Room Temperature Generation of Amplitude Squeezed Light from a Semiconductor Laser with Weak Optical Feedback

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Amplitude-squeezed states are produced from a room-temperature Fabry-Pérot quantum-well semiconductor laser using a combination of pump suppression and weak, dispersive optical feedback. Up to 0.9 dB of squeezing is measured using a balanced homodyne detector corresponding to 1.5 dB of squeezing at the output facet of the laser. A comparison of the data to theoretical predictions suggests that the excess noise measured under free-running conditions could be a result of incomplete side-mode suppression in combination with asymmetrical cross-mode nonlinear gain saturation.

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The possibility of generating nonclassical or "squeezed" states of light [1] has led to much activity in the field of quantum optics in recent years. Such states feature a redistribution of the fundamental quantum noise which occurs in two conjugate field observables due to the Heisenberg uncertainty principle. Quadrature squeezed states, the first squeezed states to be observed experimentally [2], exhibit a reduction in the noise in one quadrature of the electric field and a corresponding increase in the other. Amplitude-squeezed states are states in which the photon number exhibits reduced fluctuations at the expense of the field phase, a perfectly amplitude-squeezed state being a photon number state or Fock state. Because of the strong quantum correlations that exist in the amplitude-squeezed optical field, photoelectrons are excited uniformly during photodetection and form a regular series of charge pulses instead of occurring at random intervals as is the case for coherent state photodetection. As a result, the fluctuations in the generated photocurrent are below the standard quantum limit (SQL) or shot noise level, long thought to be a fundamental limit to detection sensitivities.

The production of amplitude-squeezed states from semiconductor lasers was first suggested by Yamamoto, Machida, and Nilsson [3] who recognized that the noise from the pumping process, the dominant noise mechanism in lasers at low frequencies, and high pump rates, could be suppressed. If the laser is pumped with a current source, then random fluctuations in the rate of radiative electron-hole recombination are compensated for by the resulting fluctuations in the laser gain. As a result, the laser pump noise is no longer determined by a Poisson process, as would be the case for optical pumping with classical light, but rather by thermal noise in the output resistance of the current source. This thermal current noise can be reduced to an arbitrarily small value by using a large enough output resistance.

Because of the asymmetrical gain profile in semiconductor lasers, a correlation, described by the α parameter [4], exists between the amplitude and the phase noise of the laser's internal optical field. This correlation extends partly into the quantum regime and can therefore be taken advantage of in order to reduce the quantum noise in semiconductor lasers. Of the fundamental noise sources in a semiconductor laser [3], dipole moment fluctuations and noise due to vacuum fluctuations produce correlated phase and amplitude noise [5]. The other standard noise sources (pump noise, noise due to spontaneous emission into nonlasing modes, and noise due to internal optical losses) cause amplitude noise without any accompanying carrier density fluctuations and hence no amplitude-phase correlation. Since the former two noise sources dominate at low pump rates and the latter three dominate at high pump rates, one expects the noise reduction to be the largest near threshold and smaller far above threshold. This is indeed true [5] but the correlation is sufficiently strong at intermediate pump rates that a significant enhancement of the squeezing can be obtained. This enhancement is perhaps most important at room temperature where the inability to pump the laser far above threshold and the existence of excess noise place limits on the amount of squeezing that can be obtained from a free-running laser. While laser operation at cryogenic temperatures has resulted in as much as 8.3 dB of squeezing [6], the largest degree of squeezing obtained to date from a free-running laser at room temperature is 0.33 dB [7]. Squeezing of 1.8 dB has also been reported from a room-temperature semiconductor laser with strong optical feedback from a grating [8].

The noise reduction is accomplished through the introduction of an element of dispersive loss [9] to the laser. The frequency-dependent cavity loss rate can be written as

$$\frac{1}{\tau_{\mathrm{ph}}} = \frac{1}{\tau_{\mathrm{ph}}^{(0)}} + 2C\,\frac{d\phi(t)}{dt}, \tag{1}$$

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where $\tau_{\rm ph}^{(0)}$ is the original photon lifetime, $d\phi(t)/dt$ is the instantaneous frequency deviation, and C is a constant. This modification of the photon lifetime couples part of the phase noise back into the field amplitude resulting in a simultaneous decorrelation and reduction in the amplitude noise. The implications of such a modification on the quantum noise in semiconductor lasers were discussed in Ref. [5]. It was found that under both pump suppression and optical feedback, the amplitude noise power spectral density at frequencies smaller than the stimulated lifetime and normalized to the SQL is given by

$$P_{\Delta r}^{(0)}(\Omega) = (1-\eta) + \eta\left[\frac{1}{R} + 2n_{sp}\left|\frac{\alpha C(\Omega) - 1/n_{sp}R}{1+\alpha C(\Omega)}\right|^2 + 2n_{sp}\left(1+\frac{1}{n_{sp}R}\right)^2 \frac{|C(\Omega)|^2}{|1+\alpha C(\Omega)|^2}\right], \quad (2)$$

where η is the internal optical efficiency, n_{sp} is the inversion parameter, $R = i/i_{\rm th} - 1$ is the pump rate, α is the linewidth enhancement factor, and $C(\Omega) = -\kappa(\Omega)\tau\cos(\phi_0)/[1+\kappa(\Omega)\tau\sin(\phi_0)]$. Here $\kappa(\Omega) = [(1-r_c^2)\tau/r_c\tau_c]\sqrt{P_{\rm fb}/P_{\rm out}}(1-e^{-i\Omega\tau})/i\Omega\tau$ is the feedback coupling rate, τ the feedback delay, r_c the facet reflectivity, τ_c the semiconductor laser roundtrip time, $P_{\rm fb}$ the feedback power, $P_{\rm out}$ the output power, and ϕ_0 the feedback phase. From this expression it can be seen that although the feedback leaves the first term inside the bracket in Eq. (2) (due to spontaneous emission into nonlasing modes) unaffected, the second term (due to dipole moment and vacuum fluctuations) can be reduced by a factor of $1+\alpha^2$ from its free-running value when $C(\Omega) = \alpha/[1+(1+\alpha^2)n_{sp}R]$. Thus, for $R \approx 1$–3 the amplitude noise can be reduced from above to below the SQL using dispersive loss.

The dispersive loss is realized experimentally through the use of weak optical feedback in combination with an atomic resonance which introduces a frequency-dependent phase shift/absorption to the feedback optical field. This technique has been used in the past to significantly reduce both the laser linewidth [10] and the classical amplitude noise [5] and has the added advantage of locking the laser to a stable frequency reference. In this Letter we present results showing that the amplitude noise reduction obtained in Ref. [5] also extends into the quantum regime. We present the first demonstration of squeezing enhancement using weak optical feedback: 0.9 dB (19%) of squeezing is obtained from a semiconductor laser operating a room temperature using a combination of pump suppression and weak optical feedback with dispersive loss. This represents an improvement in the amount of squeezing by a factor of 2.5 over the best free-running, room-temperature result.

The experimental setup is shown in Fig. 1. An unmodified commercial Fabry-Pérot, quantum-well GaAs semiconductor laser (Spectra Diode Labs SDL-5412) lasing at

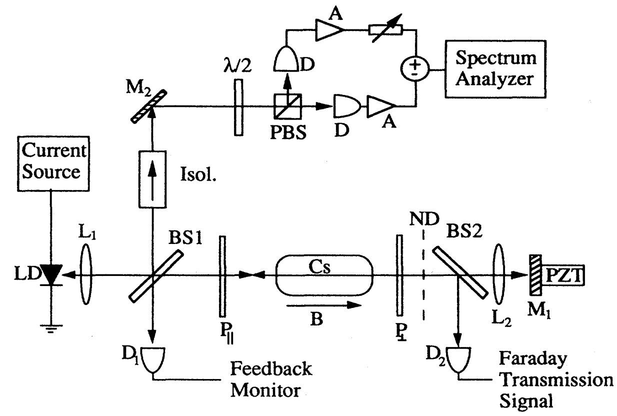

FIG. 1. Experimental setup.

852 nm was pumped with a precision, low-noise current source. Pump suppression was achieved at high frequencies while allowing the dc current to pass unimpeded by placing a 100 mH inductor in the output stage of the current source. The laser was antireflection coated (<5%) on the front facet, 98% high-reflection coated on the rear facet, had a threshold current of 17 mA, and an external differential quantum efficiency of 69% at room temperature. The laser was mounted in a hermetically sealed package which contained a thermistor and TE cooler and was actively temperature stabilized at the millidegree level with a home-built temperature controller.

The laser was coupled through a weakly transmitting beamsplitter ($T = 1\%$) to a 71 cm external cavity formed by the laser front facet and an end mirror. Inside this external cavity a cell containing Cesium vapor was placed between two crossed polarizers. An axial magnetic field of $\approx$150 G was applied to the Cs causing it to become optically active and partially transmit light when the laser was tuned to the $D2$ line in the Cs spectrum. PZT (lead zirconate titanate) attached to the end mirror and a neutral density filter in the beam path enabled control of the feedback intensity and phase. In this way, wavelength selective, dispersive optical feedback could be applied to the laser.

The reflected light from the beamsplitter was passed through an optical isolator to reduce spurious optical feedback from the detection system. In addition, all optical elements were slightly misaligned. The beam was then sent into a balanced homodyne detector consisting of a half-wave plate, polarizing beamsplitter, and high quantum efficiency (97%) photodetectors (Hamamatsu S3994, 30 MHz bandwidth). The optical transmission efficiency from laser output facet to detector was 0.63, giving a total current-to-current differential efficiency of 0.43. The homodyne detector was balanced by applying modulation to the laser injection current at the frequency of interest; common mode rejection of greater than 40 dB was obtained. The laser noise power at a single frequency of 29 MHz (in a bandwidth of 300 kHz) was then measured relative to the SQL as a function of optical feedback power for three different injection currents; the background amplifier noise was subtracted from all measured signals.

The noise of the free-running laser was found to be extremely sensitive to spurious optical feedback from optical components and, in particular, from the front of the optical isolator. Great care was required to reduce feedback not just from reflections but also from scattered light from the isolator, since feedback powers on the order of $10^{-8}P_{out}$ were found to significantly affect the measured noise level. In addition, some sources of spurious feedback such as those from the collimating lens or associated with the rear facet could not be controlled at all, and their effects on the laser noise remain unclear. When moderate feedback powers from the external cavity were applied to the laser, however, the noise was found to be much less sensitive to the spurious feedback.

The laser noise was measured as a function of feedback strength $\kappa(0)\tau$ at three different injection currents and is shown, normalized to the SQL, in Fig. 2. For each measurement, the end-mirror position (feedback phase) was adjusted to produce the minimum noise. The value for the cavity delay τ was taken to be 11.7 ns which included not only the empty cavity delay but also the estimated delay due to the dispersion of the Cs. It can be seen that at the highest injection current, the laser amplitude noise was reduced from its free-running value near the SQL to over 0.9 dB below as the feedback power was increased. This corresponds to 1.5 dB of squeezing at the laser facet. At lower injection currents the free-running laser noise increased as did the feedback-induced reduction. The maximum feedback power used was approximately $3 \times 10^{-7}P_{out}$.

The measurement above was also repeated using non-wavelength-selective feedback. The laser was turned off the Cs line, and the rear polarizer was rotated to allow partial transmission of the light from all modes of the laser through the external cavity. Again the laser noise was measured as a function of the feedback strength and results qualitatively similar to the wavelength-selective case were obtained although the maximum squeezing was somewhat less (0.75 dB).

A number of checks were performed to verify the calibration of the shot noise level. High power light-emitting diodes (LED's) were shone simultaneously onto the detectors and the resulting noise power measured in both addition and subtraction modes at an identical detector photocurrent to that of the laser. The noise in each detection mode (addition and subtraction) was found to be equal an agreed with the shot noise level measured with the laser light to within 2%. Finally, an optical attenuator was placed in the beam path and the noise power was measured as a function of attenuation. The results are plotted in Fig. 3. Again, agreement with expected behavior was found: The measurements of the SQL obtained from both the laser and the LED are reduced in a linear fashion to zero, while the laser noise is also reduced to zero but in a nonlinear fashion corresponding to the disappearance of the squeezing at high levels of attenuation. With all of these possible sources of error, we estimate the measurement of 19% squeezing to be accurate to within 3%.

The dashed lines in Fig. 2 are the theoretical prediction based on Eq. (2) with $n_{sp} = 1.5$, $\alpha = -2.5$, and ϕ_0 adjusted to produce the minimum noise. It can be seen that not only is the measured noise under free-running conditions much higher than the predicted value but also that the reduction in the noise due to the optical feedback is considerably larger. We believe that this excess noise under free-running conditions is caused at least in part by the presence of longitudinal side modes [7,11]. To investigate the possibility that the observed noise reduction was due to a change in the laser side-mode

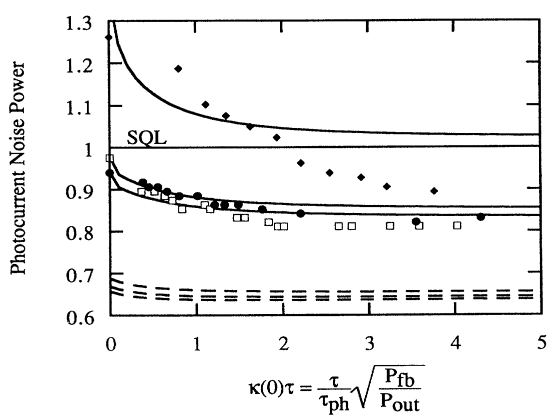

FIG. 2. Photocurrent noise power at 29 MHz normalized to the SQL. Experimental points are taken at injection currents of 100 mA (triangles), 110 mA (squares), and 117 mA (circles). The dashed lines are the prediction from the single-mode theory and the solid lines from the multimode theory.

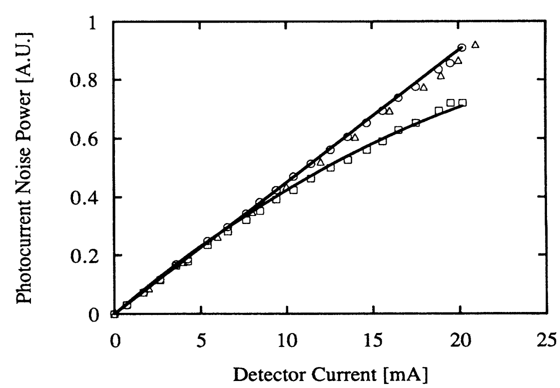

FIG. 3. The effect of optical attenuation on the measured laser noise (squares) and SQL (triangles measured with LED's and circles measured with laser and balanced homodyne detector). The solid lines are the predicted behavior.

suppression, the longitudinal mode spectrum of our laser was monitored simultaneously with the amplitude noise using an optical spectrum analyzer. It was found that the side-mode suppression was at least 28 dB and that when the optical feedback was applied the average side-mode power decreased by only $(6 \pm 4)\%$. It seems unlikely that such a small change in the side-mode power could be exclusively responsible for the more than a 17% change in the amplitude noise power. The combined power in all side modes was estimated to be about 1% of the total output power.

We suspect that the noise reduction is due instead to the amplitude-phase correlation mechanism in combination with asymmetrical cross-mode nonlinear gain saturation [12]: the gain of one mode depends on the intensity of neighboring longitudinal modes. Such an effect can result in a strong increase in the amplitude noise at low frequencies due to a renormalization of the weak mode relaxation resonance caused by the intermode coupling [13]. This explanation agrees more readily with our experimental results than either simple homogeneous or inhomogeneous broadening. The increase in the amplitude noise at low frequencies is in this case accompanied by a corresponding increase in the carrier noise which is strongly correlated with the total amplitude noise. This carrier fluctuation in turn modulates the refractive index which causes fluctuations in the phase of the main mode. The dispersive loss then couples these phase fluctuations back in to the main mode amplitude and, due to the stronger correlation between amplitude and phase, the amplitude noise is reduced by a larger amount than is expected in the single-mode theory. Thus, with this explanation, one expects both excess noise under free-running conditions and a larger feedback-induced noise reduction than in the single-mode theory.

We have theoretically modeled this mechanism of noise reduction by starting from the multimode Langevin equations given in Ref. [13], assuming only two modes, and adding to the main mode equation a feedback term [5]. The equations are then solved for the total amplitude noise using the fully quantum mechanical Langevin correlation functions [3]. In the limit of a strong main mode and weak side mode, it is found that the total amplitude noise is given by

$$P_{\Delta r}^{(T)} = P_{\Delta r}^{(0)} + P_{\Delta r}^{(\text{excess})} \left| \frac{1}{1 + \alpha C} \right|^2, \qquad (3)$$

where $P_{\Delta r}^{(0)}$ is given by Eq. (2), and $P_{\Delta r}^{(\text{excess})}$ is the excess noise found in Ref. [13] and is taken here as a fitting parameter. The noise as a function of the feedback power with $n_{sp} = 1.2$ and ϕ_0 adjusted to minimize the noise is then plotted (solid lines, Fig. 2) and somewhat better agreement with experiment is found than in the single-mode theory. We note that while this multimode model does indeed appear to explain at the original discrepancy between experiment and theory, we do not exclude the possibility that other processes might be responsible.

In summary, we have measured 0.9 dB of amplitude squeezing from a room-temperature semiconductor laser with weak optical feedback with dispersive loss. We find that the feedback can significantly reduce the quantum noise at some values of the feedback phase and enhance it at others. Excess noise is present under free-running conditions and the reduction in the amplitude noise is larger than that predicted with a single-mode theory. A multimode theory which includes cross-mode nonlinear gain is found to agree reasonably well with experiment, suggesting that such a mechanism could explain the smaller than expected squeezing typically obtained from semiconductor lasers in room-temperature measurements.

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[1] D.F. Walls, Nature (London) **306**, 141 (1983).
[2] R.E. Slusher, L.W. Hollberg, B. Yurke, J.C. Mertz, and J.F. Valley, Phys. Rev. Lett. **55**, 2409 (1985); R.M. Shelby, M.D. Levenson, S.H. Perlmutter, R.G. DeVoe, and D.F. Walls, Phys. Rev. Lett. **57**, 691 (1986); L. Wu, H.J. Kimble, J.L. Hall, and H. Wu, Phys. Rev. Lett. **57**, 2520 (1986).
[3] Y. Yamamoto, S. Machida, and O. Nilsson, Phys. Rev. A **34**, 4025 (1986).
[4] C.H. Henry, IEEE J. Quantum Electron. **QE-18**, 259 (1982); K. Vahala and A. Yariv, IEEE J. Quantum Electron. **QE-19**, 1102 (1983).
[5] J. Kitching, R. Boyd, A. Yariv, and Y. Shevy, Opt. Lett. **19**, 1331 (1994).
[6] W.H. Richardson, S. Machida, and Y. Yamamoto, Phys. Rev. Lett. **66**, 2867 (1991).
[7] S. Machida, Y. Yamamoto, and Y. Itaya, Phys. Rev. Lett. **58**, 1000 (1987).
[8] M.J. Freeman, H. Wang, D.G. Steel, R. Craig, and D.R. Scifres, Opt. Lett. **18**, 2141 (1993).
[9] A. Yariv, R. Nabiev, and K. Vahala, Opt. Lett. **15**, 1359 (1990).
[10] Y. Shevy, J. Iannelli, J. Kitching, and A. Yariv, Opt. Lett. **17**, 661 (1992).
[11] H. Wang, M.J. Freeman, and D.G. Steel, Phys. Rev. Lett. **71**, 3951 (1993).
[12] A.P. Bogatov, P.G. Eliseev, and B.N. Sverdlov, IEEE J. Quantum Electron. **QE-11**, 510 (1975).
[13] C.B. Su, J. Schlafer, and R.B. Lauer, Appl. Phys. Lett. **57**, 849 (1990).