Observation of Amplitude Squeezing in a Constant-Current–Driven Semiconductor Laser

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Electromagnetic fields with photon-number fluctuation reduced below the standard quantum limit have been generated in a constant-current–driven semiconductor laser. The generation is based on a new principle of high-impedance suppression for pump-amplitude fluctuation in a highly saturated laser oscillator. The observed noise level is 7.3% (31% after correction for detection quantum efficiency) in power below the standard quantum limit in the entire frequency range between 350 and 450 MHz.

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A number-phase minimum-uncertainty state of the electromagnetic field is mathematically defined as an eigenstate of the operator $e^{\chi}\hat{n}+ie^{-\chi}\hat{S}$, where $\hat{n}$ is the number operator, $\hat{S}$ the sine operator, and χ a squeezing parameter.[1] When χ is greater than $\ln(2\langle\hat{n}\rangle)^{-1/2}$, the photon-number noise becomes smaller than the standard quantum limit (SQL), $\langle\Delta\hat{n}^2\rangle<\langle\hat{n}\rangle$, and the sine-operator (phase) noise becomes larger than the SQL, $\langle\Delta\hat{S}^2\rangle/\langle\hat{C}\rangle^2 > 1/4\langle\hat{n}\rangle$, while the minimum-uncertainty relationship, $\langle\Delta\hat{n}^2\rangle\langle\Delta\hat{S}^2\rangle=\langle\hat{C}\rangle^2/4$, is still preserved. Here $\hat{C}$ is the cosine operator. This "nonclassical state" is analogous to a squeezed state,[2] which is an eigenstate of the operator $e^{\chi}\hat{a}_1+ie^{-\chi}\hat{a}_2$. It features reduced quantum noise in one quadrature, $\langle\Delta\hat{a}_1^2\rangle<\frac{1}{4}$, and enhanced quantum noise in the other quadrature, $\langle\Delta\hat{a}_2^2\rangle>\frac{1}{4}$, while the minimum-uncertainty relationship, $\langle\Delta\hat{a}_1^2\rangle\langle\Delta\hat{a}_2^2\rangle=\frac{1}{16}$, is still preserved. Here $\hat{a}_1$ and $\hat{a}_2$ are the two quadrature phase amplitudes.

In order to reduce one quadrature noise finally to zero in a squeezed state, an electromagnetic mode must have an infinite photon number. This is because the enhanced quadrature noise consumes the mode energy. This trade-off relationship between quantum noise reduction and required photon number places a limit on the signal-to-noise ratio improvement achievable by a squeezed state. On the other hand, photon-number noise can be reduced to zero without the requirement of an infinite photon number in a number-phase minimum-uncertainty state because enhanced phase noise does not consume energy at all. This nonclassical state approaches a photon-number state (or Fock state) as χ increases.

This generation of a number-phase minimum-uncertainty state as well as a squeezed state is of potential importance for information transmission, precision measurement, and atomic spectroscopy. A photon-number state, specifically, achieves the *maximum* channel capacity in optical communication,[3] and it also improves the performance of an interferometric gravity-wave detector.[4]

The observation of quadrature phase squeezing, which is an unmistakable mark for squeezed-state generation, was first reported by Slusher *et al.*[5] This landmark has been followed by three experimental groups.[6–8] We have proposed three schemes for generating a number-phase minimum-uncertainty state. These are self-phase modulation in a Kerr medium incorporated with an interferometer,[9] quantum nondemolition measurement incorporated with feedback,[10] and pump-amplitude fluctuation suppression in a highly saturated laser oscillator.[11] Amplitude noise reduction of 75% below SQL and sub-Poissonian photon statistics with $\langle\Delta\hat{n}^2\rangle/\langle\hat{n}\rangle\cong 0.25$ were observed in a negative-feedback semiconductor laser,[12] even though such a field cannot be extracted from the feedback loop in the initial experiment. This paper reports the first observation of open-loop amplitude squeezing, i.e., number-phase minimum-uncertainty state generation, with use of the third scheme.[13]

In the previous paper,[11] Nilsson and two of the present authors theoretically demonstrated the following.

(1) The amplitude noise of a laser *output field* (not a cavity internal field) approaches the SQL at a high pump level, and this limit stems from shot-noise–limited pump-amplitude fluctuation in the low-frequency region below the cavity bandwidth, $\Omega<\omega/Q$ (near cavity resonance), and from incident vacuum-field fluctuation in the high-frequency region, $\Omega>\omega/Q$ (off cavity resonance) as shown in Fig. 1(a).

(2) The pump-amplitude fluctuation can be eliminated either by space-charge suppression for electron-beam pumping in a vacuum tube or by high-impedance suppression for electron-injection pumping in a semiconductor laser without violating quantum-mechanical consistency, i.e., commutator bracket preservation.

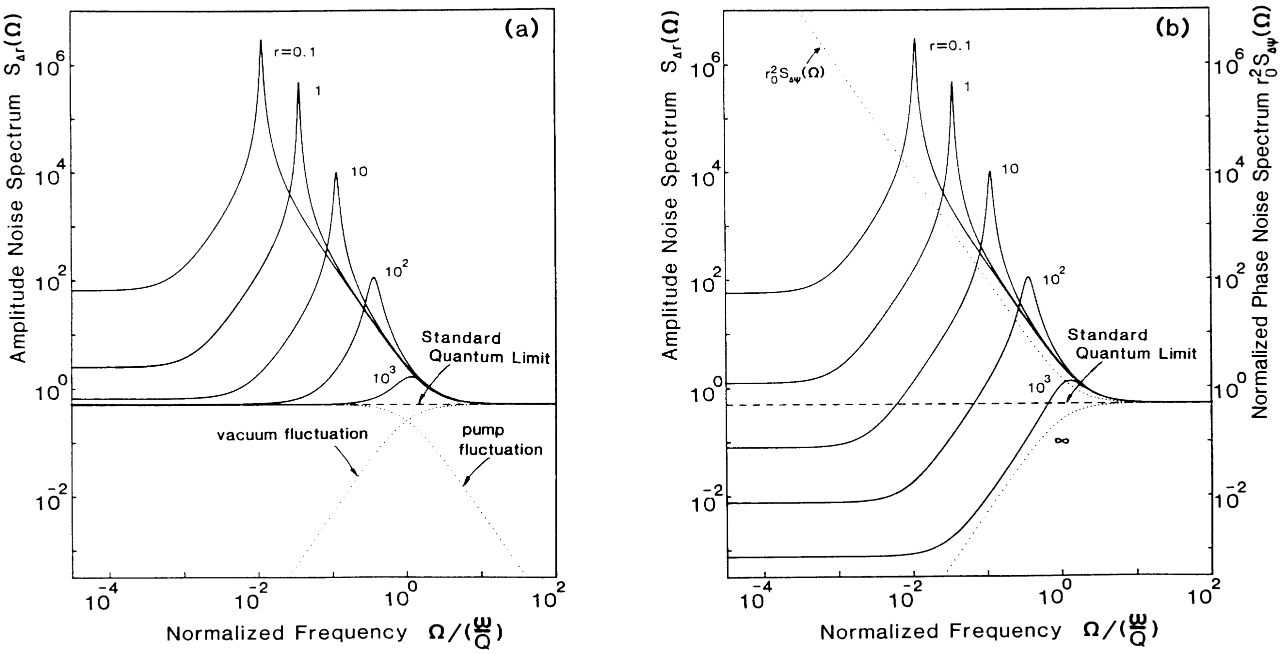

FIG. 1. (a) Amplitude noise spectra for various pump levels, $r \equiv I/I_{th} - 1$, in a laser with shot-noise–limited pump-amplitude fluctuation and the origins for the standard quantum limit (SQL). (b) Amplitude noise spectra in a laser with suppressed pump-amplitude fluctuation and phase noise spectrum.

(3) The amplitude noise is reduced to below the SQL at $\Omega < \omega/Q$ for such a case.

(4) The uncertainty relationship between amplitude and phase noise spectra is still preserved by the so-called phase-diffusion noise, as shown in Fig. 1(b).

That is, an "ideal" laser with suppressed pump-amplitude fluctuation generates coherent states at $\Omega > \omega/Q$ but it produces near number-phase minimum-uncertainty states at $\Omega < \omega/Q$.

The quantum Langevin analysis for high-impedance suppression,[14] which treats microscopic thermal and generation-recombination fluctuations in the carrier transport process, indicates that the pump-amplitude fluctuation is not the usual shot-noise–limited one but is thermal-current noise generated by the source resistance R_s. It becomes smaller than the shot-noise level when R_s is higher than twice a diode's differential resistance, $R_d \equiv (dI/dV)^{-1}$. The mutual coupling between a junction and a pump source realizes two different operational modes, i.e., constant-voltage operation when $R_s \ll R_d$ and constant-current operation when $R_s \gg R_d$. This latter situation is utilized here to generate a number-phase minimum-uncertainty state. A similar junction-source coupling effect for established macroscopic quantum coherence in a Josephson junction has recently been discussed,[15] but a detailed comparison with the present scheme has yet to be explored.

The amplitude noise calculated by the customary quantum Langevin equations is that for a cavity internal field, which does not feature large amplitude squeezing, even though the pump-amplitude fluctuation is completely suppressed.[10] The amplitude noise of an external field, however, differs from it because a partially reflected incident vacuum field at an output coupling mirror and a partially transmitted cavity internal field through it are quantum mechanically correlated. The absence of incident vacuum-field contribution in the external-field amplitude noise at $\Omega < \omega/Q$ is due to destructive interference between the two fields. The incident vacuum field at $\Omega > \omega/Q$ is simply reflected back from the laser cavity, which contributes the residual amplitude noise, as shown in Fig. 1(b).

The experimental setup is shown in Fig. 2. An InGaAsP/InP distributed-feedback (DFB) semiconductor laser with a 1.56-μm oscillation wavelength was fabricated and used in the experiments because it turned out to be difficult to observe intrinsic quantum noise in a standard Fabry-Perot cavity semiconductor laser because of longitudinal-mode–competition noise. The DFB semiconductor laser features stable single–longitudinal-mode operation, and side-mode intensity is suppressed by more than 30 dB (to less than 0.1%). The laser has a short cavity (80–110 μm) that produces a low threshold current, and an antireflection coating on the front facet and a high-reflection coating on the rear facet that achieve high quantum efficiency.

A low threshold current is necessary for saturation-free operation of photodiodes, and a high quantum efficiency is crucial to obtain large amplitude squeezing. The threshold current was 4–6 mA at room temperature

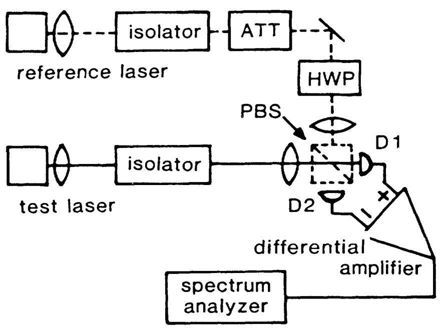

FIG. 2. Experimental setup for measurement of amplitude noise spectrum. HWP stands for a half-wavelength plate and PBS a polarization beam splitter.

and the differential quantum efficiency above threshold was 30% to 32%. The diode's differential resistance is 5 Ω at an injection current I of 10 mA and is inversely proportional to I. The diode's series resistance is 14 Ω.

An InGaAs/InP photodiode with 300-μm diameter and 550-MHz bandwidth is used as a detector. The detector surface is slanted from the optical path to avoid optical reflection feedback to the laser.

An optical isolator is used between the laser and the detector, because even a very small amount of scattered-light feedback from the detector surface causes excess amplitude noise. The detection quantum efficiency η_c including insertion losses for a collimated lens and isolator is about 22%.

The SQL is calibrated by a balanced receiver.[16] The test laser output is blocked and a polarization beam splitter is inserted in front of two identical InGaAs/InP photodiodes. A high-power (>20 mW) InGaAsP/InP DFB semiconductor laser (reference laser) output is attenuated by more than 10 dB and shone on to the two photodiodes to produce exactly the same photocurrents as the test laser did. The reference laser with the same oscillation wavelength as the test laser is used instead of a filtered incandescent light so that the wavelength dependence of detector frequency response does not introduce any error in calibration of the SQL. Precise adjustment of the two detector currents is realized by a half-wavelength plate and a polarization beam splitter. The excess amplitude noise of the reference laser beam is smaller by −1 dB than the SQL at photodiode front end. A balanced receiver's excess noise suppression factor is greater than 18 dB in the frequency range from dc to 550 MHz. Accordingly, the excess amplitude noise in the reference laser is suppressed below the SQL by more than 19 dB, so that the error in thus calibrating the SQL is less than 0.05 dB (1.3%).

The experimental result shown in Fig. 3(a) demonstrates high-impedance suppression of the pump-amplitude fluctuation. The bias circuit features a high source impedance only at the LC parallel-circuit resonant frequency, $f_r \cong 11$ MHz. The photocurrent spectrum is actually reduced at f_r. In contrast, when the bias circuit is replaced by the one that features a low source impedance at the LC-circuit resonant frequency f_r, the photocurrent spectrum is reduced except at f_r.

The photocurrent spectrum for $r \equiv I/I_{\text{th}} - 1 = 3.9$ is compared with the SQL in Fig. 3(b). The LR series circuit in this measurement has a source impedance of 750 Ω over a broad frequency range from dc to 500 MHz. The inductance $L \cong 10$ nH is used to cancel the diode's parasitic capacitance and realize a high source impedance in the higher-frequency region. The measurement frequency region between 250 and 550 MHz is well above the cutoff of $1/f$ noise and residual mode-competition noise. It is also well below the relaxation oscillation resonance [see Fig. 1(b)]. The photocurrent spectrum between 350 and 450 MHz is reduced to below the shot-noise level. The maximum noise reduction occurs at the single frequency near 400 MHz and is 0.33 dB (7.3%) in power below the SQL, and the averaged noise reduction in the frequency range between 350 and 450 MHz is 0.18 dB (4.1%). The results correspond to 1.6 dB (31%) maximum noise reduction and 1.0 dB (21%) average noise reduction at the laser output, if the

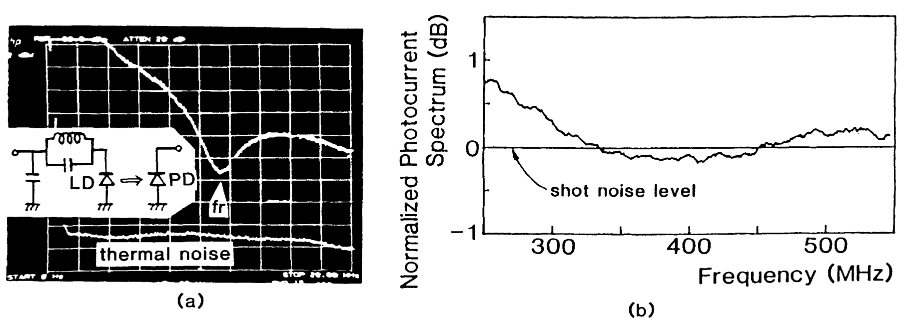

FIG. 3. (a) Photocurrent spectrum for the bias-circuit–driven laser shown in the inset. A high source impedance is realized only at the LC parallel-circuit resonant frequency f_r. The scales for the ordinate and abscissa are 2 dB/div and 2 MHz/div, respectively. (b) Photocurrent spectrum normalized by SQL at $r = 3.9$. The bias circuit consists of 750 Ω resistance and 10 nH inductance in series.

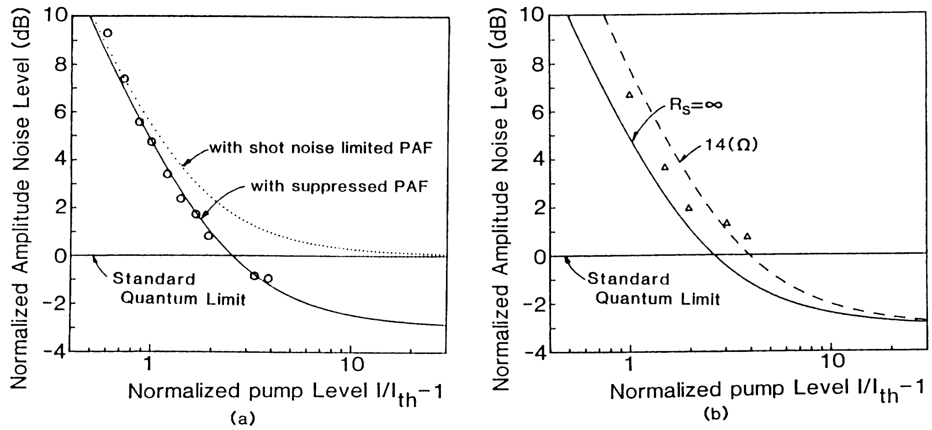

FIG. 4. (a) Theoretical and experimental amplitude noise levels vs pump level for $R_s = 750\ \Omega$. Dotted line: Theoretical amplitude noise level for a laser with shot-noise–limited pump-amplitude fluctuation. (b) Theoretical and experimental amplitude noise levels vs pump level for $R_s = 14\ \Omega$. Solid line: theoretical amplitude noise level for $R_s = \infty$.

effect of detector quantum efficiency η_c is compensated for. This is the broadest bandwidth for quantum noise reduction below SQL observed so far.

The averaged amplitude noise corrected for detector quantum efficiency versus pump level r is in good agreement with the theoretical prediction, as shown in Fig. 4(a). The theoretical amplitude noise for a laser with shot-noise–limited pump-amplitude fluctuation is also plotted for comparison. It is clear from this result that a constant-current–driven semiconductor laser is different from an ordinary optical pumped laser. When the external source impedance is made lower than R_d, the diode's series resistance of 14 Ω still has some effect in suppression of pump-amplitude fluctuation. The experimental results for such a case are compared with the theoretical curves for when R_s is ∞ and when R_s is 14 Ω in Fig. 4(b). It is seen that the noise reduction becomes incomplete when the source resistance is not large enough.

The laser used in this experiment has a relatively small differential quantum efficiency ($\eta_D \sim 0.3$) because of nonradiative (Auger) carrier recombination and free-carrier photon absorption processes. This limits the amplitude squeezing obtained when $r \gg 1$. These two loss effects can be suppressed by cooling of a laser or by an increase in its output coupling loss. A high-quantum-efficiency DFB semiconductor laser would feature large amplitude squeezing over a broad frequency bandwidth. The cavity bandwidth ω/Q, which ultimately determines the squeezing bandwidth as shown in Fig. 1(b), is higher than 100 GHz for a typical semiconductor laser. Recently, a nearly single-photon number state was produced by use of photon-pair generation in parametric down conversion.[17] The present scheme is suitable for generation of highly intense and wideband number-phase minimum-uncertainty states and it might find productive applications in optical communications and fiber gyroscopes, because a silica fiber has its minimum loss of 0.16 dB/km at this wavelength.

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