Squeezed Light from Injection-Locked Quantum Well Lasers

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Measurements based on balanced detection demonstrate more than 3 dB photon-number squeezing from a quantum well laser injection locked to a coherent signal. We show that injection locking significantly reduces the photon-number fluctuation by suppressing weak side modes that feature intensity noise far above the standard quantum limit. The measurements also reveal that the photon statistics vary qualitatively with the polarization of the laser field.

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It is now well established that squeezed light featuring macroscopic quantum effects can be generated in the laboratory and used for optical measurements with sensitivities beyond the standard quantum limit (SQL) set by the vacuum or zero-point fluctuation [1]. Light exhibiting fluctuations below the SQL in one quadrature amplitude has been produced through phase sensitive nonlinear optical processes such as four wave mixing and parametric down-conversion [1]. A conceptually different approach, which uses constant-current-driven diode lasers [2–4] or light emitting diodes [5,6], has generated photon-number squeezed light characterized by intensity noise below the SQL. In this scheme, the sub-Poissonian pumping statistics of the electron current are converted directly into nonclassical photon statistics. Balanced detection measurements of transverse junction stripe (TJS) lasers have demonstrated up to 1.5 dB of photon-number squeezing [2], while recent work close coupling a TJS laser and a detector reported photocurrent noise 8.3 dB below the SQL [4].

It has also been suggested recently that the nonclassical photon statistics of a diode laser can be converted into squeezing of a quadrature amplitude. Theoretical calculations have shown that phase locking a photon-number squeezed diode laser through external feedback can lead to nonclassical quadrature noise reduction [7]. Alternatively, injection locking the diode laser into a coherent signal may also lead to generation of quadrature amplitude squeezed light [8].

This paper reports studies of nonclassical statistics of injection-locked diode lasers. We demonstrate more than 3 dB photon-number squeezing in balanced detection measurements from an injection-locked quantum well laser. We show that injection locking significantly reduces the photon-number fluctuation by suppressing weak side modes (20 to 30 dB weaker than the main mode prior to injection locking) that contribute significantly to the intensity noise. Furthermore, the polarization dependence of the intensity noise reveals that photons polarized perpendicular to the main laser polarization feature fluctuations 8 dB above the SQL. The observed dependence also reflects quantum interference between the squeezed and the noisy components. These results show that multimode behavior, which has been largely ignored, is essential in understanding fluctuations in diode lasers and suggest that the photon statistics are closely related to carrier scattering and spin dynamics of the gain medium.

For these measurements we have used a quantum well laser from Spectra Diode Labs (SDL-5410-C). The laser and a collimating lens are held in a closed-cycle cryostat [9]. At 10 K the threshold current for the laser is 0.8 mA and the differential quantum efficiency is 78%. We measure the photon-number fluctuations and the SQL using the standard balanced detection technique [10]. An electronic relay is used to switch synchronously between the add and subtract signal from the balanced mixer during the data acquisition [11]. The SQL is also independently calibrated using a filtered white light source. Large area photodetectors (1 cm^2) with quantum efficiencies better than 97% are used to avoid detector saturation. The overall detection efficiency including optical losses and detector efficiency is near 80%.

The output from a frequency stabilized dye laser with a spectral width of 3 MHz is used as the coherent injection signal. The output is also attenuated more than 20 dB to suppress excessive noise above the SQL (see Fig. 1 for the experimental setup). Typical injection power is 2 mW with an injection efficiency of order 10%. We then monitor the output of the diode laser using a scanning Fabry-Pérot interferometer. When the laser is injection locked, the frequency of the laser output follows exactly the frequency of the injection signal within the locking bandwidth which is of order 10 GHz depending on the injection power and frequency.

Figure 2(a) shows the power spectrum of the photo-

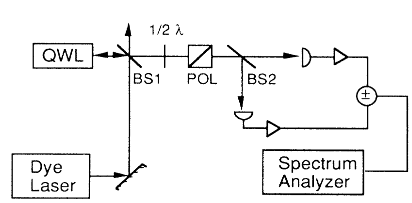

FIG. 1. Experimental setup. QWL, quantum well laser; POL, polarizer; BS1, 2% beam splitter; BS2, 50% beam splitter; $\frac{1}{2}\lambda$, half-wave plane.

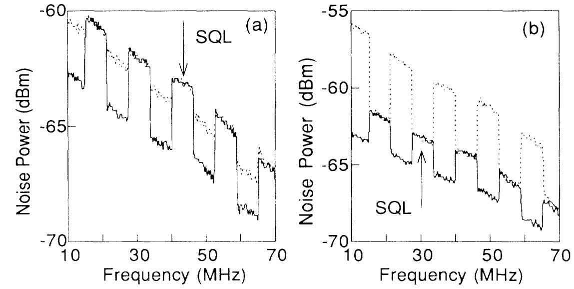

FIG. 2. Power spectra for photocurrent fluctuation at (a) 10 K and (b) 78 K. Solid and dashed lines are obtained with and without injection locking, respectively.

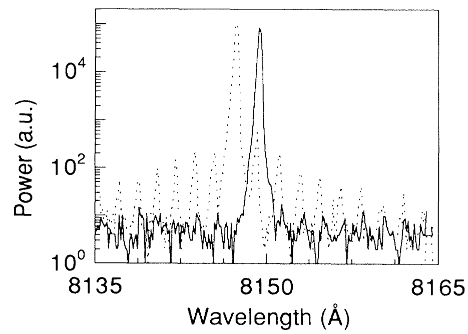

FIG. 3. Laser emission spectra at 78 K. Solid and dashed lines are obtained with and without injection locking, respectively.

current fluctuation when the laser is held at 10 K and is biased at 27.5 mA. The injection current to detector current conversion efficiency is 60%. The data shown are corrected for the thermal noise of the electronics. The photocurrent noise is nearly 1 dB below the SQL with the free-running laser and is more than 3 dB below the SQL when the laser is injection locked. Figure 2(b) shows the power spectrum of the photocurrent fluctuation when the laser is held at 78 K and is biased at 22 mA (the threshold current is 2.8 mA). Without injection the photocurrent noise is 5 dB above the SQL. The noise is reduced to 2 dB below the SQL when the laser is injection locked. Similar results with nearly 1 dB squeezing are also obtained at room temperature. The large reduction in the photon-number fluctuation when the laser is injection locked is not expected from a single-mode analysis [8,12]: For a single-mode laser biased well above the threshold, the intensity noise of the laser is expected to remain approximately the same after injection locking to a weak shot-noise-limited signal except at frequencies approaching zero. Near zero the intensity fluctuation cannot go to zero (assuming no pumping noise) because the phase fluctuation of an ideally injection-locked laser cannot go to infinity [8,12].

The underlying physical origin for noise reduction through injection locking can be understood by comparing the longitudinal mode behavior of the laser emission. Figure 3 displays both the free-running and injection-locked emission spectra obtained with the same experimental condition as in Fig. 2(b). As shown in the figure, injection locking suppresses side mode power by more than 10 dB.

To understand the above results, we first discuss photon-number fluctuations in a single-mode laser. When the laser is biased well above the threshold, the primary contribution to the intensity noise of the laser output comes from the pumping fluctuation below the cavity bandwidth and the reflected vacuum fluctuation above the cavity bandwidth [13,14]. The contribution to intensity noise from fluctuations associated with the stimulated transition (dipole moment fluctuation) can be completely suppressed by gain saturation. With shot-noise-limited pumping, the intensity noise of the laser output is also shot noise limited (or at the SQL) as is well known in the early studies [15]. The intensity noise can drop below the SQL within the cavity bandwidth with regular or sub-Poissonian pumping [13,14]. When the laser is biased very close to the threshold, the absence of strong gain saturation leads to intensity noise far above the SQL [14].

In the case of multilongitudinal modes in a homogeneously broadened gain medium, the cross-mode gain saturation is important because all the modes couple to the same electron and hole population. Complete gain saturation can only be achieved for the *total* photon number and the total gain when the laser is biased well above the threshold and the cavity loss is the same for all the longitudinal modes [16]. Hence, with regular pumping, the fluctuation in the *total* photon number can become well below the SQL while the intensity noise for each *individual* longitudinal mode is typically far above the SQL [16]. We note that the present theoretical analysis has not included effects of population pulsation on photon statistics.

However, in an inhomogeneously broadened gain medium, each longitudinal mode couples independently to the respective electron-hole population. In this limit, the weak side modes that are close to threshold exhibit photon-number fluctuations far above the SQL (more than 20 dB) as discussed above. As a result, the *total* photon-number fluctuations can be well above the SQL, while, in the absence of current partition noise [4], the *individual* mode biased well above the threshold can still feature intensity noise below the SQL, in contrast to the result for a homogeneously broadened system.

Gain saturation in a constant-current-driven diode laser is more complicated than a simple inhomogeneously broadened system because of the fast intraband carrier-carrier scattering. This scattering process drives the electron and hole population towards a quasiequilibrium Fermi-Dirac distribution. In particular, in the limit that the intraband scattering time is much shorter than the stimulated transition and cavity lifetime, the carriers can be considered to be in a Fermi-Dirac distribution (no hole burning). The laser then behaves like a homogeneously broadened system discussed above; that is, all the longitudinal modes interact with the same electron-hole distribution. Detailed theoretical analysis that considers the intermediate regime where the carrier scattering does not lead to complete cross-mode saturation has yet to be developed.

The meaning of Figs. 2 and 3 is now evident. The side modes in the free-running laser are more than 20 dB weaker than the main mode and are very close to threshold. These side modes contribute significantly to, and often overwhelm, intensity fluctuations of the laser output, which is also likely the reason why photon-number squeezed light has only been observed in very few types of diode lasers. Suppressing these side modes through injection locking can significantly reduce the *total* photon-number fluctuation.

While it is difficult to probe the photon-number fluctuation of an individual photon mode with a given wave vector without introducing significant loss, we can readily measure the fluctuation of photons with a particular polarization direction. Since the polarization extinction ratio of the laser output after the collimating lens is nearly 100, we assume that the laser field has two orthogonally polarized components. The two components experience different cavity loss and because of the selection rule couple to different electron-hole populations. Intensity fluctuations of the weak polarization component are then expected to be similar to those of longitudinal side modes; namely, the weak component may feature intensity noise far above the SQL due to incomplete gain saturation. In addition, similar to the effect of intraband carrier scattering discussed above, spin relaxation much faster than the stimulated transition time can also lead to partial suppression of the intensity noise due to the dipole moment fluctuation through cross-mode gain saturation.

The polarization dependence of the photon-number fluctuation is obtained by using a combination of a half-wave plate and a polarizer (fixed s polarized) in front of the beam splitter BS2 as shown in Fig. 1. The photocurrent power spectra shown in Fig. 2 are obtained when we adjust the half-wave plate such that near maximum transmission through the polarizer is achieved. Changing the laser polarization by rotating the half-wave plate leads to an attenuation of the laser power incident to the balanced detection setup. Figure 4 shows the corresponding experimental results. For these measurements, the injection-locked laser is held at 10 K and is biased at 15 mA. The intensity noise of the free-running laser is nearly 2 dB above the SQL. The circles are the shot-noise calibration and the dashed line is a fit to the linear relationship between the shot-noise level and the total detector current. The fit shows the excellent linearity of the detection system. The squares are the noise power of the sum current. The relative intensity fluctuation increases

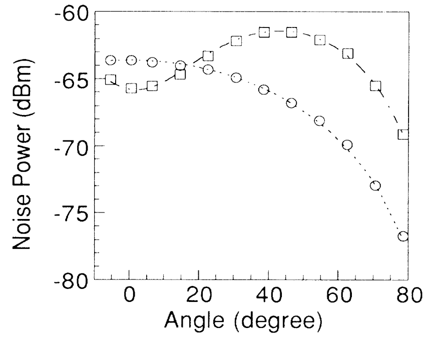

FIG. 4. Polarization dependence of the intensity noise at 10 K. The data were taken around 17 MHz from photocurrent power spectra. Circles and squares represent fluctuations of the difference and sum current of the balanced mixer, respectively.

with increasing attenuation to well above the SQL.

The angle dependence in Fig. 4 can be attributed to effects of quantum interference between the two orthogonally polarized components. The intensity fluctuation of the incident field, described by

$$a = a_1 \cos\theta + a_2 \exp(i\phi) \sin\theta ,$$

is given by the well known result for homodyne detection [17]

$$\frac{\langle(\Delta m)^2\rangle}{\langle m\rangle} = \frac{\langle(\Delta n_1)^2\rangle}{\langle n_1\rangle}\cos^2\theta + 4\langle(\Delta E_2)^2\rangle \sin^2\theta , \qquad (1)$$

where a_1 and a_2 are annihilation operators for the main and weak polarization components, respectively, θ is the angle between directions of the polarizer and the primary laser polarization, $m = a^\dagger a$, $n_1 = a_1^\dagger a_1$, E_2 is defined as

$$E_2 = \tfrac{1}{2}\{a_2 \exp(i\phi) = a_2^\dagger \exp(-i\phi)\} , \qquad (2)$$

with ϕ being the phase difference between the two components, and we have also assumed

$$|\langle a_1\rangle \cos\theta| \gg |\langle a_2\rangle \sin\theta| .$$

$\langle(\Delta E_2)^2\rangle$ represents the fluctuation of the in-phase quadrature of the weak polarization component. With vacuum input as E_2, we have $\langle(\Delta E_2)^2\rangle = \frac{1}{4}$ and recover the well known result of intensity fluctuations for an attenuated beam. The dot-dashed line in Fig. 4 shows the excellent agreement between the theory and the observed angle dependence. The intensity noise for the main polarization component is 2.2 dB below the SQL while the in-phase quadrature fluctuation for the weak component is 8 dB above the SQL.

The above interpretation is further confirmed by measuring the total photon-number fluctuation. The intensity noise obtained after removing the polarizer is very close to that with the polarizer present with $\theta = 0°$. For free-running lasers the angle dependence of the intensity fluctuation deviates from that described by Eq. (1) due to contributions from multiple longitudinal modes. We also note that quadrature fluctuations do not necessarily reflect properties of the intensity fluctuation. However, intensity noise 8 dB above the SQL is observed with θ very close to 90° where contributions to the intensity noise from the main polarization component are relatively small.

The relatively small polarization extinction ratio for the laser output is primarily due to the birefringence of the collimating lens induced at low temperature. The extinction ratio obtained after removing the collimating lens is better than 200. The induced birefringence can degrade the squeezing level of the main polarization component by mixing the squeezed component with the noisy component. This interference and polarization dependent loss in the detection system may explain why the squeezing level obtained has not reached the limit set by the overall current conversion efficiency.

In conclusion, we have demonstrated that injection locking can qualitatively modify the photon statistics of a diode laser by suppressing weak side modes that feature intensity noise far above the SQL. Our measurements clearly indicate that multimode behavior, including effects due to different polarization components, is essential in understanding the photon statistics of a diode laser. Photon-number squeezed light from injection-locked diode lasers can provide a convenient *tunable* nonclassical source for quantum optical spectroscopy [18]. Injection locking a number of lasers to the same or different wavelengths can also provide new avenues for studies of quantum correlation between these nonclassical sources [19]. Finally, we note that since this paper was submitted for publication, a theoretical discussion and demonstration of 0.91 dB of squeezing was presented by Inoue *et al.* [20].

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