Quantum Correlated Light Beams and Sub-Poissonian Electrical Partition Noise in Parallel and Series Coupled Semiconductor Light Emitters

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Quantum correlated twin beams have been generated using series and parallel coupled light emitting diodes. Furthermore, sub-Poissonian light, with a noise level 1.4 dB below the standard quantum limit, has been measured in both circuits. From the parallel coupled setup it could be deduced that electrical partition noise may be made negligible.

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It has been known for some time that the low frequency intensity noise of high quantum efficiency lasers and light emitting diodes (LED's) is caused by pump noise [1–3]. The best nonclassical intensity noise reduction to date in any system, 10 dB below the standard quantum (shot noise) limit (SQL) [4], and very broadband 1.7 dB squeezing over 1.1 GHz [5] have all been obtained using pump-noise suppressed semiconductor lasers.

Recently it was predicted [6] that the intensity fluctuations of two series coupled laser diodes or LED's may be highly correlated, and that by using the information in one laser beam the intensity noise of the second beam can be manipulated to go below SQL (sub-Poissonian). Such intensity correlated photon beams, "twin beams," are useful to increase the sensitivity of measurements involving photoabsorption, such as absorption spectroscopy [7–9]. So far, twin beams have mainly been generated by optical parametric frequency down-conversion. However, the small nonlinear coefficients in present crystal materials impose a serious trade-off between output power and bandwidth. The best parametric oscillators for twin beam generation today have a cavity bandwidth only of about 20 MHz [9, 10]. Compared to parametric down-conversion, schemes based on semiconductor light emitters may offer several advantages in terms of the freedom in choice of wavelength, broad bandwidth, and compactness of laser diodes and LED's. Furthermore, one is offered the possibility to generate not just two, but any number of correlated light beams [6].

In this work we have studied the twin beam properties of series and parallel coupled LED's. In addition, parallel coupled light emitters enable a study of the electrical partition noise occurring in current division [11]. Recently, the absence of partition noise inside a laser diode was used to explain an observed 10 dB intensity noise reduction below the SQL, despite the current-to-light transfer efficiency being only 50% [4, 12]. Our scheme allows a direct test of this assertion.

Our squeezing and correlation experiments have been made at a wavelength of 890 nm and at a temperature of 77 K, using high quantum efficiency ($\eta_d > 0.3$ at 77 K) light emitting diodes (Hamamatsu L2656) and Siemens BP104 and BPY12 photodiodes in a setup schematically illustrated in Fig. 1. The sum and the difference of the photocurrents I_{P1} and I_{P2} were formed by means of a Tektronix 7A26 differential amplifier, which was connected to a microwave spectrum analyzer. Each noise term could also be measured individually by attenuating the other signal by more than 60 dB. The normalized correlation was computed from the measured spectra using the same technique as described in Ref. [13].

An advantage using LED's compared to laser diodes is that one avoids excess noise due to spurious optical feedback. However, the quantum efficiency and the squeezing bandwidth are lower. In this experiment the squeezing bandwidth was limited by the LED's which had a cutoff in the current modulation response at about 0.5 MHz.

The intensity noise and correlation for series and parallel coupled diodes were investigated by switching between series and parallel coupling using an electrically controlled microswitch, and between a noise suppressed "constant" current and a "shot-noise" limited current. The constant current was generated using a high-impedance current source [4, 5]. The shot-noise current was generated by a photodiode illuminated by a weakly coupled LED (inside the dotted box in Fig. 1), which in turn was driven by a high-impedance current source. The current-to-current quantum efficiency η_g in this case was low, 12%, resulting in a nearly shot-noise

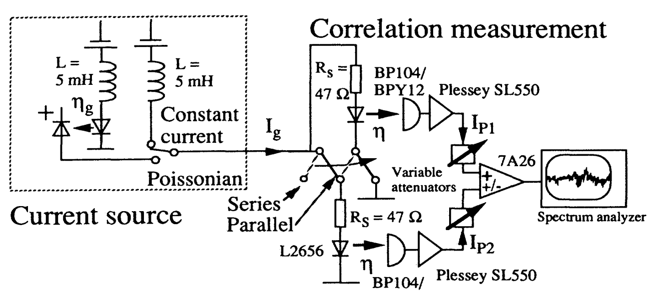

FIG. 1. Schematic picture of the experimental setup.

limited photocurrent from the photodiode.

For a LED coupled to a photodiode with quantum efficiency η, the intensity noise relative to the standard quantum limit F_P (i.e., the photocurrent Fano factor) may be written [14]

$$F_P = \eta F_g + (1 - \eta) \ , \quad (1)$$

where F_g is the Fano factor of the driving current.

Assuming a perfectly regular driving current, the Fano factor F_P of the photodiode would be $1-\eta$. Applying (1) on the shot-noise generating LED and photodiode system (inside the dotted box in Fig. 1), the Fano factor of generated current is found to be $1 - \eta_g$. In our specific case we get $F_g = 0.88$, based on $\eta_g = 0.12$. In the following we will refer to this current as shot-noise limited current although both theory and experiments (see below) confirm that the current is slightly sub-shot-noise.

Driving the series coupled LED's with the shot-noise limited current and detecting the emitted light from one of them with an efficiency η, (1) gives the detector photocurrent Fano factor $F_P = 1-\eta\eta_g \approx 0.99$ when $\eta = 0.11$. To calibrate the SQL we compared the measured noise spectral density with that of a tungsten halogen white-light source, whose emission was filtered to the same wavelength band as the emission of the LED. The noise levels at equal photocurrents agreed to within 1% for the two sources.

When the constant current source was used, the photodetector Fano factor is ideally $F_P = 1 - \eta$. To check that our high-impedance source really generated a constant current, F_P of one of the LED's was measured at various LED-to-photodetector coupling efficiencies. The coupling was varied by inserting neutral density filters between the LED and the detector. The measured points for three different driving conditions are plotted in Fig. 2. The three solid lines represent $F_P = 1 - \eta$ (constant current with $F_g = 0$, lower line, solid squares), $F_P = 1 - 0.12\eta$ (shot-noise limited current with $F_g = 0.88$, middle line, solid triangles), and $F_P = 1 + 155\eta$ (modulated current with $F_g = 156$, upper line, open triangles). All data were taken at a photodiode current of 1.8 mA in a narrow frequency interval around 200 kHz. In the case with excess current noise (an externally impressed modulation), care was taken to keep the current Fano factor constant when varying the driving current to compensate for the varying η. In the plot, measured with the BPY12 detectors, a 28% (−1.4 dB) noise reduction could be observed when $\eta = 0.31$ (no neutral density filter). In the ideal case theory predicts a 31% (−1.6 dB) reduction.

In the series coupling setup, the current through both the diodes is the same, and the normalized correlation C between the intensity noise from the respective diodes is equal to

$$C = \frac{\eta F_g}{\eta F_g + (1 - \eta)} \ . \quad (2)$$

In the parallel coupled case, the driving current is divided by a factor of 2 (for symmetrical splitting). However, as in the case of optical beam splitting, there is an additional negatively correlated partition noise term. As was shown in [12] for macroscopic electrical currents, the partition noise is simply, referring to Fig. 1, the thermal noise currents of the source resistances R_s and the voltage noise of the LED's with a current spectral density equal to $S_I = kT(2R_s + R_d)/(R_s + R_d)^2$, where R_d is the differential resistance of the LED. Unlike an optical (linear) beam splitter, where the partition noise exactly restores the Poissonian statistics in the divided beams for a Poissonian input state, the electrical partition noise depends on the relative magnitudes of R_s and R_d [12], becoming negligible when $R_s >> R_d$, as is the case in our experiment. Hence, in this case, the intensity correlation is positive, and it may be written in terms of the Fano factor of the total current and the quantum efficiency as

$$C = \frac{\eta F_g/2}{\eta F_g/2 + (1 - \eta)} \ . \quad (3)$$

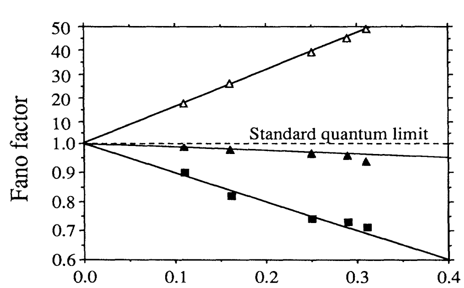

FIG. 2. Measured and calculated Fano factors as functions of the LED driving current to photodiode detection current quantum efficiency. Note that the vertical scale changes at $F_P = 1$.

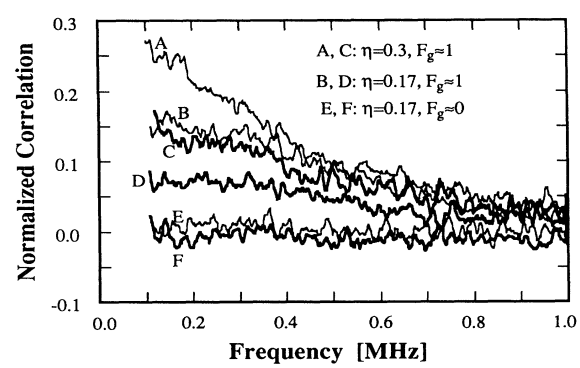

FIG. 3. Measured intensity noise correlation. In traces A, B, and E, the diodes are coupled in series; in traces C, D, and F they are coupled in parallel. Traces very similar to E and F (no correlation) were also recorded with the higher quantum efficiency setup. They have been omitted from the figure to avoid cluttering.

In Fig. 3 the experimentally measured correlation between the intensity noise of the two light beams as a function of frequency is shown. The detector photocurrents I_{P1} and I_{P2} were 0.9 mA each, in every measurement. In the series coupled cases, the correlation C is positive, and approximately equal to the quantum efficiency η, for a shot-noise limited current ($F_g \approx 1$), and zero for the constant current drive ($F_g \approx 0$), in agreement with Eq. (2). The limited correlation bandwidth is due to the current modulation response bandwidth of the LED's. It is around 500 kHz. Above this frequency the photon field fluctuations (which then are due to reflected vacuum fields) approach the shot-noise limit, just like they do in an intensity noise suppressed laser. Since different vacuum modes impinge on the two LED's, there is no intensity noise correlation at high frequencies.

Results similar to those presented above were obtained in the parallel coupled case, but the correlation in the shot-noise driven case is smaller by a factor of 2. The results agree well with Eq. (3). In contrast, a "Poissonian" partition noise would have resulted in a zero correlation for a shot-noise limited current and a negative correlation for a constant current. Edwards and co-workers [15] found that a negative correlation is still expected for thermal-noise-limited partition noise. However, due to the low quantum efficiency, it was not possible to resolve the small negatively correlated partition noise with the present measurement setup.

In Fig. 4 the measured intensity noise of a single diode in series and parallel configuration for the shot-noise limited (total) current and a constant current drive is shown. The generated photocurrent for both series and parallel coupled cases was 0.9 mA (i.e., the total drive current had to be doubled when switching from series to parallel coupling). The curved shape of the spectra is due to two effects. On the low frequency side (below 0.3 MHz), the rolloff is due to the high pass characteristics of the ac-coupled preamplifiers. Hence, the total signal level decreases with decreasing frequency, but the photocurrent noise is still much above the thermal noise of the preamplifier, so the quantum correlation is not affected. At higher frequencies (above 0.4 MHz), the noise level decrease is due to the responsitivity cutoff of the photodetectors. However, the photocurrent noise level is still much higher than the thermal noise of the preamplifier, so in this region the spectra approach the shot-noise level due to the LED modulation response cutoff mentioned earlier.

In the parallel coupled case, assuming negligible partition noise, the photocurrent Fano factor may be written

$$F_P = \eta \frac{F_g}{2} + (1 - \eta) \ . \tag{4}$$

As seen from Eq. (4), and from the experimental result, the photocurrent is sub-Poissonian even for a shot-noise limited total current. The noise spectrum lies halfway between trace A (near the SQL, cf. Fig. 2) and trace C (ideally $1-\eta$ times the SQL) in agreement with (4). This is a consequence of the negligible partition noise. The incoming fluctuations are simply damped by the splitting process with essentially no noise being added in the process. Thus, current division may under certain conditions reduce current noise. These results support Richardson's claim of negligible partition noise inside a laser diode [4, 12].

In Fig. 5 the measured spectra of the electrically combined (post detection) noise signals from two LED's driven with a shot-noise limited current are shown. If the photon streams are positively correlated, the spectrum of the difference signal may be lower than the noise signal of a solitary LED, as is the case in Fig. 5. In general, optimum noise reduction is obtained when one of the signal amplitudes is damped (after preamplification) by a factor equal to the quantum efficiency η [3, 9, 11, 16]. Minimization of the difference signal in the series case, using a variable microwave attenuator, yielded a noise decrease of -0.28 dB when the attenuation was -10 dB (corresponding to an amplitude attenuation of 0.32). Theory predicts the optimum damping factor to

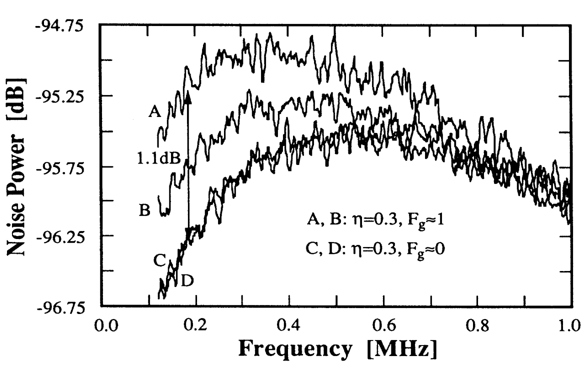

FIG. 4. Measured single diode intensity noise level in series (traces A and C) and parallel (traces B and D) coupling.

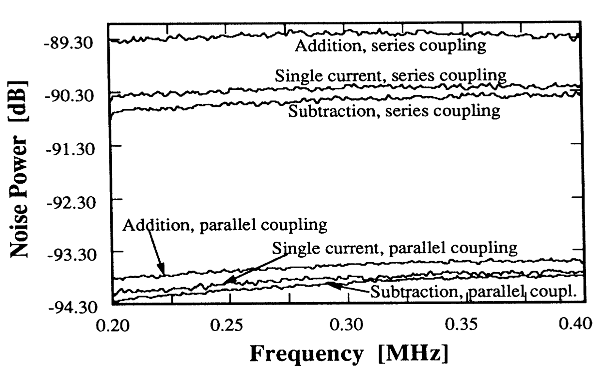

FIG. 5. Measured sum and difference noise spectrum from series and parallel coupled light emitting diodes, demonstrating quantum correlated twin beam generation.

be 0.31 and the noise reduction to be $1 - \eta^2 \approx -0.44$ dB. The sum spectrum at this optimum attenuation is higher than the single diode noise level by 1.0 dB. This is in good agreement with the theoretical estimate of $1 + 3\eta^2 \approx 1.1$ dB.

In the parallel configuration the difference spectrum was -0.1 dB below, and the sum spectrum was 0.25 dB above the solitary LED noise level at an attenuation of -16.1 dB. Theory predicts a difference spectrum $1 - \eta^2/4 \approx -0.11$ dB below and a sum spectrum $1 + 3\eta^2/4 \approx 0.30$ dB above the solitary LED noise signal at an attenuation of -16.5 dB. It is worth noticing that in this case the noise of the solitary LED is already substantially lower than the SQL, cf. Fig. 4. The noise reduction manifested in the difference spectrum is therefore a clear indicator of *quantum* correlation. The photocurrents I_P were 1.4 mA at this measurement and 3.0 mA in the series measurement described above. This is the source of the 3.3 dB difference in the solitary LED noise levels. Taking the noise reduction in the solitary parallel coupled LED into account, there should be an additional $1 - \eta/2 = -0.7$ dB (theory) or -0.55 dB (measurement, cf. Fig. 4) difference, adding up to 4 dB (theory) or 3.85 dB (experiment), close to the 3.75 dB difference shown in Fig. 5.

The present results all agree well with theory [4, 6, 11, 12], and we may infer that the squeezing and correlation are limited primarily by the low overall quantum efficiency [6, 11] and detector bandwidth. If laser diodes are used instead, higher quantum efficiencies ($\eta \approx 0.8 - 0.9$) are possible, paving the way to a much larger correlation and noise reduction.

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[1] Y. Yamamoto and N. Imoto, IEEE J. Quantum Electron. **22**, 2032 (1986).
[2] Y. Yamamoto, M. Machida, and O. Nilsson, Phys. Rev. A **34**, 4025 (1986).
[3] H-A. Bachor, P. Rottengarter, and C. M. Savage, Appl. Phys. B **55**, 258 (1992).
[4] W. H. Richardson and Y. Yamamoto, Phys. Rev. Lett. **66**, 1963 (1991).
[5] S. Machida and Y. Yamamoto, Phys. Rev. Lett. **60**, 792 (1988).
[6] G. Björk, Phys. Rev. A **45**, 8259 (1992).
[7] H. P. Yuen, Phys. Rev. Lett. **56**, 2176 (1986).
[8] G. Björk and Y. Yamamoto, Phys. Rev. A **37**, 125 (1988).
[9] J. Mertz, A. Heidmann, and C. Fabre, Phys. Rev. A **44**, 3229 (1991).
[10] A. Heidmann, R. J. Horowicz, S. Reynaud, E. Giacobino, and C. Fabre, Phys. Rev. Lett. **59**, 2555 (1987).
[11] A. Karlsson, E. Goobar, P. J. Rigole, and G. Björk, in IQEC'92 Technical Digest, Proceedings of the Eighteenth International Conference on Quantum Electronics, Vienna, Austria, 1992 (to be published), Paper No. PWe041.
[12] Y. Yamamoto and H. Haus, Phys. Rev. A **45**, 6596 (1992).
[13] E. Goobar, A. Karlsson, and S. Machida, IEEE J. Quantum Electron. (to be published).
[14] P. J. Edwards, Int. J. Optoelectronics **6**, 23 (1991); M. C. Teich, F. Capasso, and B. E. Saleh, J. Opt. Soc. Am. B **4**, 1663 (1987).
[15] P. J. Edwards, G. N. French, D. O' Brien, and J. P. Lynam, in IQEC'92 Technical Digest, Proceedings of the Eighteenth International Conference on Quantum Electronics, Vienna, Austria, 1992 (to be published), Paper No. PWe046; P. J. Edwards and G. H. Pollard, Phys. Rev. Lett. **69**, 1757 (1992).
[16] A. Karlsson and G. Björk, Phys. Rev. A **44**, 7669 (1991).