Squeezed Photon-Number Noise and Sub-Poissonian Electrical Partition Noise in a Semiconductor Laser

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(Received 26 February 1991)

Amplitude noise on the light from a semiconductor laser produced a photocurrent fluctuation spectrum that was a maximum of 85% (-8.3 dB) below the shot-noise limit. Squeezing in semiconductor lasers is not limited by the overall quantum, or current transfer, efficiency from the laser injection current to the detector photocurrent. Current leakage away from the lasing junction does not introduce Poissonian partition noise.

PACS numbers: 42.50.Dv

Photon-number eigenstates or Fock states of the electromagnetic field appear to be ideal for optical communication[1,2] and for a variety of high-precision measurements.[3] It has been shown theoretically[4] that the amplitude fluctuation on the field from a pump-noise-suppressed laser can be reduced to below the standard quantum limit (SQL). In the case of a semiconductor laser, the pump noise is suppressed by a high-impedance constant-current source. Light from constant-current-driven semiconductor lasers featuring squeezed amplitude fluctuation has been demonstrated.[5,6] However, the modest degree of squeezing observed was ascribed to various deficiencies associated with the measurement system. In this experiment, we were able to reduce the effects of optical feedback from the measurement system, and increase the light collection efficiency by direct "face-to-face" coupling of the laser and detector. Consequently we improved the noise reduction and further elucidated the basic physical processes that affect the noise properties of the device. The spectrum of photocurrent fluctuation was measured to be $85^{+3}_{-7}\%$ below the shot-noise limit (SNL). Given that the detection quantum efficiency was approximately 89%, this corresponds to a squeezed amplitude fluctuation (at the front facet) of 96% (-14 dB) below the SQL. This is by far the largest quantum noise reduction observed in any experiment;[7] and it represents the closest approach so far to a number state. Apparently, amplitude squeezing in semiconductor lasers is not limited by the overall quantum efficiency but only by the optical output coupling efficiency. An explanation of this unexpected result is that current division does not introduce Poissonian partition noise, in contrast to the Poissonian partition noise associated with optical field division.[8]

Quadrature fluctuations of a number state, $\Delta X_1^2 = \Delta X_2^2 = (2n+1)/4$, are larger than the vacuum noise floor. This is in contrast to a quadrature squeezed state, which is a minimum-uncertainty state, where the fluctuation in the quadrature with reduced noise (X_1 for example) is below that of the vacuum ($\Delta X_1^2 \leq \frac{1}{4}$). The field from a semiconductor laser is not in a minimum-uncertainty state; more importantly, the photon-number fluctuation may approach that of a number state. Removal of the residual noise or reduction to a number state, on detection, requires that all the spontaneous emission be fed into the lasing mode, and the output field be referred to a measurement of the junction voltage.[9]

The basic experimental arrangement is shown in Fig. 1. Measurement of the phase-dependent noise reduction (a characteristic of squeezed states), in general, requires homodyne detection. On the other hand, sub-Poissonian photon-number fluctuation can be verified by direct detection. The apparatus is mounted on a single copper block and cooled to roughly 66 K. Two identical silicon *p-i-n* detectors (NEC NDL2208) were arranged in a balanced configuration.[10] In order to minimize the deleterious effect of optical feedback on the amplitude noise, the front facet of the Mitsubishi TJS laser (ML 3308) was placed less than 2 mm from the surface of the detector. This "face-to-face" coupling arrangement of laser and detector also allowed a high light collection efficiency. A light-emitting diode (LED) (NEC NDL4105A) was similarly positioned facing the other detector. Reflectivity of the front facet of the laser ($\mathcal{R}_1$) was less than 3% and that of the rear facet ($\mathcal{R}_2$), more than 90%. The laser external differential quantum efficiency at 66 K was 0.57 (slope efficiency 0.88

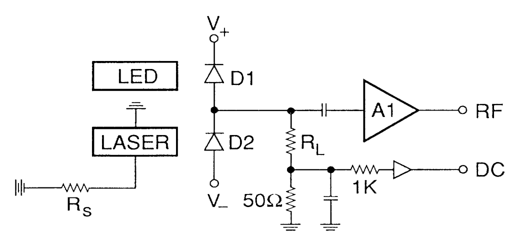

FIG. 1. The principal elements of the experimental apparatus that were inside the cryostat. The power spectrum of the amplified photocurrent is displayed on a spectrum analyzer (not shown), and the average detector current is monitored at the output labeled dc.

mW/mA and wavelength $\lambda = 0.786$ μm) and the threshold current was 0.45 mA. At driving currents far above the threshold, the overall quantum efficiency [(detector current)/(laser current)] was 0.48. Amplifier A1 was a homemade device based on packaged GaAs MMIC (microwave monolithic integrated circuits). The gain was 18 dB from 50 MHz to 2.5 GHz, and the noise figure was estimated to be less than the room-temperature value of approximately 3 dB. Typically the photocurrent spectra associated with an average current of 1 mA from the LED were 4 dB above the dark level for frequencies between 20 and 200 MHz.

The identical response of the two detectors, which is crucial for accurate comparison of the laser and LED noise levels, was confirmed in several ways. On replacing the laser with an LED, the photocurrent spectra due to two LEDs were found to be identical to within 0.2 dB. A common mode suppression ratio of 18 dB was measured by illuminating both detectors (after removing the LED and laser) with beams from a modulated Hitachi HLP1400 laser and beam-splitter combination.

We equated the SNL with the photocurrent spectrum due to the LED. However, a current transfer efficiency [(detected current)/(LED drive current)] of approximately 10% indicted that the LED noise level may even have been lower than the actual SNL.[11] Linearity of the LED noise power versus detector current (I_d) was confirmed for I_d below 7 mA, at $\Omega/2\pi = 100$ MHz. At detector currents above 7 mA, the rf response of the detector gradually saturated.

Typical photocurrent spectra that illustrate the squeezing of the amplitude noise are shown in Fig. 2.

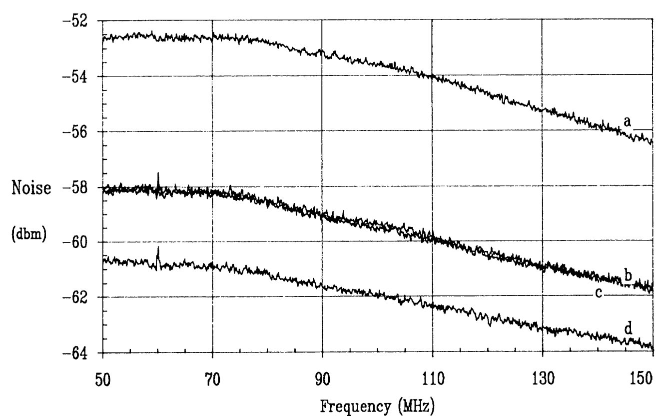

FIG. 2. Amplitude fluctuation spectra of the laser field (traces b and c) and LED (trace a) for identical detector currents of 8.6 mA. The laser is either coupled to a different detector (trace b) or to the same detector (trace c) as the LED. Trace d is the amplitude noise at a higher pump level, and the corresponding detector current was 11.3 mA. In this case the shot-noise level was also set equal to trace a. The thermal background noise was subtracted from all of the traces.

Manipulation of the data consisted solely of the subtraction of the dark level from all the traces. Traces a, b, and c were recorded for identical detector currents of $I_d = 8.6$ mA. Trace a is the noise level due to the LED, while traces b and c are those due to the laser. On recording the noise level due to a particular device, the drive current to the other device was turned off. The SNL was 14 dB above the dark level. For traces a and b, the laser and LED were coupled to different detectors and the laser was biased at $r \equiv I/I_{\text{th}} - 1 = 39$. For trace c, the laser was coupled to the same detectors as the LED and the bias level was $r = 41$. The difference in the pump rate between traces b and c was due to a small difference in the light collection efficiency. The same noise levels of b and c support the identical responses of the two detector channels. The amplitude noise is at least 5.6 dB below the SNL. Trace d is the laser noise at a higher pump rate $r = 52$. At this pump level I_d was 11.3 mA, the estimated output power was 14 mW, and trace a was also taken as the shot-noise level. The reduction of the amplitude noise was 8.3 dB below the SNL. Taking the detector quantum efficiency into account, the noise reduction at the laser front facet was 14 dB below the SNL. Even though the detector starts to saturate at a photocurrent $I_d \simeq 7$ mA, the linear response for a small fluctuating signal is still preserved. This was confirmed by detecting the rf-modulated output from a laser that was biased at a high pump level. This suggests that the difference between the laser noise and LED noise is accurate, in spite of the detector saturation. If the saturated rf response of the detector to the laser field is not identical to that from the LED, owing, for example, to the more directional character of the laser beam, then some correction is expected.

Given that the overall quantum efficiency from the laser injection current to the detector photocurrent was 0.48, amplitude squeezing of more than 3 dB would be impossible if all the loss processes introduce a Poissonian partition noise. An explanation of our counterintuitive result starts with Fig. 3. The TJS laser is known to have a nonlasing junction in parallel with the lasing junc-

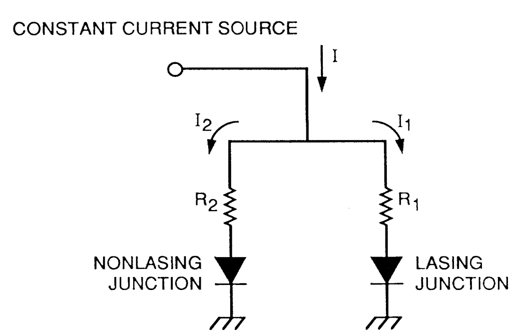

FIG. 3. A model for current division into a lasing junction and a nonlasing junction.

tion.[12] In general, current division probably does not introduce Poissonian noise because current flow in an open channel is not quantized. Recently, the observation of continuous charging of a capacitor in increments of charge less than e, and the discharge of that capacitor in increments of e, was observed in mesoscopic systems.[13] A dividing current in a solid naturally encounters barriers, abrupt changes in the Fermi level. The flow of current, and noise on the dividing current, is probably not determined by the quasirandom passage of an individual electron but by the sea of electrons below the Fermi level. In the case shown in Fig. 3, the current from a high-impedance constant-current source is split into the two junctions. This introduces a new noise source, which serves as a pump noise for the lasing junction. When the noise of the total current I is suppressed completely by a high-impedance constant-current source, the low-frequency current noise of the divided currents I_1 and I_2 are calculated by Kirchhoff's law as

$$i_1 = -i_2 = \frac{v_2 + v_{d2} - v_1 - v_{d1}}{2(R+R_d)} . \tag{1}$$

Here it is assumed for simplicity that the two series resistances are equal, $R_1 = R_2 = R$, and the differential resistances of the two junctions are also equal, $R_{d1} = R_{d2} = R_d$. Therefore, $I_1 = I_2 = I/2$. v_i and v_{di} are the voltage noise sources associated with the series resistance R and differential resistance R_d. The spectra of v_i and v_{di} are given by $S_{v_i} = 4k_BTR$ and $S_{v_{di}} = 2e(I/2)R_d^2 = 2k_BTR_d$, where $R_d = 2V_T/I$ and $V_T = k_BT/e$ (Ref. 4). The spectra of i_1 and i_2 are given by

$$S_{i_1} = S_{i_2} = \frac{k_BT(2R+R_d)}{(R+R_d)^2} \simeq \begin{cases} 2k_BT/R & (R \gg R_d), \\ \frac{1}{2}eI & (R \ll R_d). \end{cases} \tag{2}$$

If $R \ll R_d$, the current noise is only -3 dB below the shot-noise level. This is analogous to 50%-50% beam splitting of a number-state photon flux. The quantum-noise-limited partition noise destroys the quantum squeezing whenever there is a loss. However, if the series resistance R becomes much larger than the differential resistance R_d, the current noise spectrum $2k_BT/R$ can be negligible compared with the shot-noise level eI. The above condition is satisfied at a high current level $I/2 \gg V_T/R$ for whatever small series resistance R. In this way, the (classical) squeezing of electrical currents is not destroyed by the thermal-noise-limited partition noise.

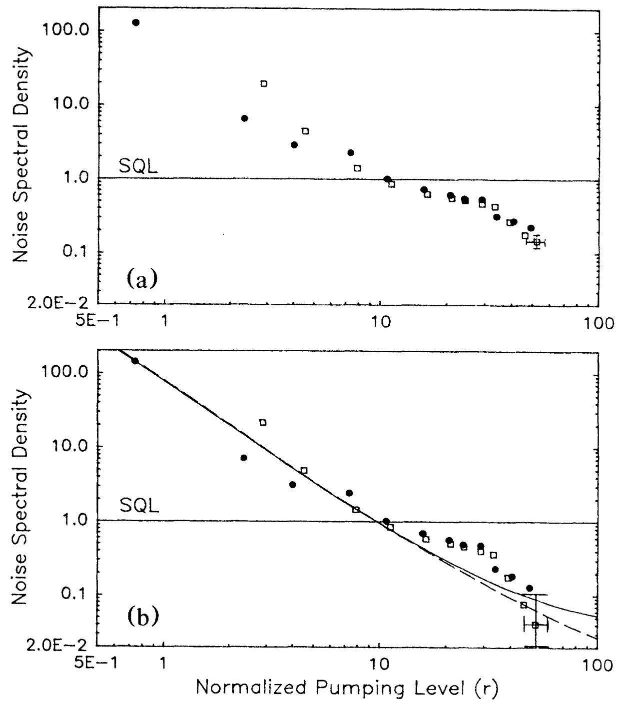

FIG. 4. Normalized amplitude fluctuation spectral density at 100 MHz vs the normalized pump rate. Solid circles are for the LED and laser coupled to the different detectors, while the open squares are for the laser and LED coupled to the same detector. (a) The measured noise (normalized photocurrent spectra). (b) The noise at the laser front facet. Solid and dashed lines are theoretical estimates. If $R_1 = 0.01$ and $R_2 = 0.99$, then the theoretically minimum noise level is 2×10^{-3}.

A comparison between the theoretical normalized amplitude fluctuation power spectrum $S_{\Delta r}$ and experimental results before and after correcting for detector quantum efficiency are shown in Figs. 4(a) and 4(b). The expression for $S_{\Delta r}$ is given by[4]

$$S_{\Delta r} = 1 + 2\tau_{pe}^{-1}[A_3^2 S_{FN} + (\Omega^2 + A_1^2)\tau_p^{-1} + 4A_1A_3A_0 n_{sp}\tau_p^{-1}]/\{[\Omega^2 - (\tau_p\tau_{st})^{-1}]^2 + \Omega^2 A_1^2\} , \tag{3}$$

where $A_1 = -(\tau_{st}^{-1} + \tau_{sp}^{-1} + \tau_{CR}^{-1})$, $A_3 = 1/2A_0\tau_{st}$, and

$$S_{FN} = 2A_0^2\tau_{st}\tau_p^{-1}[1/\tau_p + (2n_{sp}-1)/\tau_{st} + 1/\tau_{CR}] .$$

Other parameters are the photon lifetime τ_p, the output coupling rate τ_{pe}^{-1}, the stimulated emission lifetime $\tau_{st} = \tau_{sp}/n_{sp}r$, the pump circuit CR time constant τ_{CR}, and the number of photons in the cavity A_0^2. Estimates of the population inversion parameter $n_{sp} = 1.1$ and series resistance $R = 50\ \Omega$ were used. To fit the noise at a low pump rate, the spontaneous emission lifetime τ_{sp} was taken as 10 ns. At 66 K the estimated internal absorption was negligible compared to the output coupling rate. The solid line was obtained using the manufacturer's quoted upper limit on $\mathcal{R}_1 = 0.03$, and the lower limit on the rear facet reflectivity $\mathcal{R}_2 = 0.90$, while $\mathcal{R}_1 = 0.01$ and $\mathcal{R}_2 = 0.99$ were assumed for the dashed curve. The maximum squeezing is approximately equal to the lower limit on the output coupling efficiency

$$\eta_{oc} = \frac{\ln(1/\mathcal{R}_1)}{\ln(1/\mathcal{R}_1\mathcal{R}_2)} \simeq 0.97 .$$

Deviation of the measured noise from the theoretical values at $r \simeq 30$ is due to either weak optical reflection feedback[6] or longitudinal mode hopping. If the phase of the reflected light is in quadrature with that of the cavity field, then the amplitude noise is increased. This is because a fraction of the phase noise is converted into amplitude noise. The phase of the feedback light changes with drive current, because the laser frequency varies with the drive current. Longitudinal mode hopping may also occur at specific driving currents; an increase in the amplitude noise, above the squeezed level for a single mode, is expected because both modes are operating at an effectively lower pump level. Small differences in noise levels and pump rates for data collected with opposite detectors, for the same detector current, are seen in Fig. 4. Those disparities are due to the difficulty of obtaining identical alignment of the laser with each detector, and optimum coupling in each case.

The error bar in the laser noise level is due to the uncertainty in the detector quantum efficiency, the small nonlinearity of the detector rf response, and the uncertainty in the SQL. Uncertainty in the threshold current, and the nonlinearity of the laser differential quantum efficiency, determined the error bar in the pump level. These errors are most pronounced at high current levels, and when the degree of squeezing approaches the detector quantum efficiency. Worst-case error bars are shown in Fig. 4. At pump levels below $r \simeq 10$, the error bars are on the order of the graph symbol. Uncertainty in the theoretical curve is due to the uncertainty in R and τ_{sp}. Our experimental results are in good agreement with the theoretical curve, in which the thermal-noise-limited electrical partition noise is taken into account. The most surprising point about the observation of amplitude squeezing reported previously[5,6] was that the pump current noise of a semiconductor laser does not carry the full shot noise. The most surprising point about the observation of more than 10 dB squeezing reported here is that the electrical current division does not introduce a Poissonian partition noise. This result illuminates the interesting issue of electron correlation during transport[14] and division, and motivates further investigation into the applicability of Kirchhoff's current law in the quantum regime.

W. Richardson expresses his gratitude to the many individuals at NTT, whose graciousness contributed enormously to his inspiring one year stay in Japan. W.H.R. is the Ichiban NTT Post Doctoral Fellow.

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