Room-temperature generation of amplitude-squeezed light from 1550-nm distributed-feedback semiconductor lasers

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Experimental results are reported for amplitude-squeezed states generated from two kinds of 1550-nm distributed-feedback semiconductor laser at room temperature. Both lasers exhibit excess noise under free-running conditions, but the origin of this noise is different for the two lasers. For one of the lasers the excess noise is reduced by enhancement of the side-mode–suppression ratio. For the other the excess noise that degrades the squeezing is reduced by weak dispersive optical feedback produced by a grating detuned from the maximum of its first-order reflection. Thus the grating is used to convert phase noise into intensity noise.
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1. INTRODUCTION

Squeezed states of the electromagnetic field are beginning to create new possibilities for precision measurements limited by the shot-noise level (SNL). They are expected to improve signal-to-noise ratios in precision optical measurements and optical communications.

Twelve years ago amplitude squeezing produced with constant-current–driven semiconductor lasers was demonstrated by Yamamoto and his colleagues.[1] Although measurements of amplitude squeezing achieved with a Fabry–Perot semiconductor laser have shown substantial amounts of squeezing, the generation of amplitude-squeezed light from other devices has been considerably less successful. The mechanisms capable of explaining why some laser diodes and not others generate sub-Poissonian light remain unclear; there have been some efforts recently to understand the origin of the noise in semiconductor lasers.[2–4] These efforts have been motivated by a desire to understand the excess noise sources that occur in semiconductor lasers and by the hope of being able to produce large amounts of squeezing from unmodified commercial products at room temperature.

Obtaining significant room-temperature squeezing by enhancing the longitudinal side-mode suppression of the lasers was attempted by classical techniques such as injection locking and optical feedback.[5,6] Most of these experiments suggest that rigorous single-mode operation is essential for achieving squeezing. Thus distributed feedback (DFB) lasers seem an alternative solution for the generation of amplitude-squeezed light. In such devices optical gain in narrow modes comes not only from mirror reflectivity as in a Fabry–Perot laser, but rather from optical wave coupling that is uniformly distributed throughout the gain region. This coupling is periodic and causes feedback only near wavelengths having twice the coupling wavelength, as in Bragg reflection. The periodic feedback itself may be affected by variations in refractive index or gain by physical corrugation in the vicinity of the region. However, the generation of amplitude-squeezed light by DFB, although single moded (DFB lasers often exhibit more than 25 dB of side-mode–suppression rejection, SMSR), until now have achieved little success.[7]

In this study we investigate the intensity noises of two different 1.5-μm multiple–quantum-well DFB lasers operating at room temperature. These two lasers, produced by Alcatel Alsthom Research, are experimental devices. Both lasers exhibit excess noise under free-running conditions. The excess noise of the first laser is of an intermodal origin. Thus the enhancement of its SMSR, through an external cavity including a grating, leads to a significant level of amplitude squeezing, as was shown by Freeman *et al.*[8] The origin of the excess noise of the second laser has not yet been identified, but experimental results indicate that it can be reduced by weak dispersive optical feedback produced by a grating detuned from the maximum of its first-order reflection. The present experiment employs the grating as a dispersive element to convert phase noise into intensity noise; the fundamental coupling between field amplitude and phase fluctuations induces a correlation between the fluctuations, and this correlation may be used to reduce intensity noise by a method called amplitude–phase decorrelation.[9]

We first introduce the experimental setup. The experimental results are presented in Section 2. The theoretical model for the reduction of excess noise by the amplitude–phase decorrelation mechanism is presented in Section 3. Finally, the experimental results are compared with the model.

2. EXPERIMENTS

The simulations of Marcenac and Caroll[10] indicate that DFB structures with high coupling-coefficient–length

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products, κL, are unlikely to be good sources of squeezed light because of the evanescence of the optical fields along the grating. They also show that for low κL values the lowest achievable intensity noise depends on the structure of the laser diode and can be higher than expected from the laser quantum efficiency alone.

The two 1.55-μm compressively strained multiple–quantum-well lasers tested have κL values of 1.0 (four quantum wells) and 0.6 (six quantum wells) and external differential quantum efficiencies of 0.5 and 0.63, respectively. The external differential quantum efficiency is defined as $\eta_d = \eta_i \times$ (photon escape rate/photon generation rate), where η_i is the internal quantum efficiency, indicating what fraction of injected carriers is converted into photons. The SMSR's (the ratio of the main mode power to the power carried by the most intense side mode) measured by an optical spectrum analyser are more than 28 dB.

A. Balanced Dual Detector Setup

Simultaneous measurements of the signal-noise level and the associated shot-noise level (SNL) are performed with a delay-line balanced receiver. The electronic delay present in one arm of the receiver induces a periodic frequency-dependent phase shift between the two signals coming into the hybrid junction, with the result that the output current-noise power from the receiver periodically changes, as a function of frequency, between the actual laser noise and the SNL.[11] A typical mode rejection of more than 30 dB was obtained with the balanced receiver alone when the laser was modulated at a frequency of 30 MHz, and the optical isolator provided more than 60 dB of isolation. Consistency between the SNL calibration measured with this method and the noise of a filtered white-light source was carefully checked.

B. Pump-Noise–Suppression Principle

Quantum noise reduction in laser emission based on pump-noise suppression was first predicted in 1984.[12] The quantum Langevin analysis indicates that the pump amplitude fluctuation is the thermal current noise generated by the driven source resistance R and becomes smaller than SNL when R is higher than the diode differential resistance (R_d) of the laser. The electron statistics of pumping is then transferred to light emission, yielding sub-Poissonian operation.[13]

C. First Laser

1. *Pump-Noise–Suppression Experiment*

For a high pumping rate (the pumping rate is defined as $r = I/I_{\mathrm{th}} - 1$) the noise level of the first laser decreases by 0.7 dB when changed from a constant-current driver ($R = 100\Omega \gg R_d$) to a constant-voltage driver ($R \cong 0\Omega \ll R_d$). However, it is found that the laser fluctuations in both biasing conditions exceed the SNL as shown in Fig. 1. At very high pump levels the SMSR of the laser decreases because of the spatial hole burning, and the noise levels are similar for both biasing conditions.

The excess noise that degrades the squeezing of this laser was also investigated by spectral analysis with a

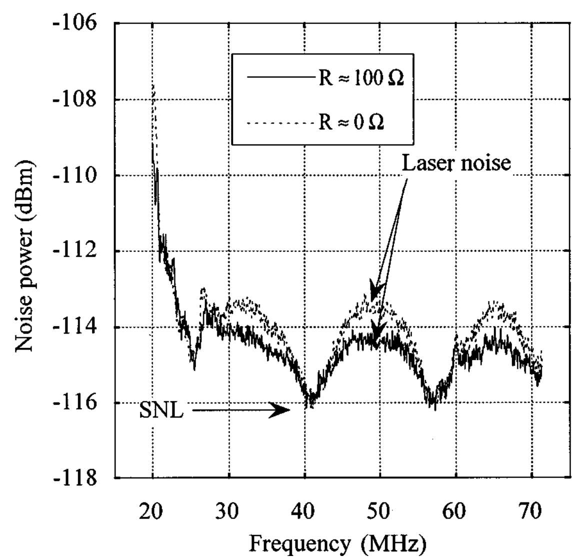

Fig. 1. Laser noise and SNL under both pump conditions.

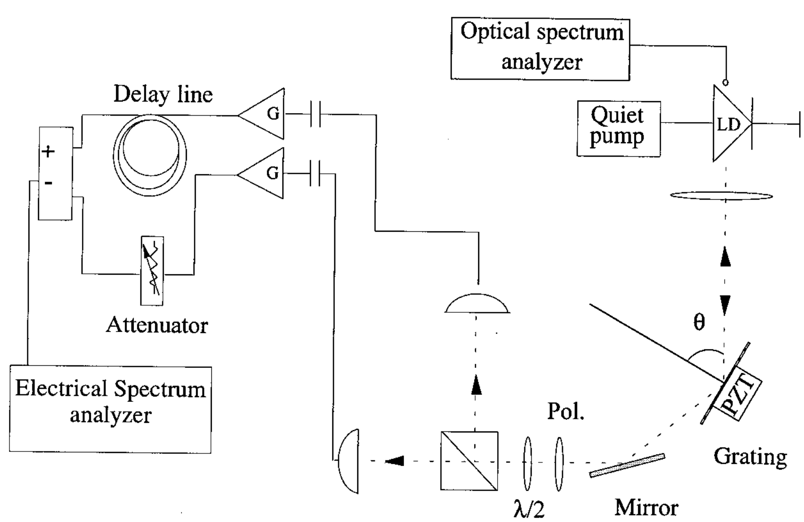

Fig. 2. External grating stabilization scheme. LD, laser diode; PZT, piezoelectric transducer; Pol., polarizer.

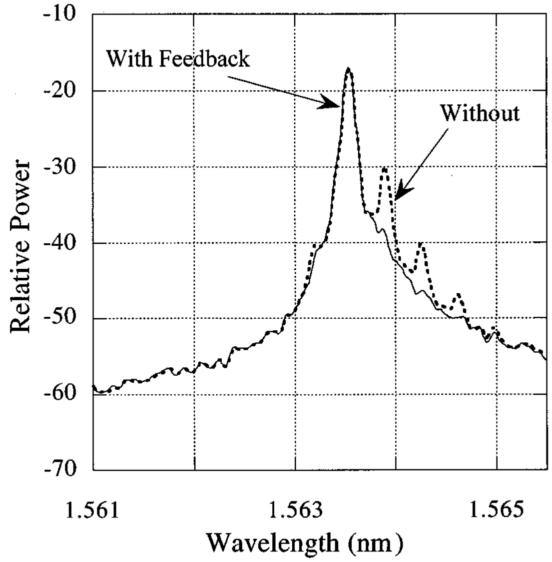

Fig. 3. Optical spectrum analyzer scans obtained with (solid curve) and without (dashed curve) optical feedback from the Littrow grating. $I_L = 147$ mA.

Mach–Zehnder interferometer,[14] and it appears that under a wide range of operating conditions most of this noise is associated with the presence of longitudinal sides modes even when the SMSR is high.

Inoue *et al.*[15] demonstrated that the cross-gain saturation associated with a fully homogeneous gain medium leads to amplitude squeezing under multimode operation, but a weak inhomogeneous broadening results in an incomplete correlation among longitudinal mode powers and leads to the loss of squeezing if the SMSR is insufficient. Thus the SMSR required depends on the gain medium broadening.[3]

2. *Pump-Noise Suppression Associated with Optical Feedback*

To enhance the SMSR we set up an external cavity with wavelength-dependent feedback provided by a Littrow-configured grating as shown in Fig. 2. The cavity is extended to 10 cm with a reflection holographic grating (1200 lines/mm) reflecting the first order into the cavity while the zero order is rejected. The grating and a rotating mirror were mounted on a platform that rotated about the line of intersection of their front surface planes. This configuration allows the angle θ between the grating and the laser beam to be changed without modifying the angle of the output beam. Using the previously described balanced detection setup, we investigate the effect of the external cavity on the amplitude-noise properties of this laser. The longitudinal mode spectrum of the beam emerging from the rear facet of the laser was simultaneously observed with an optical spectrum analyzer.

When the principal maximum of the first order (~10% of the light) is backinjected into the laser, the dc power of the side modes decreases to ~1 order of magnitude below the dc power of the main mode at very high pump level (Fig. 3). The amplitude noise then shows 0.7 dB of squeezing (Fig. 4) instead of being 2 dB above the SNL as shown in Fig. 1. We conclude that in this case the excess noise is really due to the presence of the weak side modes.

D. Second Laser

The second tested laser presents a laser noise level ~2 dB above the SNL with a quiet pump and a normal pump ($R \gg R_d$ and $R \ll R_d$). The origin of the excess noise is not exactly determinate. When the laser is included inside the external cavity and the principal maximum of the first-order diffraction is injected, there is still no squeezing. However, when the grating is tilted, a new and rather unexpected result is obtained: The laser noise decreases and increases as a function of θ. Finally, for $\theta \approx 55°$, the laser noise is below the SNL. In this configuration the optical feedback power used is approximately $10^{-4} \times P_{\text{out}}$. Figure 5 shows the current noise spectra observed for different pump rates. At low pump levels the noise that is due to spontaneous emission is important, and no position yields squeezing. At $r = 4.7$, the current-fluctuation spectrum is inverted, showing that the laser noise is 1.6 dB below the SNL. A polarizer placed at the output of the laser diode proves that the effect of the grating is really a feedback effect. Next the possibility that the observed noise reduction was due to a change in the laser SMSR was investigated. It was found that the SMSR was at least 28 dB and that when the optical feedback was applied the average side-mode power decreased by only 2%. It seems unlikely that such a small change in the SMSR could be the only reason for such an important change in the amplitude noise power.

We suspect that the excess noise reduction is due to a subsequent amplitude–phase decorrelation mechanism, as was reported first by Newkirk and Vahala.[9] Detuned to the maximum of its first-order reflection, the frequency-dependent reflection $R(\omega)$ has a nonzero slope in the vicinity of the line center, ω_L, and the grating can act as a dispersive loss element. The enhanced phase noise, which contains an image of the intensity noise through the linewidth enhancement factor α, causes jitter in the instantaneous cavity loss owing to a dispersive loss

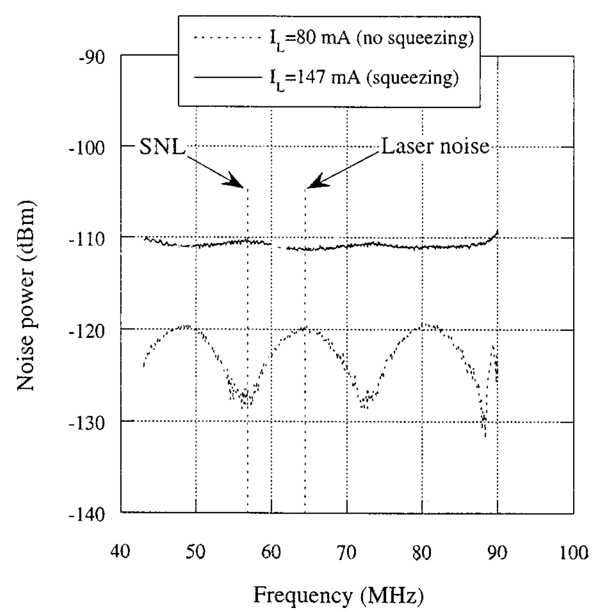

Fig. 4. Current-noise spectra obtained with optical feedback produced by a grating in Littrow configuration.

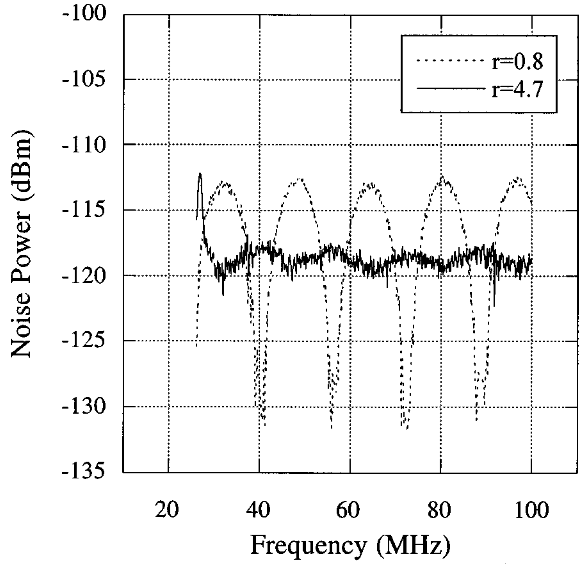

Fig. 5. Current-noise spectra for two pump rates. The amplifier thermal noise is subtracted. $\theta \approx 55°$.

function. The gain adjusts to counteract the fluctuating loss and so reduces the intensity noise when the loss function has the right slope sign.

3. THEORETICAL MODEL

To model the reduction of the amplitude noise of a semiconductor laser with such a mechanism, we follow the approach introduced in Ref. 16 and include in the photon-number equation a term that represents the dispersive feedback from the external cavity.[17]

Solving the Fourier-transformed algebraic equations, we obtain the power spectral density of the external photon rate, $S_{\rho\rho}(\omega)$, normalized to the SNL under both pump-noise suppression and optical feedback at frequencies below the relaxation resonance. The following equation shows the calculation obtained at zero detection frequency with the feedback phase adjusted to produce minimum noise:

$$\begin{aligned}\frac{S_{\rho\rho}(0)}{\mathrm{SNL}} = 1 - \frac{\tau_P}{\tau_M} + 2n_{\mathrm{sp}}\frac{C^2}{(1 + C\alpha)^2}\left(1 + \frac{1}{n_{\mathrm{sp}}r}\right)^2\frac{\tau_P}{\tau_M} \\ + 2n_{\mathrm{sp}}\frac{\tau_P}{\tau_M}\frac{(C\alpha - 1/n_{\mathrm{sp}}r)^2}{(1 + C\alpha)^2} + \frac{2}{r}\frac{\tau_P}{\tau_M} \\ + 2\left[\frac{R(\omega_L)}{R_L}\right]^{1/2}\frac{\tau_P}{\tau_M}\left(1 + \frac{1}{n_{\mathrm{sp}}r}\right)\frac{1}{(1 + C\alpha)} \\ \times\left[1 - \frac{\tau_P}{\tau_M}\frac{1}{(1 + C\alpha)}\left(1 + \frac{1}{n_{\mathrm{sp}}r}\right)\right], \qquad (1)\end{aligned}$$

where

$$C = \xi/(2\tau_M[R(\omega)R_L]^{1/2}\{1 + [R(\omega)/R_L]^{1/2}\tau/\tau_M\}),$$

τ_P is the photon lifetime, n_{sp} is the spontaneous emission factor, τ_M is the time associated with the mirrors' losses, τ is the feedback delay, R_L is the laser front facet reflectivity, and $\xi = \Delta R(\omega)/\Delta\omega$ is referred to as the slope of the grating reflectivity in the vicinity of ω_L.

A detailed analysis of Eq. (1) yields several important consequences. Pump noise and noise that is due to internal losses are unaffected by such optical feedback. On the right-hand side the third and the fourth terms, which are due to dipole moment fluctuations and partition noise, can be reduced by a factor of $1 + \alpha^2$ from their free-running value when $C = C_{\mathrm{opt}} = \alpha/[1 + (1 + \alpha^2)n_{\mathrm{sp}}r]$. The contribution of the last term can be neglected only if the optical feedback power is extremely low.

Figure 6 presents the external photon noise normalized to the SNL versus the frequency calculated from Eq. (1) when the laser is quietly pumped. The solid curve represents the free-running laser diode. The dashed curve represents the extended-cavity laser diode with $C = C_{\mathrm{opt}}$ and $R(\omega_L) = 10^{-4}$.

Figure 7 presents the external photon noise normalized to the SNL versus the ratio C/C_{opt} calculated when the laser is quietly pumped. For $C < C_{\mathrm{opt}}$ the laser noise level

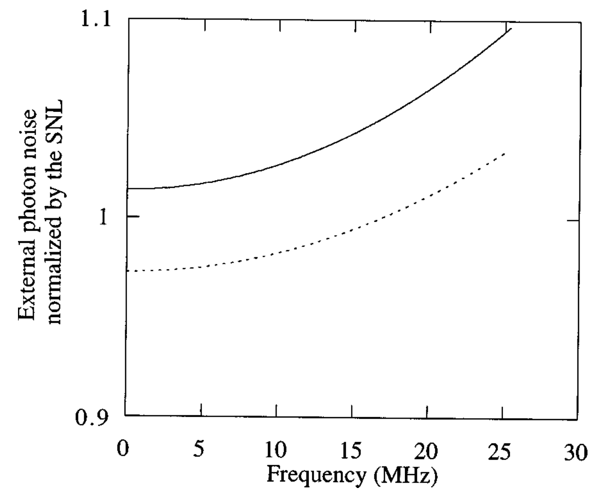

Fig. 6. External photon noise normalized to the SNL calculated versus frequency for a quietly pumped laser; solid curve, free-running conditions; dashed curve, extended-cavity laser diode. The parameter values used are $r = 3$, $\tau = 66\,\mathrm{ns}$, $n_{\mathrm{sp}} = 1.5$, $R_L = 0.2$, and $\tau_M = 5.6 \times 10^{-12}\,\mathrm{s}$.

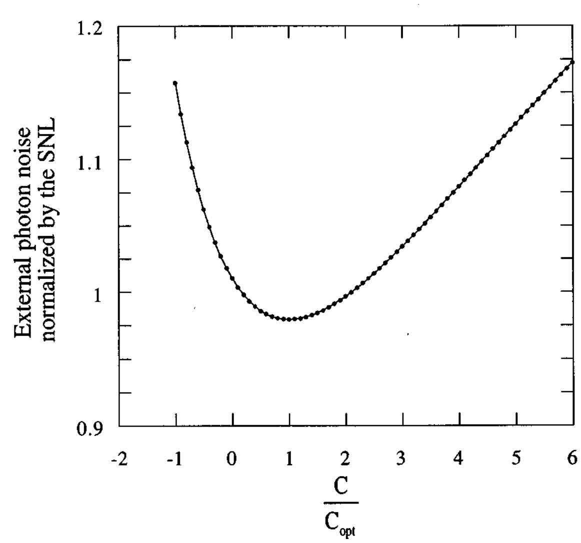

Fig. 7. External photon noise normalized to the SNL, calculated versus the rate C/C_{opt}.

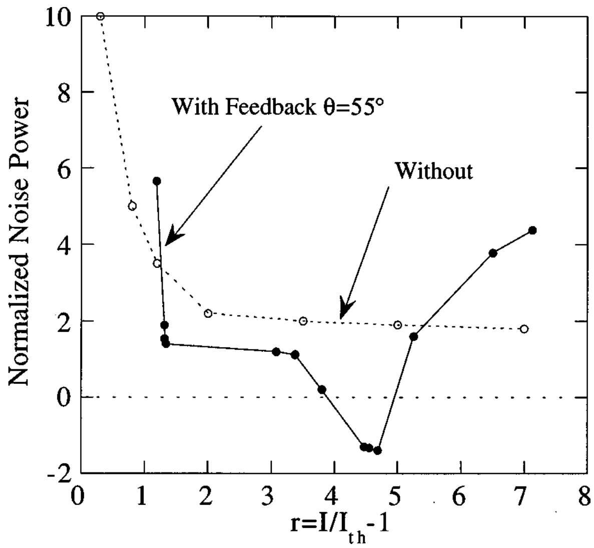

Fig. 8. Laser noise normalized by the SNL, measured as a function of the pumping rate.

is weakly reduced, and for $C > C_{\mathrm{opt}}$ the dispersive optical feedback leads to an increase of the noise level. For $C = C_{\mathrm{opt}}$ the effect of the dispersive optical feedback is optimal, and the squeezing appears. Thus the feedback can significantly reduce the noise for some values of C and enhance it for others.

This theoretical study shows that, for low pump rates, the amplitude noise can be reduced from above to below the SNL by use of the weak dispersive optical feedback produced by the weak secondary maximum of the grating. For the tested laser, C must be $\sim 10^{-2}$, and $\xi/R(\omega_L)$ $\sim 10^{-14}$. The calculated optimum grating position is obtained for θ between 50° and 60°, which is consistent with the experiment. However the reduction of the noise in our experiment is larger than is predicted by the model. The disagreement can be explained by the presence of excess noise under free-running conditions, which is not taken into account by the theoretical approach, the origin of the excess noise being indeterminate. However, the possibility of reducing this excess noise by an amplitude–phase decorrelation mechanism indicates that it is correlated to the phase fluctuations.

As a final test, the grating position is maintained at $\theta = 55°$, and the normalized noise power is measured as a function of the bias current. As is expected, Fig. 8 shows that if this position corresponds to an optimum C value for $r = 4.7$, this value is too large for higher pump levels, leading to an increase of the noise, and it is too small for lower pump levels, leading to a weak reduction of the noise.

4. CONCLUSION

In conclusion, we have investigated the intensity noise of two 1550-nm DFB lasers at room temperature. Both lasers exhibit excess noise under free-running conditions. For the first laser the excess noise is classically due to the presence of weak longitudinal side modes associated with a weak inhomogeneous gain medium and is reduced by enhancement of the SMSR.

The origin of the excess noise of the second laser has not yet been identified. However, the noise degrades the squeezing and can be reduced by a weak dispersive optical feedback produced by a grating detuned from the maximum of its first-order reflection. This result agrees with Kitching's experiments, which showed reduction of excess noise when weak optical feedback is used with dispersive loss produced by a cesium vapour cell.[18] Thus, whatever the origin of the excess noise, this experiment shows that it is correlated to the phase fluctuation, and amplitude squeezing was achieved through the excess noise's cancellation by the frequency noise.

We believe that these observations have important practical applications for the generation of amplitude-squeezed states with a DFB-structure laser, which until now has seen little success.

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