Ultrabroadband Amplitude Squeezing in a Semiconductor Laser

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A constant-current–driven semiconductor laser produced a field with amplitude noise reduced to below the standard quantum limit by -1.7 dB (32%) over an entire frequency range from near dc to 1.1 GHz. The amplitude-squeezing dependence on laser pump rate and optical loss was in good agreement with theoretical prediction. The new squeezed-state generation principle of high impedance suppression for pump-amplitude fluctuation was thus confirmed experimentally.

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It has been widely accepted for many years that an ideal laser produces a nearly coherent state which features full shot noise in a photodetector. The present authors and Nilsson claimed that an ideal laser generates a number-phase squeezed state if the pump noise is eliminated.[1] In a previous paper,[2] we reported the first observation of amplitude squeezing, i.e., number-phase squeezed-state generation, by a constant-current–driven semiconductor laser. The generation is based on a new principle of high impedance suppression for pump-amplitude fluctuation in a semiconductor laser oscillator.[3] A light-emitting diode driven by a constant-current source based on a similar principle also generates light with reduced photon-number fluctuation.[4] The detailed and quantitative comparison between experimental and theoretical results, however, has yet to be studied to make the claim convincing. A semiconductor laser is a preferable device for this purpose, because large amplitude noise reduction is attainable through inherent high quantum efficiency, and broad squeezing bandwidth is achievable because of short photon and electron lifetimes. These properties also make a semiconductor laser attractive for applications.

The broadest squeezing bandwidths reported in the literature are about 100 MHz for amplitude squeezing in semiconductor lasers[2] and about 10 MHz for quadrature-phase squeezing in fiber four-wave mixers.[5] Recently, an atom-cavity coupled system was proposed as a broad-band squeezer.[6] However, the squeezing bandwidth in this system does not extend to dc, which places a serious limit on several applications. This paper reports the first quantitative comparison between theoretical and experimental results for amplitude squeezing in a semiconductor laser and the observation of broad-band squeezing bandwidth extending from near dc to 1.1 GHz, which is the broadest bandwidth reported so far.

The experimental setup is shown in Fig. 1. A laser, its high-impedance bias circuit, and a collimating microlens are mounted inside a cryostat. An AlGaAs/GaAs transverse junction stripe semiconductor laser (Mitsubishi model ML-2308) with 0.81-μm oscillation wavelength was used at 77°K. Stable single-longitudinal-mode operation was obtained at a wide pump-level range, $r \equiv p/p_{\text{th}} - 1 = 1-10$. The threshold current was about 1 mA and the differential quantum efficiency above threshold was about 40%. Output coupling loss from a rear facet and internal absorption loss are responsible for the relatively small differential quantum efficiency. But these two factors are not fundamental limitations and, in fact, internal quantum efficiency, i.e., conversion efficiency from injected electrons to coherent photons, is close to unity at well above threshold. The diode's differential resistance is 20 Ω at an injection current I of 1 mA and is inversely proportional to I. The diode's series resistance is smaller than 7 Ω The current-bias circuit has a series resistance of 1 kΩ. Theoretical calculation shows that the source resistance $R_s \cong 1$ kΩ is high enough, as compared with the diode's differential resistance $R_d \cong 2-20$ Ω, to suppress the pump-amplitude fluctuation well below the shot-noise level (Fig. 13 in Ref. 3).

Si photodiodes with 240-μm diam and 1-nsec response time (NEC model NDL-2102) are used as photodetectors. GaAs field-effect transistors with input impedance of 240 Ω are used as front-end electronic amplifiers of a balanced-mixer receiver. The common mode suppression of the balanced mixer has been measured by modulation of the semiconductor-laser output and observation of the coherent peak reduction on the spectrum analyzer. It is higher than 30 dB in the entire frequency region from near dc to 1.1 GHz. The quantum efficiency of a Si photodiode is about 93% and the overall detection quantum efficiency, including collimating-lens insertion loss, cryostat window loss, gold mirror reflection loss, isolator in-

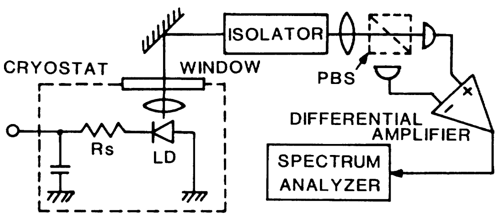

FIG. 1. An experimental apparaatus used to detect amplitude-squeezed light.

sertion loss, and focusing-lens insertion loss, is about 55%.

The single detector photocurrent spectrum for the laser at $r=8.5$ (trace A) is compared with the standard quantum limit (SQL, dashed line B) in Fig. 2. The SQL is calibrated by use of a dc-current-driven high-power laser (Hitachi model HLP1400) and balance mixer. The detailed procedure was described in the previous report.[2] The amplitude noise of this laser beam is 1.2 to 1.4 dB higher than the SQL at the photodiode front end after large optical attenuation. This means that the excess amplitude noise is smaller by -5 dB than the SQL. Since a balanced-mixer's excess noise suppression factor is greater than 30 dB, the excess amplitude noise is suppressed to below the SQL by more than 34 dB and so the calibration error of the SQL is less than 0.002 dB (0.2%). The photocurrent spectrum A is reduced to below the SQL B in the entire frequency range from near dc to 1.1 GHz. The noise reduction is 0.4 to 0.9 dB (9% to 19%) depending on the frequency.

A balanced mixer must also feature the SQL for amplitude-squeezed light.[7] Trace C in Fig. 2 shows the balanced-mixer output spectrum for the test laser at the same pump rate as trace A. The above-mentioned SQL (trace B) is retraced from near dc to 0.6 GHz by the amplitude-squeezed light. In a higher-frequency region, however, there is a deviation of 0.2–0.4 dB. The reason for this discrepancy is not yet clear. It is, however, obvious in spite of such small ambiguity for the SQL that the amplitude squeezing occurs over the entire frequency range from near dc to 1.1 GHz. We would like to stress that the squeezing bandwidth reported here is not an intrinsic squeezing bandwidth of the semiconductor laser but rather is limited by the bandwidth of the balanced mixer. The theory predicts that the squeezing bandwidth of a semiconductor laser is starting exactly from dc up to a few hundred gigahertz.[1,3] The noise measurements at a low frequency below 10 MHz and at a high frequency above 1.5 GHz are prevented by the $1/f$ noise of the front-end GaAs field-effect transistor amplifiers and the cutoff characteristics of the Si photodiode. Repeated measurements reproduced the result presented in Fig. 2 and similar results were obtained by other laser diodes with the same structure.

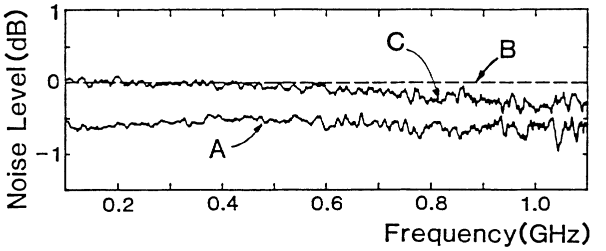

FIG. 2. Amplitude noise spectra normalized by the standard quantum limit. Traces A and C: single detector output and balanced-mixer output for the laser at $r=8.5$; trace B (dashed line): the SQL calibrated by the other laser and the balanced mixer.

The observed amplitude noise level at $r=10.4$ and $f=800$ MHz versus artificial optical attenuation L is shown in Fig. 3. The observed noise level increases to approach the SQL as optical attenuation increases, i.e., quantum efficiency decreases, which is an unmistakable mark of amplitude squeezing. The overall quantum efficiency from the laser injection-current increment to photodetector current increment is 22% when artificial optical attenuation is eliminated. The overall detection quantum efficiency of 55% consists of a photodetector quantum efficiency of 0.93, focusing-lens loss of 0.90, isolator insertion loss of 0.81, mirror reflection loss of 0.95, cryostat window loss of 0.93, and laser collimating lens loss of 0.93. The amplitude noise levels corrected for these factors are shown by A, B, C, D, E, and F, in Fig. 3. The observed noise level corresponds to amplitude squeezing of -1.7 dB (32%) below the SQL at the output of the laser facet (F), as shown in Fig. 3. This is the noise level that the laser actually produced at the output mirror. The laser output coupling efficiency is given by

$$\eta c = L^{-1}\ln(R_1^{-1/2})/\alpha + L^{-1}\ln\left[(R_1R_2)^{-1/2}\right]$$

where $L=250$ μm is the cavity length, $R_1=0.32$ and $R_2=0.6$ are power reflectivities of the front and rear facets, and $\alpha=22$ cm^{-1} is the internal absorption loss.

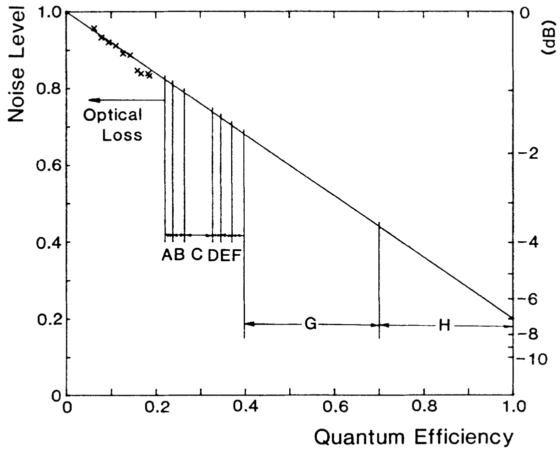

FIG. 3. Amplitude noise level normalized by the SQL at $r=10.4$ and $f=800$ MHz vs optical attenuation. Amplitude noise levels corrected for detection quantum efficiency and laser output coupling efficiency are also shown. The points A–H indicate the amplitude noise levels corrected for (A) photodetector quantum efficiency of 0.93, (B) focusing lens loss of 0.90, (C) isolator loss of 0.81, (D) mirror reflection loss of 0.95, (E) cryostat window loss of 0.93, (F) collimating lens loss of 0.93, (G) laser rear facet output loss of 0.57, and (H) laser internal absorption loss of 0.70.

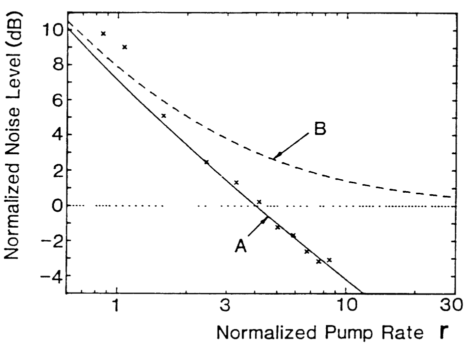

FIG. 4. Theoretical and experimental amplitude noise levels normalized by the SQL vs laser pump level. Experimental results are corrected for detection and laser output coupling quantum efficiency. Theoretical results shown by solid line (A) are obtained by (6.1) in Ref. 3 with the parameters τ_{sp}, n_{sp}, and β that are independently measured. Dashed line (B) indicates the theoretical result for the shot-noise–limited pump fluctuation.

If the laser output-coupling efficiency due to nonideal rear-facet reflectivity $\eta_M \cong 0.57$ (G) and that due to internal loss $\eta_A = 0.70$ (H) are also corrected, the observed noise level corresponds to amplitude squeezing of -7 dB (80%) below the SQL as shown in Fig. 3. This is the intrinsic noise level achievable if the rear-facet reflectivity is increased to 100% and internal absorption loss is eliminated.

The amplitude noise levels corrected for detection and laser quantum efficiency are plotted as functions of r in Fig. 4. The solid line is the theoretical amplitude noise level for the laser with unity output-coupling efficiency with use of Eq. (6.1) of Ref. 3. The theoretical curve does not employ any fitting parameters. The theoretical curve depends on parameters such as population inversion parameter n_{sp}, spontaneous emission factor β, and electron lifetime τ_{sp} due to spontaneous emission.[8] The value $\tau_{sp} = 1$ nsec is measured by the response time of spontaneous emission at a bias level just below the oscillation threshold. The value $n_{sp} = 1.6$ is obtained by the relaxation oscillation frequency dependence on the bias level. The value $\beta = 2.2 \times 10^{-4}$ is determined by the output power dependence on the bias level. The detailed procedure is described in Ref. 8. Good agreement between experimental and theoretical results is obtained.

The experimental results reported here fully confirm the principle of generating amplitude-squeezed light with high impedance suppression of pump-amplitude noise. The advantages of the present scheme follow.

(1) Amplitude noise reduction is not limited by nonlinear optical material constants but is determined only by laser quantum efficiency. Amplitude squeezing of more than 10 dB is achievable, since a quantum efficiency higher than 90% is not so difficult to realize.

(2) The squeezing bandwidth is ultimately determined by a photon lifetime on the order of 1 psec. Squeezing bandwidth higher than 100 GHz is achievable at a reasonable pump level. This broad-band property suggests the potential capability of the production of an amplitude-squeezed pulse of very short duration.

(3) Amplitude-squeezed light is available at any wavelength between 0.7 and 10 μm by choice of an appropriate semiconductor material system.

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