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ABSTRACT

We illustrate the generation of single-mode amplitude squeezing in a distributed feedback quantum dot laser driven by a constant-current pump. Achieving broadband amplitude squeezing of 1.7 dB over a 10 GHz range at room temperature is realized by suppressing carrier noise and implementing optical feedback. The noise-corrected squeezing level reached 5.1 dB. Furthermore, the examination of the zero-delay second-order correlation function demonstrates the robust feedback stability of the amplitude-squeezed state in the quantum dot laser compared to a reference quantum well laser. This investigation lays the groundwork for future advancements in integrated optical quantum chips.

I. INTRODUCTION

The ever-evolving optical information technology has been persistently pushing the development of high-performance light sources with ever-lower noise levels. At present, these sources play pivotal roles both in classical optics such as light detection and ranging (LiDAR) and optical communications[1–3] and in newer quantum photonics applications such as continuous-variable quantum key distribution (CV-QKD), quantum computing, and ultra-precise quantum sensing.[4–6]

Notably, the generation of squeezed states offers great potential for the above-mentioned quantum applications. The idea of squeezed states follows from the Heisenberg uncertainty principle. In contrast to the coherent state whose quadrature components (Δx and Δp) are the same, the quadrature squeezed states exhibit noise suppression below the standard quantum limit [SQL, or as shot noise level (SNL)] on one quadrature component.[7] Another squeezed state, the amplitude squeezed state known as the photon number squeezed state is defined as having a photon number noise $\langle \Delta \hat{n}^2 \rangle$ below the SNL, and the relationship between the photon number and the phase noise is $\langle \Delta \hat{n}^2 \rangle \langle \Delta \hat{\phi}^2 \rangle = 1/4$. Analogously, if the phase noise of the light is suppressed below the SNL, the phase squeezed state emerges.[8] To obtain quadrature and amplitude squeezed states below the SQL in experiments, mostly using $\chi^{(2)}$ or $\chi^{(3)}$ optical nonlinearities, such as Kerr effect and four-wave mixing,[9–11] has been proposed. Various platforms have been considered wherein these nonlinearities can be evoked. On the one hand, there is the use of nonlinear crystals, which have historically been the workhorse for generating squeezed states.[12,13] On the other hand, the nonlinear crystals, while being a well-established tool, might lack the desired miniaturization for some applications. Indeed, with the advent of integrated photonics, on-chip nonlinearities that utilize structures such as micro-rings to generate the Kerr effect have begun to receive attention.[14] The signal of four-wave mixing from the microcavity could bring a wide comb two-mode squeezed state[15] or the squeezed vacuum.[16] However, these nonlinear effects are based on two-photon processes, which cannot produce single-mode amplitude squeezed states, and the processes are very complex. This is the reason why the single-mode amplitude squeezed states are the focus of this work, which are well suited for high-precision interferometry, such as gravitational wave detection.[17]

A simple and stunning way to generate single-mode amplitude squeezed states is to employ external sub-Poissonian distributed carriers from a quiet pump. The noise properties of the pump can significantly influence the amplitude noise of semiconductor lasers. Based on the microscopic theory of junction current noise in the active layer of a semiconductor laser, it is known that the pump fluctuations of a semiconductor laser are a thermal noise that could be lower than the SNL. That is exactly the reason why electrically pumped semiconductor lasers have the potential for amplitude squeezing.[8] For instance, Yamamoto *et al.* demonstrated that using a quiet pump to drive quantum well (QW) distributed feedback (DFB) lasers can produce single-mode amplitude squeezed states, and, subsequently, a substantial amount of theoretical research has been conducted in this direction.[8,18] Taking advantage of the photoelectric conversion process that is related to the laser structure and the quantum confinement effect of the active region, several investigations have shown that the injection of sub-Poissonian distributed carriers can be transformed into sub-Poissonian photon emission, thus achieving amplitude squeezed states of light.[19–21] In addition, the weak dispersive optical feedback based on a quiet pump can further enhance the SL.[22–24] This is due to the fact that the changes in amplitude and phase interactions introduced by the optical feedback process alter the emission characteristics of the laser.[24,25] In this backdrop, quantum dot (QD) laser emerges as a promising candidate for achieving an on-chip squeezed state generator, thanks to their superior characteristics such as high quantum efficiency, easy integration, and reflection insensitivity.[26,27] Our previous work demonstrated that the utilization of the quiet pump combined with QD laser technology can improve the noise characteristics and produce the amplitude squeezed states, which was demonstrated both experimentally and theoretically.[28,29]

Here, we go a step further by comparing the noise and squeezing properties of a QW DFB laser and a QD DFB laser operating under external optical feedback. Results revealed that QD lasers not only have a classical noise highly robust against external optical feedback, but also their quantum noise remains perfectly steady under the most severe optical feedback conditions with the squeezing level (SL) and bandwidth increasing to 1.7 dB and 10 GHz, respectively. In addition, after correction, the noise squeezing level is found as high as 5.7 dB. To further support our conclusions, we also implement the zero-delay second-order correlation function $g^{(2)}(0)$ measurement, which is used to assess whether the squeezed light exhibits anti-bunching properties. Overall, we believe that these results confirm the very high potential of QD laser technology for innovative and compact, ultralow-noise and on-chip building blocks to advance precision optical sensing, quantum communication, and quantum computing.

II. SQUEEZING EXPERIMENTS IN THE PRESENCE OF EXTERNAL OPTICAL FEEDBACK

Figure 1 displays the tabletop experiment used for extracting the squeezing characteristics in the presence of external optical feedback. It involves a quiet pump for amplitude squeezed state generation and the balanced self-homodyne detection part. A single-mode QD DFB laser with a threshold current of 9 mA and emitted

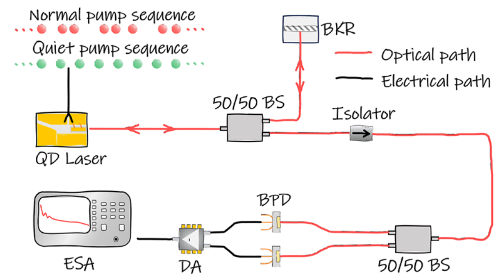

FIG. 1. Experimental setup for amplitude squeezed state generation employing external optical feedback.

at a wavelength of 1.31 μm at 20 °C is used. First of all, it is crucial to accurately calibrate the SNL. For this purpose, we use a normal pump (Keithley 2401) to drive the QD DFB laser and manipulate the local oscillator (LO) phase. If the RF signal remains constant, the SQL can be determined accordingly. The red small bullets in Fig. 1 represent the bunched carrier sequence of the normal pump. The 50/50 beam splitter (BS) and back-reflector (BKR) in front of the optical isolator are removed when the SNL calibration is performed. When performing amplitude squeezed state measurements, the QD DFB laser is driven by a quiet pump (ILX Lightwave LDX-3620). The latter is set to operate at 40 mA (4.4 $\times I_{th}$). Such a setting is required to achieve a stable squeezed state for accurate measurements. Therefore, the small green bullets provided in Fig. 1 represent the anti-bunched carrier sequence of the quiet pump, illustrating the smooth and consistent carrier transport. The laser beam was then split into two paths by a 50/50 BS. The first path led to the BKR, which consists of a mirror and a variable attenuator (attenuation ranging from 2.3 dB to 55 dB). The total feedback strength is defined as the attenuation of the BKR combined with the coupling loss of the laser and the loss of the feedback optical path. The second path was assigned with the task of detecting the squeezed signal. It required monitoring under optical feedback conditions. The laser beam needs to pass through an optical isolator to avoid any uncontrolled optical feedback. After that, the beam passed through an accurate 50/50 BS and was directed to a balanced photodetector (BPD, Discovery Semiconductors DSC-R405ER). The variations in the photocurrent between the two signals are amplified by passing through a differential amplifier (DA) and analyzed using an electrical spectrum analyzer (ESA, Rohde & Schwarz FSU, 43 GHz) for noise spectrum evaluation.

A QW DFB laser with a threshold current of 8.5 mA and a lasing wavelength of 1.31 μm close to that of the QD DFB laser is used for reference experiments. Before investigating the quantum noise, we first analyze the response of the classical noise to external optical feedback for both the QD and QW DFB lasers as shown in Figs. 2(a) and 2(c). For the QW laser, there is a critical feedback level, i.e., coherence collapse, of −21 dB above which instabilities such as periodic oscillations and chaotic states appear.[30] In contrast, the QD laser remains stable regardless of the range of feedback strengths. To further investigate the superiority of QD lasers in terms of quantum noise, we also compare the amplitude squeezing performance of the QW laser with that of the QD laser regarding the noise level

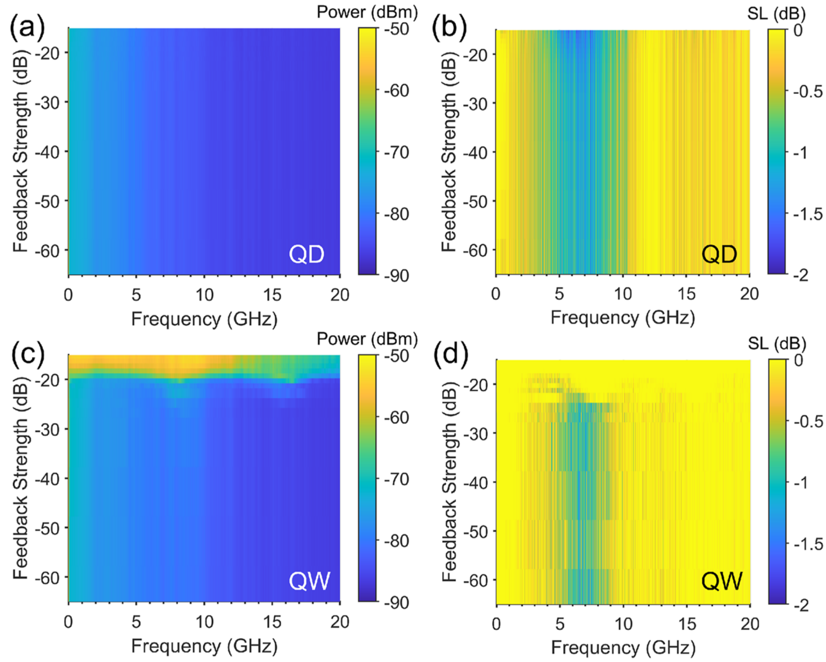

FIG. 2. Measured classical noise at different feedback strengths for (a) QD laser and (c) QW laser. Squeezing level at different feedback strengths for (b) QD laser and (d) QW laser.

and squeezing bandwidth. As shown in Figs. 2(b) and 2(d), the negative values indicate the occurrence of squeezing regimes, whereas the positive ones signify that the squeezing operation is lost. In the following, we will only analyze operating squeezed state by using its corresponding SL value without negative sign, in order to focus on its magnitude. These diagrams demonstrated that the QD DFB laser displays a broadband squeezing and high SL characteristics, which is even slightly intensified as the feedback strength increases. Meanwhile, the QW laser also exhibits a squeezing behavior but with a smaller SL along with a narrower bandwidth of 5 GHz, which is almost twice narrower than the 10 GHz achieved with the QD laser. In addition, it has to be noted that due to the occurrence of the critical feedback level, the QW laser does not display a squeezing regime above −21 dB. In other words, the large feedback sensitivity of the QW material contributes to fundamentally limiting the squeezing performance through a sharp suppression of the squeezing regime. These maps confirm the high potential of the QD gain chip as a feedback-insensitive source in the context of both classical and quantum noise.

In addition, the comparison of the SL spectra of both QD and QW lasers before and after optical feedback allows us to further understand the detailed process of noise evolution. Figures 3(a)–3(c) display the SL spectra of the QD laser without optical feedback and with feedback strengths of −67.8, −18.8, and −15.1 dB, respectively. Figures 3(d)–3(f) present the results for the QW laser under the same conditions. For the QD laser, as the optical feedback strength increases, the SL gradually increases with a maximum value of 1.7 dB at 6 GHz. On the contrary, the QW laser maintains a squeezed state operation, whereas beyond −21 dB optical feedback strength, the squeezed state vanishes, and the noise spectrum exhibits a periodic oscillation, which further develops into a chaotic state at higher feedback intensities. In the latter case, it is interesting to stress that the chaotic-like noise is found 10 dB higher than the SQL with a 12 GHz bandwidth, which may be useful for secure optical communications.

When considering the loss of the BS and the vacuum contributions in the setup, the quantum efficiency (η) usually needs to be close to 0.9 to guarantee the effectiveness of the squeezed states. To express the propagation loss and the effect of vacuum fluctuations on the single-mode amplitude squeezed state, the following equation is considered:[17]

$$\langle \Delta X_{out}^2 \rangle = \eta \langle \Delta X_{sig}^2 \rangle + (1-\eta) \langle \Delta X_{vac}^2 \rangle, \tag{1}$$

where $\langle \Delta X_{out}^2 \rangle$ is the variance of the measured squeezed state signal, $\langle \Delta X_{sig}^2 \rangle$ is the variance of the initially generated squeezed state signal, and $\langle \Delta X_{vac}^2 \rangle$ is the variance of the vacuum signal. η contains the electrical noise (η_{elec}), the efficiency of the photodetector (η_{PD}), and the quality of the interference between the beams in front of the photodetectors (η_{mod}). Finally, η_{elec} is related to the shot-noise clearance (SNC) of the homodyne detector defined, such as $\eta_{elec} = 1 - 1/SNC$. In the experiment, the homodyne detector has a SNC of 20 dB and a linearity value of 0.01. The expression giving the efficiency of the photodetector is $\eta_{PD} = S_{PD} \times (\hbar\omega/e)$, where $S_{PD} = 0.95$ A/W corresponds to the typical photosensitivity of the InGaAs photodetector, while $\hbar$ is the reduced Planck constant, ω is the laser angular frequency, and e is the elementary charge of the electron. Considering the self-homodyne detection, the interference between LO and signal is quite high, and η_{mod} can be taken as 0.94.[31] Based on the product of the three efficiencies, the η is of 0.86 and the weights

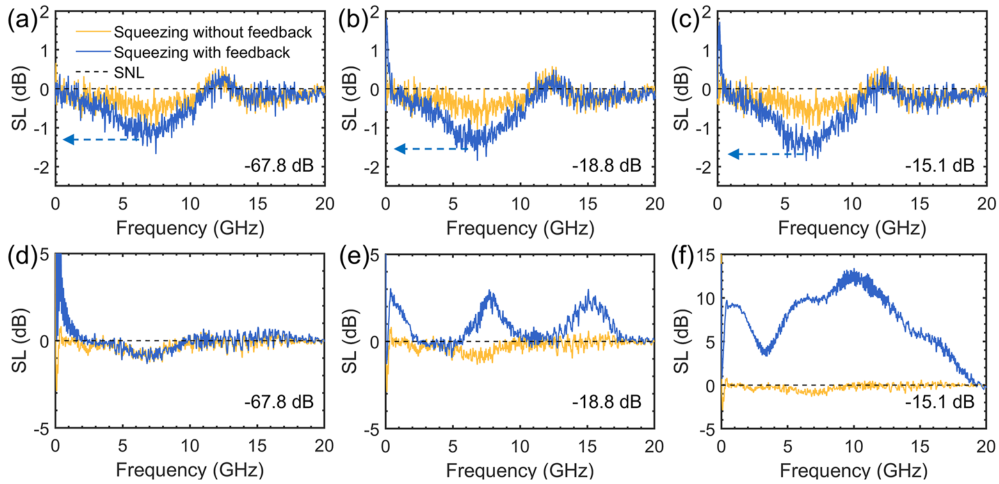

FIG. 3. Squeezing level spectrum for (a)–(c) QD laser and (d)–(f) QW laser without or with optical feedback under −67.8, −18.8, and −15.1 dB, respectively.

of the squeezed state and vacuum fluctuations can be obtained as $\sqrt{\eta} = 0.927$ and $\sqrt{1-\eta} = 0.374$, respectively. The weight of the squeezing signal is higher compared to the vacuum fluctuations, and, therefore, the SL results are reliable.[17,32,33]

In addition, to identify the limits of our QD squeezer, the various contributions of the loss originating from all the different optical components are also considered. Given the total quantum efficiency (including the coupling efficiency of 0.4 and optical efficiency of 0.6) and taking the $\langle \Delta X_{vac}^2 \rangle$ as 1/2, the noise-corrected SL (SL_{corr}) can be obtained by transforming the experimentally obtained SL to a linear value by substituting $\langle \Delta X_{out}^2 \rangle$ in Eq. (1).[17] The SL_{corr} is shown in Fig. 4 after noise correction. The maximum SL at 6 GHz of the QD laser is improved from 1.7 to 5.1 dB. The QW laser also improves to a maximum of 3.9 dB at 5 GHz, but this number only remains constrained to the low feedback region (less than −24 dB), and it disappears above.

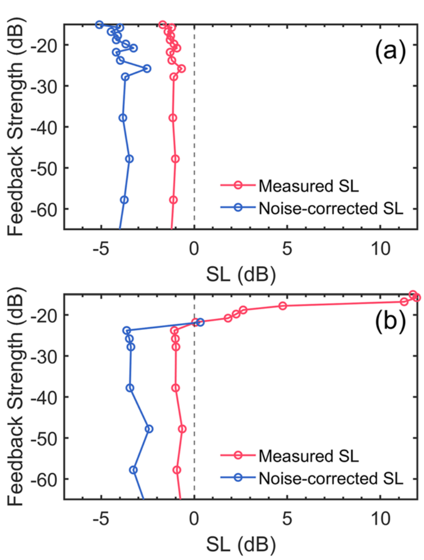

FIG. 4. Noise-corrected squeezing level (blue) and corresponding measured squeezing level (red) of (a) QD laser (at 6 GHz) and (b) QW laser (at 7 GHz) as a function of the optical feedback strength.

III. SECOND-ORDER CORRELATION FUNCTION

To further validate the quantum characteristics of the squeezed states, the $g^{(2)}(0)$ must be considered as a convincing metric to evaluate whether a light exhibits anti-bunching, bunching, or a coherent behavior. If $g^{(2)}(0)$ is less than 1, then single-mode amplitude squeezed state can be confirmed.[34] The $g^{(2)}(0)$ is typically expressed as follows:[35,36]

$$g^{(2)}(0) = \frac{\langle \hat{a}^\dagger \hat{a}^\dagger \hat{a}\hat{a} \rangle}{\langle \hat{a}^\dagger \hat{a} \rangle^2} = \frac{\langle (\hat{a}^\dagger \hat{a})^2 \rangle - \langle \hat{a}^\dagger \hat{a} \rangle}{\langle \hat{a}^\dagger \hat{a} \rangle^2}, \tag{2}$$

where $\hat{a}$ and $\hat{a}^\dagger$ are the field creation and annihilation operators, respectively. After substitution by covariance matrix operations and operator expressions, the $g^{(2)}(0)$ expression for single-mode light is expressed as follows:[35,37]

$$\begin{aligned} g^{(2)}(0) = 2 + \{&(1+2\bar{n}_{th})\sinh(2r) \\ &\times\left[(1+2\bar{n}_{th})\sinh(2r) + 4\bar{\alpha}^2\cos\psi\right] - 4\bar{\alpha}^4\} \\ &\times\left[(1+2\bar{n}_{th})\cosh(2r) + 2\bar{\alpha}^2 - 1\right]^{-2}, \end{aligned} \tag{3}$$

where $\bar{\alpha}$ is called the displacement amplitude, $\bar{n}_{th}$ is the mean photon of the thermal state, and r is the squeezing parameter. $\psi = 2\phi$, where ϕ represents the phase in the phasor diagram. It should be emphasized that the above-mentioned parameters can be calculated by the experimental results of the squeezed state. The mean photon of the thermal state is a parameter intrinsically related to both the temperature and the energy of photons at a particular wavelength. The squeezing parameter is correlated with the SL ($10^{(-SL/10)} = e^{-2r}$). The ψ can be set to π, which is the value for the amplitude squeezed state.[35] From the literature, it is possible to link the displacement amplitude, to the squeezed parameter, and the mean photon in the thermal state through the following equation:[36]

$$\bar{\alpha}[r, \bar{n}_{\text{th}}] = \sqrt{\frac{(2\bar{n}_{\text{th}} + 1)(e^{r}\bar{n}_{\text{th}} + \sinh(r))\sinh(2r)}{e^{-3r}(e^{2r} - (2\bar{n}_{\text{th}} + 1))}}. \tag{4}$$

As the lasing wavelength is 1.31 μm and the experimental operating temperature is 20 °C, $\bar{n}_{\text{th}}$ can be calculated to be ~0.04. Through the noise spectrum, it is known that without external optical feedback, the maximum squeezing level is about 0.8 dB. The measured $g^{(2)}(0)$ corresponds to the SL at all frequencies, so we cannot just use the maximum SL for the squeezing parameter operation. Here, we use 0.4 dB to represent the average SL at all frequencies. Hence, the fitted $g^{(2)}(0)$ of QD and QW lasers as a function of the optical feedback strength is shown in Fig. 5(b). It can be observed that, under the conditions of the quiet pump, the $g^{(2)}(0)$ of the QD laser fitted from the squeezed state gradually decreases with the feedback strength, namely dropping from 0.98 to around 0.96. Meanwhile, the $g^{(2)}(0)$ derived from the QW laser is consistent with the SL. When the feedback strength is less than −24 dB, the $g^{(2)}(0)$ slightly declines, reaching a minimum of ~0.97. When the feedback strength exceeds the critical feedback level of −21 dB, it rapidly increases to above 1 and approaches 2. The latter value indicates that the QW laser operates within a chaotic state at high feedback strength. The $g^{(2)}(0)$ is entirely consistent with the parameters of the laser's squeezed state, which validates the accuracy of the squeezing characteristic measurement.

To bolster the reliability of the previously mentioned theoretical parameters, we also assembled a $g^{(2)}(0)$ testing platform. Figure 5(a) illustrates the Hanbury Brown and Twiss (HBT) setup, devised for measuring $g^{(2)}(0)$. In this arrangement, both QD and QW lasers are individually driven by a quiet pump. After this, the laser beam traverses through two optical attenuators, which offer a peak attenuation of up to 110 dB. This precautionary measure is instituted to guarantee that the optical power impinging upon the single-photon detectors is maintained within a secure range. Proceeding further, an adjustable BS, which ensures that the laser beam is accurately split 50/50, was used to ensure that the two-arm configuration is balanced between the two single-photon avalanche detectors (SPADs, sourced from ID Quantique, model ID200). The photocurrent signals, generated by the detectors, are subsequently directed into a time-to-digital converter (TDC, sourced from ID Quantique, model ID800) to ascertain the coherence between the two signals. Throughout the measurement process, the coincidence time interval δ is determinedly set at 50 ns, while the total testing duration T spans 2 s. During this period, the count rates R_1 and R_2 for the two channels are meticulously logged. In addition, the coincidence events R_{12} interceding between the two channels are also assiduously compiled. By leveraging this dataset, the normalized $g^{(2)}(0)$ can be calculated.[38,39]

The $g^{(2)}(0)$ values for the QD laser at weak feedback strength (−67.8 dB) and at a high feedback intensity (−18.8 dB) are 0.9835 ± 0.0029 and 0.9692 ± 0.0043, respectively. The $g^{(2)}(0)$ trends for the QW laser are also consistent with the fitted ones: 0.9852 ± 0.0032 at weak feedback strength (−67.8 dB) and 1.7213 ± 0.0037 at high feedback strength (−18.8 dB), where the squeezed state disappears. The error is determined from multiple counts. The increased anti-bunching characteristics of photons from the QD laser demonstrate that the amplitude squeezing performance is preserved and enhanced under optical feedback. The measured results of $g^{(2)}(0)$ perfectly demonstrate the tendency of the squeezing state of QD and QW lasers analyzed by the electric spectrum to vary with the optical feedback. Noteworthy is that the feedback light could affect the quantum noise of the laser due to the amplitude–phase coupling and spontaneous emission contribution reduction.[24,25] The QD laser is more likely to exhibit lower relative intensity noise and a stronger suppression of intensity noise under external optical feedback. In addition, we believe that the reduction in the cavity photon lifetime due to the increased photon density in the cavity, gain saturation, and the reduced depletion layer capacitance will further increase the squeezing bandwidth.[24,40]

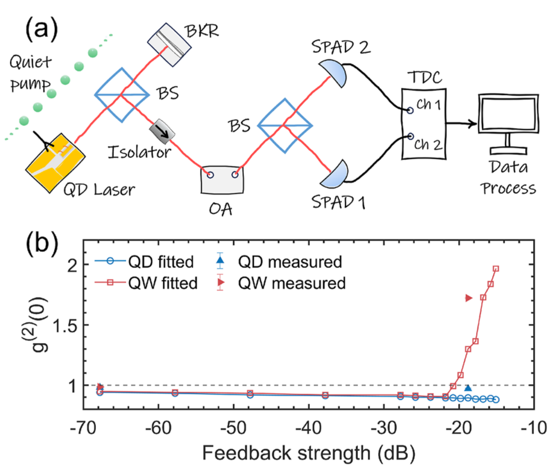

FIG. 5. (a) Experimental setup for $g^{(2)}(0)$ of the amplitude squeezed state under optical feedback. (b) Fitted and measured $g^{(2)}(0)$ for QD and QW lasers as a function of the optical feedback strength.

IV. CONCLUSION

In this work, we have explored the amplitude squeezing properties of a QD DFB laser under optical feedback. We have shown that the QD laser showcases a superior promising squeezing performance under the quiet pumping configuration. In addition to the feedback insensitivity already shown with the classical noise, our experiments also reveal that the quantum noise remains perfectly stable against optical feedback, by comparison with the QW laser. In the latter, the squeezing properties are found to vanish due to the occurrence of the so-called critical feedback level. In addition, the measurement of the second-order correlation function further validates all the aforementioned concepts. It is foreseen that future QD lasers with silicon-based integrated squeezed state sources can further reduce the effect of transmission noise and are more favorable to meet the needs of on-chip applications than QW lasers. This research establishes a solid foundation for the development of future compact, energy-efficient quantum photonics integrated circuits. Further work will now investigate how to improve the SL and bandwidth along with the utilization of the QD technology for deploying quantum frequency combs where modes of the comb spectrum are populated by squeezed fields from the quiet pump.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

S.D. and S.Z. contributed equally to this work.

Shihao Ding: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Writing – original draft (equal). **Shiyuan Zhao**: Investigation (equal); Methodology (equal); Writing – review & editing (equal). **Heming Huang**: Supervision (equal); Validation (equal); Writing – review & editing (equal). **Frédéric Grillot**: Project administration (equal); Resources (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

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

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