & + \hat{a}_s^+ \hat{a}_s \left[-g \cosh r \sinh r (e^{i(\theta_p - \theta)} + e^{-i(\theta_p - \theta)}) \right. \\ & \left. + (\cosh^2 r + \sinh^2 r) \Delta_c \right] \\ & - \frac{g}{2} \cosh r \sinh r (e^{i(\theta_p - \theta)} + e^{-i(\theta_p - \theta)}) + \Delta_c \sinh^2 r, \end{aligned} \quad (1)$$

where g is the parametric coupling strength, and r is the squeezing parameter. Apparently, this Hamiltonian offers a possibility to modify the parametric interaction, and engineer the squeezed vacuum reservoir by controlling the squeezing angle θ and parameter r . We set $\theta_p - \theta = \pi$; the interaction term of \hat{H}_s reduces to $\hat{a}_s^2 [-(g_s/2) - \Delta_c \cosh r \sinh r] + \text{H.c.}$. With $\Delta_c = 0$, the resulting parametric coupling strength g_s is exponentially enhanced by a factor of $\cosh 2r$, i.e., $g_s = g \cosh 2r$ [16,29,30,38–41].

Taking a phase squeezed vacuum reservoir coupled to an amplitude squeezed basis as an example, i.e., $\theta_p = \pi$ and $\theta = 0$, we substitute the Hamiltonian of Eq. (1) into the conventional motion equation of the OPO, the quadrature variance of amplitude \hat{X}_{out} of the squeezed laser can be derived as [41]

$$\delta^2 \hat{x}_{\text{out}} = \left(\frac{\kappa^2}{2M} + \sqrt{1 - \kappa} \right)^2 e^{2r} - \left[\frac{\kappa}{M} (-i\omega + A - B) \right]^2 e^{-2r}, \quad (2)$$

where $A = -(i\Delta_c/\hbar) \cosh 2r - ig \sinh 2r$, $B = (i\Delta_c/\hbar) \sinh 2r + ig_s$, $M = (i\omega - A + \sqrt{\kappa})(-i\omega - A^* + \sqrt{\kappa})$, κ is the cavity damping constant, and ω is the sideband frequency of the carrier. The detailed derivation is shown in Supplemental Material [41].

Experimental realization of squeezed laser—Figure 2 illustrates the schematic diagram of our experimental setup. A pump laser with the wavelength of 532 nm is prepared by a second harmonic generator (SHG). Its output is divided into two beams to provide the pump sources of the two OPOs. The OPOs are both semimonolithic resonators, which consist of a concave mirror and a PPKTP crystal. When they work independently, more than $-12/-10$ dB amplitude squeezing had been observed [42,45]. It indicates a high squeezing parameter and low intracavity loss is available, which provides the basic conditions for squeezed lasing generation. OPO1 with a linewidth of 68 MHz and a free spectral range of 3.33 GHz is applied for squeezed vacuum preparation, and OPO2 plays a crucial role for squeezed basis supply and parametric amplification, which linewidth is 97 MHz and free spectral range is 3.76 GHz. In lasing emission, OPO1 operates at parametric amplification status with phase quadrature squeezing, while OPO2 is locked at opposite phase versus OPO1 to generate an amplitude squeezed light. The small length difference of the two OPOs ensures a stable single mode operation under squeezing enhanced regime, which ensures only one cavity mode of OPO2 in the center of the PPKTP spectral acceptance bandwidth is exponentially amplified. The detailed parameters of the OPOs and laser properties can be found in Supplemental Material [41].

Of the squeezed vacuum existing from OPO1, 99% transmits through a Faraday isolator (FI), and is mode

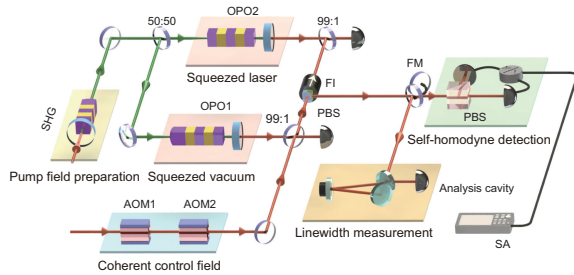


FIG. 2. Schematic of the experimental setup for squeezed laser generation and evaluation. HR, high reflectivity; FI, Faraday isolator; PBS, polarization beam splitter; SHG, second harmonic generator; OPO1,2, optical parametric oscillator; AOM, acousto-optic modulator; BS, beam splitter; FM, folding mirror; SA, electrical spectrum analyzer.

matched to OPO2 with an efficiency of 99% to excite the exponentially amplified parametric coupling. Of the squeezing signal, 1% is coupled with a coherent control beam ($\sim 100 \mu\text{W}$) [46], which passes through a two-stage acousto-optic modulator (AOM) to produce a frequency shift beam of 20 MHz, and is demodulated at 40 MHz to create an error signal to lock the relative phase between the control and squeezing beams to 0. The coupled beam acts as an auxiliary signal to control the relative phase between the squeezed laser and pump field to π . The frequency shifted beam has a linewidth of 300 kHz, i.e., 20 ± 0.15 MHz, which has no risk for the sideband noise variance evaluation at 18 MHz. Owing to the superiority and advancement of our OPOs and control technologies [42,45,47,48], the squeezed lasing can be continuously radiated from OPO2. The generated squeezed laser exits from the output coupler of OPO2, and is reflected by the input port of FI. Its noise variance of the amplitude quadrature at sideband frequency and laser linewidth are measured by the self-homodyne detection [49] and β -separation line algorithm [41,50] methods, respectively. In linewidth characterization, an analysis cavity is utilized to calibrate the frequency noise spectrum of the laser [33,43,44,49].

Results and discussion—The experimental arrangements supply a squeezed vacuum reservoir and guarantee an amplitude squeezed lasing, in which only the generated photons with carrier frequency are exponentially amplified. To comprehensively evaluate the squeezed lasing performance, we optimize the pump ratio and squeezing parameters of the OPOs to excavate the transformation law for the optimum laser power, squeezing level, and coherence, as shown in Figs. 3 and 4.

Squeezed laser power versus pump power P : A -10.4 dB squeezed light of phase quadrature generated from OPO1 is coherently coupled to OPO2. Propagation loss sets the fundamental limit to the possible enhancement of parametric amplification in squeezed lasing. The expected losses for components between the two OPOs are 5%, measured by the powers of the signal beam at the output port of OPO1 and input port of OPO2. The remainder squeezing coupled to OPO2 is reduced to -8.6 dB, which supplies a 3.7 times enhancement for parametric gain. The result can be also confirmed by the changes of threshold power P_{th} of OPO2, which decreases from $P_{\text{th}} = 45$ mW to $P'_{\text{th}} = 11.4$ mW (more details are provided in Supplemental Material). With constant squeezed vacuum injection, the output power of the squeezed laser against the pump ratio $P'_s = P/P'_{\text{th}}$, normalized to the new threshold power of OPO2, is measured by a power meter, as shown in Fig. 3(a). The laser output power increases from 0.5 to 2.6 mW as P'_s changes from 1 to 1.75, corresponding to the pump powers from 11.4 to 20 mW. It is markedly below the physical threshold power with vacuum reservoir. To increase P'_s further, the squeezed lasing becomes unstable. We speculate

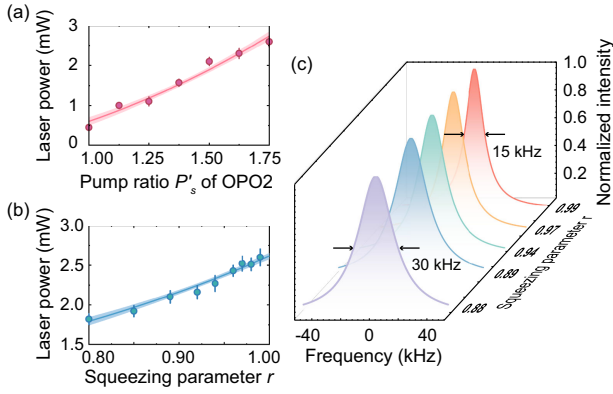


FIG. 3. (a) Squeezed laser power versus pump ratio P'_s of OPO2 with reservoir engineered by a -10.4 dB squeezed state of phase quadrature. (b) Squeezed laser power at the pump ratio of $P'_s = 1.75$ versus the squeezing parameter r . (c) Variation of laser linewidth with the squeezing parameter r measured by β -separation line algorithm method. The data (dots) are fitted with analytical expressions (solid lines) adopted from (S2.9) and (S2.10) in Supplemental Material [41]. The results show that the squeezed laser power increases linearly with pump power (red curve), and increases with the squeezing parameter r by a factor of $\cosh 2r$ (blue curve). The data is fitted with 68% confidence bands (shaded area) and the error bars stand for 1 s.d.

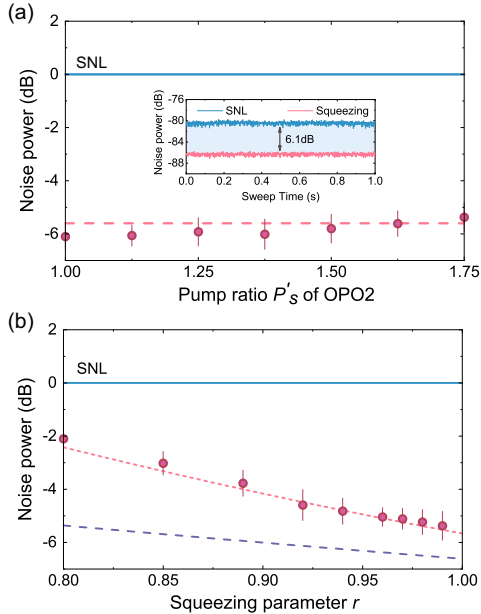


FIG. 4. Noise power of the squeezed laser versus pump ratio P'_s (a) and injected squeezing parameter r (b). Red solid dot points, experimental data; red dashed lines, theoretical fitting with undesired noise; blue dashed line, theoretical result without undesired noise. The theoretical curves are followed by equations (S2.13) and (S2.14) in Supplemental Material. Blue solid line represents the shot noise limit (SNL) level. All the data are measured at the sideband frequency of 18 MHz. RBW, 300 kHz; VBW, 200 Hz. The error bars stand for 1 s.d.

two reasons contribute to this effect, one is the multiple cavity-mode overlapping shown in Fig. S3 of Supplemental Material [41], which results in multimode competition; the other one is more undesired noise production due to higher pump strength, which causes the relative phase θ_p drifting from π and unlocked.

Squeezed laser power versus squeezing parameter r : With $P'_s = 1.75$, we also investigate the laser power versus the squeezing parameter r , which is continuously controlled by the pump ratio of OPO1. The results are shown in Fig. 3(b), which indicate the power is monotonically amplified to a maximum value of 2.6 mW along with r increased from 0.8 to 0.99. The observed power increment represents the direct experimental manifestation of lasing behavior driven by a squeezed vacuum to stimulate a macroscopic photonic occupation with squeezing property. Additionally, the phase squeezed light from OPO1 has a bright amplitude, which power is raised with r increasing, and is seeded into OPO2 [41]. But we have experimentally demonstrated that this weak mean field has negligible influence to the squeezed laser power due to its opposite phase to that of the squeezed laser, and only the photons generated in the cavity are amplified [41]. Therefore, the power of the bright squeezed light is directly deduced from the results in Figs. 3(a) and 3(b). A detailed analysis can be found in Supplemental Material [41].

Laser linewidth evolution: Laser linewidth Γ is connected with the coherence of a laser, which is one of the key features of the squeezed lasing distinguishing with the squeezed vacuum state. We also synchronously evaluate the linewidth enhanced by squeezed vacuum under the identical experimental circumstances of (b), which is characterized by a β -separation line algorithm method [41]. In the first step, we calibrate the accuracy of the β -separation line algorithm method with the standard delayed self-heterodyne one [51]. Taking the initial 1064 nm laser source used in the experiment as an example, the measured linewidths are 13 kHz (delayed self-heterodyne) and 15 kHz (β -separation line algorithm), respectively. The tiny difference between the two technologies certifies that β -separation line method is reliable to evaluate the linewidth of squeezed laser. Next, the improvement of the linewidth Γ with squeezing enhancement is characterized as shown in Fig. 3(c). When r changes from 0.8 to 0.99, the linewidth of the squeezed laser reduces from 30 to 15 kHz. It is apparent that the linewidth gradually approaches that of the original laser. The linewidth preservation also gives the credit to strong coupling mechanism with assistance of squeezed vacuum reservoir in OPO2, which stimulates a coherent parametric interaction between the photons and dipoles to circumvent the optical decaying in the system.

Squeezing property preservation: The final essential feature of a squeezed laser is the quantum correlation. Figure 4 shows the squeezing degree of the squeezed laser at the sideband frequency of 18 MHz versus the pump ratio

P'_s of OPO2 and the injected squeezing parameter r . Figure 4(a) depicts a maximum squeezing level with the same experimental conditions of Fig. 3(a). With the injected squeezing parametric $r = 0.99$, the squeezing degrees are basically close to -6 dB, slowly decreasing with the increasing of pump ratio P'_s , which is mainly attributed to more undesired noise coupling with stronger pump strength. With $P'_s = 1$, the optimal squeezing is observed to be -6.1 dB, which is mainly limited by the propagation loss between OPO1, OPO2, and the self-homodyne detection unit; more details can be found in Supplemental Material [41]. For $P'_s = 1.75$, we change the injected squeezing parametric r from 0.8 to 0.99, the noise power of the sideband frequency evolves from -3.2 to -5.4 dB, shown in Fig. 4(b). By comparing the difference between the theoretical results with and without undesired noise [the red and blue dashed lines in Fig. 4(b)], we can infer that the residual undesired noise exists in the system, which decreases the squeezing level of the squeezed laser. Distinctly, the higher the injected squeezing parametric r , the stronger the generated squeezing is, because of more undesired noise is suppressed with stronger squeezing input. The deviation between the theoretical (red dashed line) and experimental results maybe mainly come from the uncertainty of the threshold power calibration, and non-linear noise coupling from the pump beam. Therefore, it can be predicted that more than 6.1 dB squeezing is available, e.g., in our state-of-the-art OPO [18,52], quantum noise in the sideband frequency can be squeezed more than -13.1 dB [41], but only if we further reduce the propagation losses between the two OPOs, and increase their squeezing level.

We perform the entire measurement several times on different days to show reproducibility of the regime. Our experimental results are in good agreement with the theoretical analysis, and demonstrate an efficient protocol for squeezed lasing emission with a reservoir-engineered OPO regime. The experimental scheme can be utilized to circumvent the interaction with environment, and preserve both the coherence and quantum properties of the system.

Conclusion and outlook—We have shown how to engineer the vacuum reservoir of a OPO with assistance of a squeezed vacuum state that emits laser into a squeezed state in a parametric coupling scenario. Our scheme relies on two squeezed states of opposite phases to exponentially amplify the parametric interaction: for one thing it turns the spontaneous photon emission into a stimulated one to perform a laser radiation, while for the other it allows engineering the vacuum reservoir with squeezed state injection to drive the lasing action into a squeezing operation before phase transition. Therefore, the coherence of a laser and quantum property of a squeezed state can be simultaneously preserved in one laser beam. For the first time, a 15 kHz narrow linewidth, -6.1 dB squeezed laser with an output power of 2.6 mW is experimentally

generated in optical domain. Our demonstration provides a promising route for implementing squeezed lasing with current state-of-the-art squeezed state preparation technology, while further reducing the propagation loss, and more stable phase-locking improvement would produce a stronger squeezing more than 10 dB and more robust operated nonclassical lasing. Our work opens a possibility to simultaneously preserve the coherence and quantum properties of a squeezed lasing regime, and may find applications in quantum sensing and metrology.

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Data availability—The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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