Quantum Noise-Correlated Operation of Electrically Coupled Semiconductor Light Emitters

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Electrically coupled light-emitting diodes have been configured to demonstrate multiple light beams with correlated sub-shot-noise intensity fluctuations. Photocurrent covariance measurements of the two light beams from a pair of series-connected diodes show a positive correlation, similar to that observed with nonlinear crystal down-converters. Shunt-connected diodes are shown to generate negatively correlated light beams.

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Sub-shot-noise "amplitude-squeezed" operation of laser and light-emitting diodes using the high-impedance "quantum-watchdog" noise suppression technique [1] is now well established [1-3]. This technique appears to offer a technically simple way of reducing quantum noise well below the standard quantum limit in tightly coupled optoelectronic systems, constrained only by the magnitude of the attainable quantum transfer efficiency between light emitter and detector. Such a reduction in quantum noise is of great practical interest with potential applications in shot-noise-limited metrology and information transfer.

The high-impedance quantum noise suppression technique, which simply involves driving a laser diode or light-emitting diode from a low-noise high-impedance current source, is also of considerable theoretical interest. Particular interest currently centers on the appropriate quantum-mechanical description of the interaction between the classical electrical pump (macroscopic reservoir) and the quantum-mechanical electron-hole recombination (microscopic) system. Richardson and Yamamoto [1] interpret this interaction, in which the junction voltage of a laser diode "measures" the photon number fluctuation, as an example of a quantum-mechanical-watchdog effect.

We have extensively studied the phenomenology of quantum noise reduction using high-efficiency infrared-emitting diodes [3]. These are simpler to analyze and measure than laser diodes because of the absence of amplified spontaneous emission. Following the work of Teich and Saleh [4], we have found a conceptual and quantitative description in terms of electronic and photonic stochastic point processes to be entirely adequate. In particular, in investigating the Richardson, Machida, and Yamamoto partition noise model of the transverse junction stripe laser, which they used to obtain an 85% reduction below the shot-noise limit [5], we have been led to the realization of a new class of multiple-beam light-emitting devices. These are arrays of laser or light-emitting diodes which generate twin (or multiple) light beams between which the intensity fluctuations are strongly correlated and in which the correlation extends into the quantum (sub-Poissonian photon statistics) regime.

The largest reported (85%) noise reduction, achieved with a transverse junction stripe laser [5], has been the subject of considerable debate. It appears to run counter to the conventional wisdom that the fractional noise reduction, relative to the shot-noise level, is just equal to the quantum efficiency η as measured by the current transfer ratio between mean emitter and detector currents.

Referring to the light-emitting junction diode–diode detector noise equivalent circuit of Fig. 1 and utilizing the Burgess variance theorem [4], the mean-square photocurrent noise fluctuation (the photocurrent variance) in bandwidth B in the detector is given by

$$\langle i_d^2\rangle = \eta^2\langle i^2\rangle + \eta(1-\eta)2\langle I\rangle eB\,, \tag{1}$$

where the mean quantum efficiency $\eta=\langle I_d\rangle/\langle I\rangle$, and $I=\langle I\rangle+i$, $I_d=\langle I_d\rangle+i_d$. We have verified [3,6] Eq. (1) using high-quantum-efficiency infrared-emitting diodes

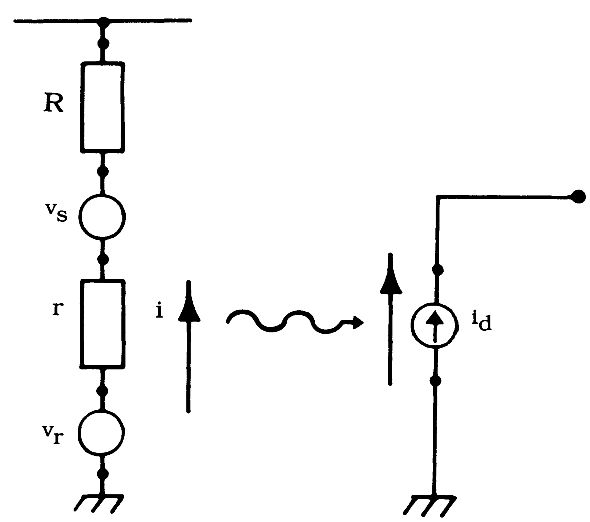

FIG. 1. Simplified low-frequency noise equivalent circuit of light-emitting junction diode (with R = series resistance, $\langle v_s^2\rangle = 4kTRB$, r = differential resistance $= mkT/e\langle I\rangle$, $\langle v_r^2\rangle = 2mk \times TrB$) coupled to lightwave detector with quantum efficiency $\eta=\langle I_d\rangle/\langle I\rangle$. Detector current and junction diode current variances are related through Eq. (1). For the diodes used, $m=1.3$, $R=2.5\ \Omega$.

(Hamamatsu L2656) for the situation in which $\langle i^2\rangle/2\langle I\rangle eB \ll 1$. Referring to Fig. 1, this result holds providing the series resistance $R \gg r$, the differential diode resistance. In this case Eq. (1) gives the Fano factor for the photocurrent spectral density,

$$F=\langle i_d^2\rangle/2\langle I_d\rangle eB=1-\eta\,. \qquad (2)$$

These initial results [3] have now been extended to obtain a noise suppression greater than 1.5 dB of amplitude squeezing using (a) balanced delay line direct detection, and (b) direct detection using an incandescent lamp as a shot-noise reference source. Figure 2 shows the measured spectral density to be a linear function of the system quantum efficiency η, as expected from Eq. (2). Measurements by the NTT group of greater quantum noise reduction have been interpreted [5] in terms of the suppression of current partition noise within the diode structure.

Referring to Fig. 3 which represents two shunt-connected light-emitting diodes, configured to simulate the proposed physical laser model [5], it may be shown from Kirchoff's circuit equations that the branch current noise variance may be written in the form

$$\langle i_1^2\rangle=\langle i_s^2\rangle/4+\langle i_p^2\rangle\,. \qquad (3)$$

The first term in Eq. (3) represents the mean-square current noise, $\langle i_s^2\rangle$, split between the two current branches, and the second term, $\langle i_p^2\rangle$, represents the current partition noise. The partition noise term for identical branches and symmetric current splitting is

$$\langle i_p^2\rangle=kTB(mr+2R)/(r+R)^2\,, \qquad (4)$$

so that the additional partition noise, together with the junction current noise, should be suppressed as the differential resistance of the diodes

$$r=mkT/e\langle I_1\rangle$$

is reduced relative to R, the series resistance. In the limit as $\langle I_1\rangle$ increases and $R \gg r$, sub-shot-noise operation is restored, since

$$\langle i_1^2\rangle/2\langle I_1\rangle eB=r/R\ll 1\,.$$

The branch current fluctuations i_1 and i_2 may be shown by a simple application of the classical Kirchoff circuit laws to be negatively correlated via the current partition noise.

Their covariance may be written

$$\langle i_1 i_2\rangle=\langle i_s^2\rangle/4-\langle i_p^2\rangle\,. \qquad (5)$$

Equation (5) indicates that the partition noise may be directly measured by cross correlation of the two branch fluctuation currents i_1 and i_2. We note in passing that Eqs. (3)-(5) are analogous to those describing the random partitioning of a photon beam at an optical beam splitter or an electron beam between charge-collecting

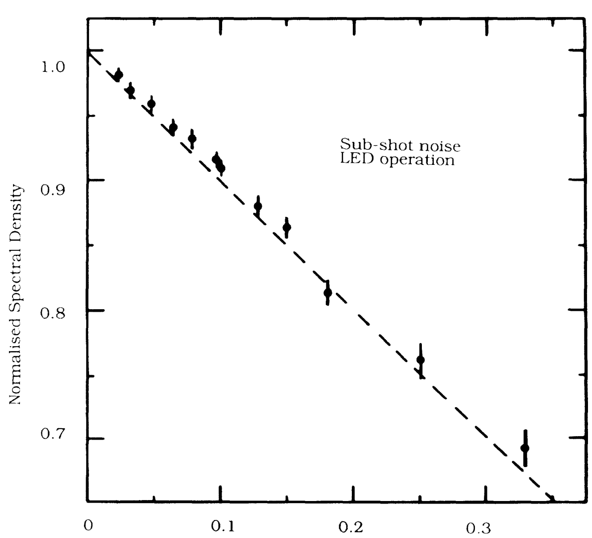

FIG. 2. Noise power spectral density as a function of current transfer (quantum) efficiency (η) measured at 300 kHz, normalized to the shot-noise level for infrared-emitting diode (Hamamatsu L2656) coupled to silicon *p-i-n* diode detector. The dashed line is given by Eq. (2).

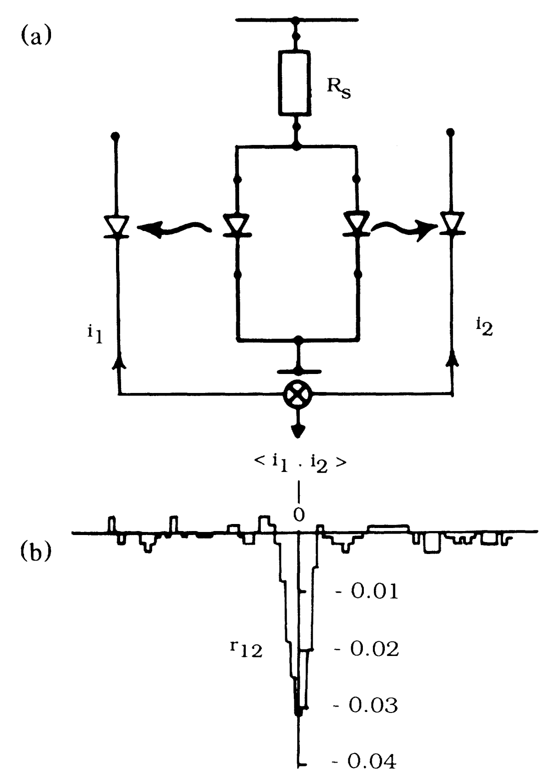

FIG. 3. (a) Shunt-connected infrared-emitting diodes configured to generate negatively correlated lightwave intensity fluctuations. (b) Detector photocurrent covariance plot for shunt-connected L2656 infrared-emitting diodes (η=0.12). Horizontal scale, 0.5 μs/bin. R_S=1000 Ω. Maximum (negative) correlation: -0.030 ± 0.005.

electrodes in a vacuum tube. The current partition noise term $\langle i_p^2 \rangle$ is evidently the classical analog of the quantum-mechanical vacuum fluctuation as has been pointed out by Yamamoto [7].

We have verified the physical basis of the NTT model [5] by cross correlating the detected photocurrent fluctuations from two shunt-connected Hamamatsu L2656 light-emitting diodes, as shown in Fig. 3(a). The output currents from two large-area (100 mm^2) silicon photodiode detectors were amplified, low-pass filtered ($B=350$ kHz), sampled at 2×10^6/s, and cross correlated in a single-bit digital correlator (Saicor model 42A). All measurements were performed in an electromagnetically screened room. As in previous measurements on single light-emitting diodes [3], particular attention was given to reducing common-mode power supply and amplifier noise and to minimizing parasitic coupling between correlator channels. These measures were facilitated by the high sensitivity of the digital correlator when operated for integrating periods of the order of minutes. As predicted, a small negative correlation was observed. Figure 3(b) shows a typical result. We find that this correlation, due to partition noise according to Eqs. (4) and (5), disappears in the limit $r/R \ll 1$, as expected. For convenience, the measurements were performed at room temperature with a relatively low value (12%) of the quantum efficiencies (η_1, η_2). Operation at and below the shot-noise level was confirmed as in previous experiments [3] to eliminate the possibility of spurious classical noise correlations.

These results directly support the proposed laser model. Also, it is to our knowledge the first demonstration of intensity-correlated operation of a pair of semiconductor light-emitting devices. We believe from the similarity between the noise equivalent circuit representations of laser and light-emitting diodes that the result holds for pairs of shunt-connected laser diodes as well as for shunt-connected light-emitting diodes.

The covariance between the detected photocurrent fluctuations is related to the branch current covariance by

$$\langle i_1 i_2 \rangle_d = \eta_1 \eta_2 \langle i_1 i_2 \rangle , \tag{6}$$

and the relation between the variances is given by Eq. (1). Accordingly, we may show that the correlation coefficient for symmetric, current-balanced partition with $\eta_1 = \eta_2 = \eta$ is given by

$$r_{12}(\eta, x) = -\eta F_e(x) / \{1 + \eta [F_e(x) - 1]\} , \tag{7}$$

where $F_e(x) = x(2+mx)/m(1+x)^2$ is the "electron" Fano factor in either branch, taken here to be dominated by the partition noise ($\langle i_p^2 \rangle \gg \langle i_s^2 \rangle$), and $x = r/R$ is the ratio of differential diode resistance to series resistance in each branch.

It is evident that full negative correlation is expected for $\eta = 1$, and that the covariance vanishes for either $\eta = 0$ (high attenuation) or $F_e(x) = 0$ ($r/R = 0$, complete partition noise suppression). The maximum negative correlation coefficient

$$r_{12}(\eta, \infty) = (-\eta/2)/(1-\eta/2)$$

occurs for the limiting case $x \gg 1$, for which case, $F_e = 0.5$.

The situation is similar for series-connected diodes [Fig. 4(a)] in which case the correlation is positive, as shown in Fig. 4(b). Considering the case of n series-connected diodes, and using the equivalent circuit of Fig. 1, we find the electron Fano factor in the current loop,

$$F_e(x) = x(2+mx)/mn(1+x)^2 . \tag{8}$$

The correlation coefficient between the photocurrent fluctuations due to a pair of series-connected light-emitting diodes is then given by Eq. (7) with a change of sign.

It is evident that full correlation again occurs for $\eta = 1$ and also that maximum quantum noise reduction occurs in the limit as x tends to zero. For the "ideal" case of negligible series resistance ($x \gg 1$), the electron Fano factor $F_e = 1/n$. The measured correlation of 0.047 ± 0.005 shown in Fig. 4(b) for $n=2$, $x=2.6$, and $\eta = 0.12$, is in

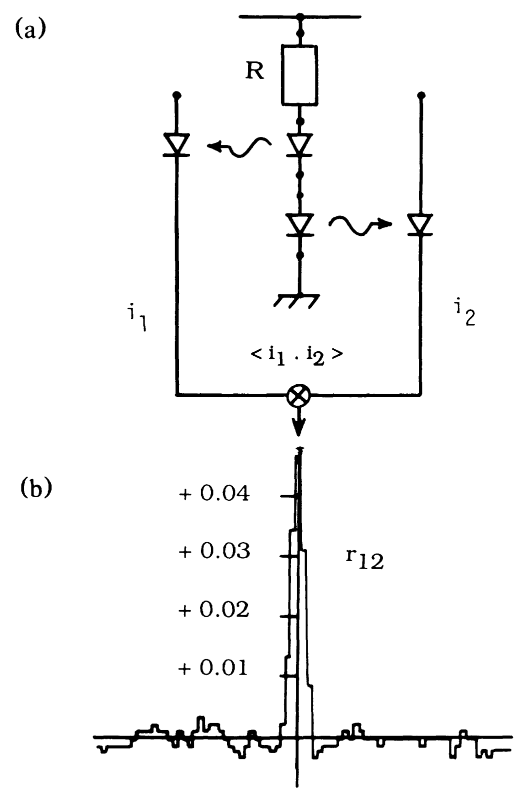

FIG. 4. (a) Series-connected infrared-emitting diodes configured to generate positively correlated intensity fluctuations. (b) Detector photocurrent covariance plot for series-connected L2656 infrared-emitting diodes ($\eta = 0.12$). Horizontal scale, 0.5 μs/bin. $R = 5\ \Omega$ (internal to diodes). Maximum correlation, 0.047 ± 0.005.

reasonable agreement with the predicted value of 0.052.

This demonstration of a strong positive quantum correlation for series-connected light-emitting diodes is of theoretical and practical interest. Providing the correlation is maintained at low photon fluxes, series-connected light-emitting diodes evidently provide a technically simple means of generating quantum noise-correlated light beams similar to the "photon-paired" beams generated in nondegenerate parametric down-converters [8]. Although we have not yet demonstrated this phenomenon with laser diodes, the similarity between the electronic and photonic models of LEDs and laser diodes encourages us to expect similar behavior. Unlike photon-pair generation in nonlinear crystals, there is no momentum, polarization, or energy coupling between the photon pairs. The mean photon energies in each of the beams may be varied independently of those in the other beams by varying the energy band gaps. Also, unlike the situation with nonlinear crystals, one is not limited to photon pairs. Triplets and high-order multiplets may just as easily be generated with no loss of correlation. Of course, from Eqs. (7) and (8), the maximum photocurrent correlation between any pair in an array of n emitters is just

$$r_{12}(\eta=1)=\eta/[\eta+n(1-\eta)]\,. \tag{9}$$

The correlation evidently extends below the shot-noise limit. Indeed, for both series and shunt diodes the individual beams will normally be amplitude squeezed, as we have demonstrated. We see here a clear example of a quantum noise correlation [9], in the form of a classical correlation between sub-Poissonian photon fluxes. No violation of the "two-beam" Cauchy-Schwarz inequality [10] occurs because the magnitude of the correlation coefficient is always less than or equal to unity.

One of the practical applications of the correlation may lie in those optical attenuation measurements in which the noise is dominated by intensity fluctuations in the source [8]. In the present case we might consider the use of dual-beam absorption spectrophotometry of weakly attenuating media as an example. Note that by subtracting from each of the single-beam photocurrents I_d a fraction η of the diode array current I, we recover the case described by Eq. (2) in which the noise reduction below the shot-noise level is the maximum permitted by statistical fluctuations in the single-beam quantum transfer efficiency.

Another possible application is in the generation, by n-fold replication, of robust near-photon-number states as proposed by Yuen [11].

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