Nonclassical Light from a Semiconductor Laser Operating at 4 K

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Amplitude fluctuations of the light from a semiconductor laser, operating at 4 K, have been measured to be 11% below the shot-noise limit in the detected photocurrent. Weak optical reflection into the laser reduces the squeezing from the expected detector-current–to–laser-current transfer ratio of 25%. Results compare favorably with a theory which includes effects of optical feedback.

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Nonclassical states of the electromagnetic fields such as squeezed states[1] and number-phase states[2,3] are of fundamental importance in optical physics, and are also of current interest partly because of possible applications in optical communication and high-precision measurements.[1,4] In a squeezed state, the noise in one quadrature of the field is below the vacuum noise level or standard quantum limit (SQL). A number-phase state is also a minimum uncertainty state, in which the photon-number noise ($\langle \Delta \hat{n}^2 \rangle$) and sine-operator noise satisfy the relationship[2-4] $\langle \Delta \hat{n}^2 \rangle \langle \hat{S}^2 \rangle = \langle \hat{C} \rangle^2/4$. Here $\hat{n}$, $\hat{S}$, and $\hat{C}$ are the photon-number operator, the sine operator, and the cosine operator, respectively.[5] In a number-phase state the photon-number noise is less than for a coherent state (i.e., $\langle \Delta \hat{n}^2 \rangle < \langle \hat{n} \rangle$). While quadrature-squeezed states require quite sophisticated and complex means of generation,[1] a light beam with sub-Poissonian photon-number noise can be generated directly by a semiconductor laser.[2,3] Moreover for some applications these states offer significant advantages over coherent states and squeezed states.[2-4] The current investigation of the mechanisms necessary to observe amplitude-squeezed light from a diode laser was prompted by the apparent simplicity and potential technological importance of this nonclassical light source.

We have observed 11% reduction below the shot-noise limit in the measured spectrum of photocurrent noise power for the light from a semiconductor laser that is biased far above threshold. Given that the overall collection efficiency η_c (photoelectrons divided by photons emitted from the laser front facet) is 66%, this may imply that the noise level at the laser facet was 17% (0.8 dB) below the vacuum noise level. However, the measured detector-current–to–laser-current transfer ratio was 25%, limited principally by loss through the rear laser facet. Since the pumping-current fluctuations are believed to be more than 15 dB below the shot-noise level, we suspect that the discrepancy between this ratio and the measured squeezing is due to weak optical feedback from the measurement apparatus. Hence the amplitude fluctuation at the front facet, in the absence of feedback, is expected to be 38% (2.2 dB) below the SQL. Moreover a beam with 70% amplitude-noise reduction could in principle be obtained by coating the rear facet for 90% reflectivity and the front facet for 10%. To understand our experimental results we have formulated a theoretical model which includes the effects of optical feedback, and the resulting agreement is one of the points of this paper. The maximum noise reduction was obtained when the laser diode was cooled to 4 K. The amplitude-noise characteristics of a semiconductor diode laser at such a low temperature had not previously been investigated.

The amplitude fluctuation $\Delta E(t)$ and phase fluctuation $\Delta\phi(t)$ in a laser external field

$$E(t) = [E_0 + \Delta E(t)] \cos[\omega t + \Delta\phi(t)]$$

have been the subject of numerous investigations.[2,3,6] As is well known, the average intensity, proportional to E_0^2, is clamped above threshold. The amplitude fluctuation (ΔE) is restrained by the saturated gain, and in the conventional theory the associated noise spectral density is at the vacuum level. There is no restoring force on the phase fluctuation ($\Delta\phi$) which is driven by spontaneous emission. It is this phase noise that determines the laser linewidth. The possibility of reducing the amplitude fluctuations to below the shot-noise limit, by regular ultrashort number-state optical pulse excitation of the gain medium, was considered by Golubev and Sokolov.[7] Yamamoto and co-workers[2] were the first to recognize that the pump source (the driving current) in the case of a semiconductor laser is usually below the shot-noise limit and hence the external-field amplitude fluctuations can be below those of the vacuum. Recently other authors have reached similar conclusions.[8] In the absence of pump noise, the noise on the internal laser field is determined primarily by vacuum fluctuations entering the cavity through the output coupler. The external-field fluctuation, however, is the quantum-mechanical interference between the transmitted internal field and the reflected vacuum field. At fluctuation frequencies, Ω, less than the cavity linewidth ω/Q ($\omega/Q = 1/\tau_p$, where τ_p is the photon lifetime), partial cancellation of the external-field amplitude noise results, since the internal field and reflected field are correlated.[2] The laser-output amplitude fluctuation is reduced below the SQL provided that (1) the laser internal quantum efficiency is sufficient to transfer the statistics of the pump source to the output light, (2) the laser can be pumped far above threshold, enabling the saturated gain to restrain the amplitude fluctuation, and (3) the internal loss-to-output coupling ratio is small, since loss destroys the correlation between the internal field and reflected vacuum field.

Excess noise on the internal field may arise from fluctuations in the gain medium that are not correlated with the dipole-moment fluctuations, for example, due to traps which capture and release electrons. In these cases the external field would simply reflect this excess noise.

The experimental arrangement is shown in Fig. 1. A Mitsubishi transverse junction semiconductor laser (Model ML3101) is cooled to 4 K, and driven by an ordinary power supply. Above 1 MHz, the current noise on an average-filtered power supply is typically more than 15 dB below the shot-noise limit. The bias resistor was $R_s = 750\ \Omega$. The slope efficiency at the front facet was 0.51 mW/mA, the wavelength $\lambda \simeq 0.78\ \mu$m, the external differential efficiency $\eta_{ex} = 0.62$, and the threshold current $I_{th} = 0.3$ mA. A microlens, antireflection coated and mounted on the same brass fixture that held the laser, collimated the beam. The laser was isolated with a polarizer and quarter-wave plate. Beam splitter BS_1, which allowed the laser spectral mode to be monitored by a Fabry-Perot interferometer (FP), was removed when noise measurements were being performed. Beam splitter BS_2 directed the beam to two silicon *p-i-n* photodiodes, D_1 and D_2 (RCA 30971E, quantum efficiency $\eta_d = 0.84$), in a balanced homodyne arrangement. The ac photocurrent signals were amplified by homemade two-stage field-effect-transistor preamplifiers followed by broadband postamplifiers. The delay line (delay $= T_d$) was a semirigid coaxial cable, and the ac photocurrents i_1 and i_2 are subtracted at a wideband microwave tee. The common mode suppression ratio of 25 dB could be obtained over any 100-MHz frequency span

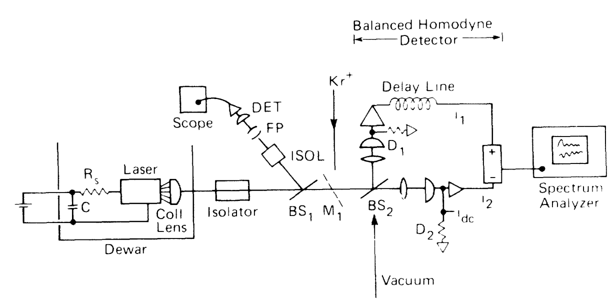

FIG. 1. Experimental arrangement and apparatus, described in detail in the text. The beam from a cryogenic GaAs laser is collimated, can be mode analyzed by a Fabry-Perot interferometer (FP), and its amplitude noise is compared with the vacuum level using a balanced homodyne detector. The movable mirror M_1 is inserted for Kr^+-beam calibration of the SQL.

between 10 MHz and 1.5 GHz, limited by frequency-dependent losses.

Optical balanced homodyne detection is discussed in Ref. 9. If vacuum enters one port, as in Fig. 1, and the arms of the detector are identical (the delay line is absent), $i_1 - i_2$ is proportional to the operator $2E_0\Delta\hat{c}_1$, where E_0 is the mean amplitude of the light field and $\Delta\hat{c}_1$ is the fluctuation operator for one quadrature (in phase with the mean field) of the field entering the unused beam-splitter port, in this case vacuum. The quantity $|2E_0|^2\langle\Delta\hat{c}_1^2\rangle$ is the vacuum noise level or SQL, corresponding to the full shot-noise level. Conversely, $i_1 + i_2$ is proportional to $2E_0\Delta\hat{a}$, where $\Delta\hat{a}$ is the fluctuation operator for the amplitude quadrature of the incident laser field. For the magnitude of squeezing presently available from a diode laser or from other sources, a linearized, small-fluctuation approximation is quite accurate, and the field-amplitude fluctuation and the amplitude-quadrature fluctuation are indistinguishable. The delay line introduces a phase shift ΩT_d between i_1 and i_2. Hence at the rf frequencies $\Omega_d = (2n+1)\pi/T_d$, the output of the hybrid tee is proportional to $i_1 - i_2$, and the fluctuations correspond to the SQL. At frequencies $\Omega_s = 2n\pi/T_d$, the laser fluctuation $|2E_0|^2\langle\Delta\hat{a}\rangle$ is measured; i.e., the observed noise spectral density is proportional to

$$\langle\Delta\hat{c}_1^2\rangle\sin^2(\Omega T_d/2) + \langle\Delta\hat{a}^2\rangle\cos^2(\Omega T_d/2)\,.$$

This sinusoidal, "ripple" signal provides a precise internal calibration of the vacuum level,[10] measured simultaneously with the diode-laser amplitude-noise spectrum. The beam from a single-mode krypton-ion laser operating at 765 nm could also be introduced using a removable mirror, M_1, and was used as a coherent source to provide an independent confirmation of this calibration of the vacuum noise.

A typical photocurrent noise spectrum obtained when the diode laser was biased close to threshold (as defined by the threshold parameter $r \equiv I/I_{th} - 1 = 0.7$) and the laser output power was $P = 113\ \mu$W is shown in Fig. 2, trace *a*. Also shown (trace *b*) is the corresponding spectrum obtained with a beam of equal power from the Kr^+ laser. In all traces, the dark noise has been subtracted and the signal numerically filtered with a Gaussian of full width 175 kHz. The coincidence at frequencies Ω_d between the laser-diode ripple signal and the shot-noise-limited Kr^+-laser signal confirms the coincident level as the SQL or vacuum level.[11] With an increase of the driving current to the laser (see Fig. 2, traces *c* and *d*), the ripple signal corresponding to the diode-laser amplitude noise falls to or below that due to the Kr^+. This reversal of the sign of the ripple signal (i.e., the noise at frequencies Ω_s below that a Ω_d), in concert with the noise at Ω_s falling below that due to the Kr^+ laser, forms an unmistakable signature for squeezing. At frequencies Ω_d the diode-laser and Kr^+-laser noise levels coincide as expected. The laser power was 5.9 mW for traces b and c of Fig. 2, and the squeezing was observable throughout the entire frequency range over which it was possible to balance the detector.

We have found it necessary to take into account the effects of optical feedback in order to obtain quantitative agreement between our results and theory. Although effects of feedback on semiconductor laser dynamics have been previously described,[12] the role of quantum fluctuations was not considered. We have applied this description of optical feedback to the quantum Langevin equations developed to describe a semiconductor laser.[2,6] We obtain the following coupled equations that describe the internal-field amplitude fluctuation ($\Delta\hat{A}$), electron-number fluctuation $\Delta\hat{N}_c$, and phase variation ϕ:

$$(1+a)\frac{d}{dt}\Delta\hat{A}+bA_0\frac{d}{dt}\phi=-\left[\frac{1}{\tau_p}-(E_{cv}-E_{vc})\right]\Delta\hat{A}+\frac{\Delta\hat{N}}{2A_0\tau_{st}}+\hat{F}_{\Delta A}\,, \quad (1)$$

$$\frac{d}{dt}\Delta\hat{N}_c=-\left[\frac{1}{\tau_n}+\frac{1}{\tau_{CR}}\right]\Delta\hat{N}_c-(E_{cv}-E_{vc})2A_0\Delta\hat{A}+\hat{F}_{\Delta N}\,, \quad (2)$$

$$(1+a)\frac{d}{dt}\phi-\frac{b}{A_0}\frac{d}{dt}\Delta\hat{A}=\frac{\alpha}{2A_0^2\tau_{st}}\Delta\hat{N}+\hat{F}_\phi\,. \quad (3)$$

Here A_0^2 is the total number of photons in the cavity, τ_p is the cavity photon lifetime, $n_{sp}=E_{cv}/(E_{cv}-E_{vc})$, $E_{cv}=n_{sp}/\tau_p$ is the absorption rate, $E_{vc}=5\times10^{11}\ \mathrm{sec}^{-1}$ is the rate of stimulated emission, τ_{sp} is the electron lifetime due to spontaneous emission, $\tau_{st}=\tau_{sp}/n_{sp}r$ is the electron lifetime due to stimulated emission, $\tau_n=1/\tau_{st}+1/\tau_{sp}$ is the electron lifetime, $\tau_{CR}=CR_s$, $C=q^2N_c/2k_BT$ is the diffusion capacitance, and α is the amplitude-phase coupling factor.[13] The parameters $a=\kappa\tau\cos\theta$ and $b=\kappa\tau\times\sin\theta$ describe optical feedback. Here $\theta=\omega_0\tau$ is the phase of the reflected light, and the rate of optical feedback is $\kappa=(1-r_c^2)r_{ex}/r_c\tau_c$, where r_c is the facet reflectivity, τ_c is the diode-cavity round-trip time, and r_{ex} is the fraction of externally reflected power that is fed back into the cavity, after a delay τ.

The Langevin noise operators $\hat{F}_{\Delta A}$, $\hat{F}_{\Delta N}$, and $\hat{F}_\phi$ have low-frequency power spectra

$$S_{F\Delta A}(0)=S_{F\phi}(0)=\tfrac{1}{2}(E_{cv}+E_{vc}+1/\tau_p)$$

and

$$S_{F\Delta N}(0)=2\{N_c/\tau_{sp}+(E_{cv}+E_{vc})A_0^2+4k_BT/q^2R_s\}\,.$$

The external-field amplitude fluctuation ($\Delta\hat{a}$) is given by $\Delta\hat{a}=\Delta\hat{A}\tau_{pe}^{-1/2}-\hat{f}_r\tau_{pe}^{1/2}$, where τ_{pe} is the photon decay rate due to output coupling and $\hat{f}_r$ is an operator that describes the interface of the vacuum field and the transmitted internal-field fluctuation.[2]

The power spectrum in the presence of feedback $S'_{\Delta\hat{a}}(\Omega)=\langle\Delta\hat{a}(\Omega)^\dagger\Delta\hat{a}(\Omega)\rangle$ [$\Delta\hat{a}(\Omega)$ is the Fourier transform of $\Delta\hat{a}$] is given by

$$S'_{\Delta\hat{a}}(\Omega)=((\eta/2A_0\tau_{st})^2S_{F\Delta N}+(A_1^2+\Omega^2)\{S_{F\Delta A}+[b/(1+a)]^2S_{F\phi}\}+[E_{cv}+E_{vc}+1/\tau_p]A_1\eta/\tau_{st})+\tfrac{1}{2}\,, \quad (4)$$

where $\eta=1-b\alpha/(1+a)$, and $A_1=-(1/\tau_n+1/\tau_{CR})$. The main contribution from optical feedback is the mixing in of a small fraction of the phase noise $[b/(1+a)]^2S_{F\phi}$ to $S_{F\Delta A}$.

The measured amplitude-noise spectral density versus laser driving current, at three frequencies near 300 MHz, is shown in Fig. 3. The measured noise has been

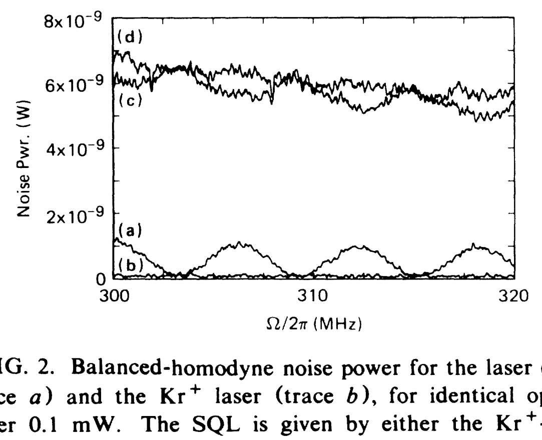

FIG. 2. Balanced-homodyne noise power for the laser diode (trace a) and the Kr^+ laser (trace b), for identical optical power 0.1 mW. The SQL is given by either the Kr^+-laser noise (b), or the minimum of the "ripple signal" (a). The maxima in trace a at $\Omega_s\simeq307$, 313 MHz, etc., indicate noise in excess of the SQL. Trace c is for the diode laser far above threshold ($r=40$) while trace d is for the Kr^+ laser at the same optical power. The amplitude fluctuations of the diode laser are clearly below the SQL. The resolution bandwidth of the spectrum analyzer was 300 kHz.

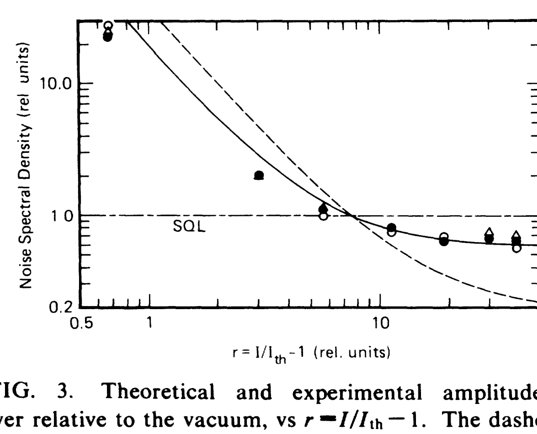

FIG. 3. Theoretical and experimental amplitude-noise power relative to the vacuum, vs $r=I/I_{th}-1$. The dashed line is a theoretical estimate ignoring effects of optical feedback, and the solid line is our theory. The open circles, filled circles, and triangles correspond to the rf noise frequencies $\Omega_s=307$, 313, and 319 MHz, respectively.

corrected for light-collection efficiency and loss through the rear facet. The dashed line is the theoretical estimate in the absence of feedback and the solid line is the result of our theory. Numerical values for parameters not given above are $\theta \simeq 212°$, $n_{sp} = 1$, $\alpha = 1.1$, and $\kappa\tau = 0.42$ with τ estimated as $\tau = 6.5$ nsec. The value for $\kappa\tau$ is realistic for our experimental arrangement; however, it was chosen to give the best fit to our data. The phase of the feedback field varies with driving current and also depends on the mechanical stability of the apparatus. If the phase that yields the maximum noise is assumed, then the predicted amplitude noise is more than 15 dB above the measured value for low pumping currents and for realistic values of $\kappa\tau$. Since this was not observed, we suspect that for our data runs, the feedback phase was usually out of phase with the internal field, and the value given is from a range of values that give a reasonable fit.

In conclusion, a reduction of 0.8 dB in the amplitude fluctuation of light at the front facet of a semiconductor laser has been observed. A theory which includes the effects of optical feedback yielded values which compared favorably with experimental results.

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