Photon noise correlations in electrically coupled semiconductor lasers

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Measurements of the correlation between the photon noise of two semiconductor lasers sharing a bias circuit are presented. The photon noise of the electrically coupled lasers is found to be correlated by as much as 70%. The photon noise correlations are measured at low frequencies as a function of the bias current for lasers connected in series and in parallel, and for high and low impedance biases. The magnitude and sign of the noise correlations are consistent with theoretical expectations. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1539548]

In semiconductor lasers, the noise in the emitted photon stream depends on both the internal dynamics of the laser and the electrical circuit used to bias the laser.[1,2] Likewise, the noise on the bias current of the laser receives contributions not only from external sources such as the thermal noise of resistances in the bias circuit, but also from the laser itself. In cascade lasers, or when multiple lasers are biased in one electrical circuit, the photon noise between the lasers can become correlated as a result of the shared electrical noise. The correlations are of interest in understanding the noise in cascade lasers and in evaluating the suitability of cascade lasers for communications applications.[3] In a cascade laser, each electron can emit several photons in each stage of the laser. The total photon noise of the laser is the sum of the photon noise from all of the stages. If the light from each stage were uncorrelated with the light from every other stage, one would expect a signal to noise ratio $\sqrt{N}$ times that of an individual stage, where N is the number of light emitting stages. Positive correlations between the light emitted from the different stages will decrease the signal to noise ratio,[4] while negative correlations will increase the signal to noise ratio. Using the photon correlations of circuit-coupled lasers to generate quantum intensity correlated beams has also been suggested.[5] Measurements of the photon noise correlations in electrically coupled light-emitting diodes (LEDs) have been made.[6,7] Measurements similar to those presented here demonstrated correlations of around 4% for circuit-coupled LEDs, and it was suggested that similar correlations might hold for laser diodes.[7] This letter presents measurements of the photon noise correlations between electrically coupled lasers.

The noise correlation measurements were performed for four distinct circuit configurations, and as a function of bias. The configurations differed in whether the lasers were positioned in series or in parallel, and in whether the bias circuitry seen by the laser has a high or low impedance at the frequencies of the measurement (450–650 kHz).

The experimental setup is shown in Fig. 1. The measurements were performed at room temperature using two identical lasers emitting at wavelengths of 850 nm. The lasers were single transverse mode, high output power AlGaAs Fabry–Pérot lasers (SDL-5400-C). They were biased with a battery in series with a variable resistor and a large inductor. The battery provided a quiet source of bias current for the lasers. The inductor provided a high impedance at the measurement frequencies and helped prevent the small amount of thermal noise produced in the variable resistor from entering the lasers. Also included in the laser bias circuit was a large capacitor which could be switched in to bias the lasers with small impedance. The lasers had internal parasitic series resistances of 2.3 Ω. Two identical large area silicon p-i-n photodiodes (Hamamatsu S3590-01) were used to collect light from the two lasers. The quantum efficiency of the laser was 0.73, and the total current-to-current efficiency of the laser-photodiode link was 0.62. The ac part of the photocurrents was amplified using low noise transimpedance amplifiers, and sampled at 25 MHz using a 14 bit analogue-to-digital converter. Because large dc photocurrents can saturate the photodiodes, a reverse bias of 40 V was applied. The small signal response of the laser-photodiode links was checked to be unaffected by the level of incident dc power from the lasers. The lasers were mounted in good thermal contact with a Peltier cooler and stabilized at 16 °C.

Known sources of unwanted noise in the transmission (laser) circuit included thermal noise of the variable resistor and external noise capacitively or inductively coupled into the circuit. The thermal noise coupled into the lasers from the variable resistor was too small to measure, but was cal-

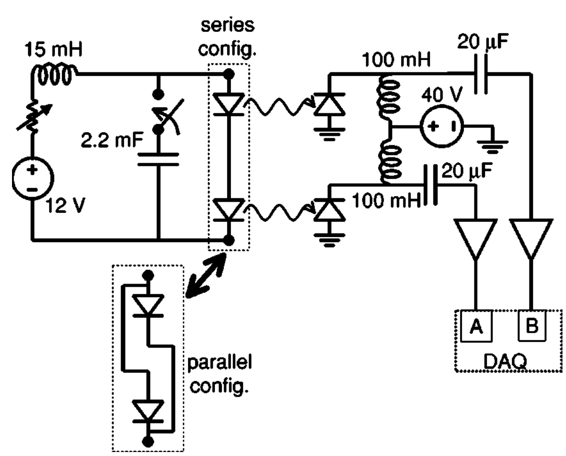

FIG. 1. The correlated photon noise measurement setup.

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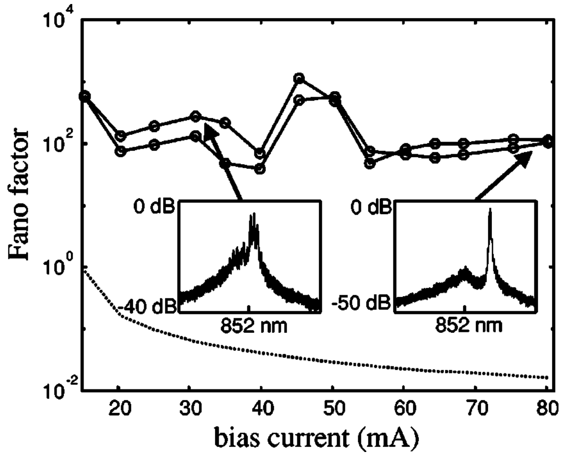

FIG. 2. Measured photon noise of each laser. Insets depict optical spectrum of one of the lasers at two bias points (31 and 78 mA) over a 10 nm wavelength span. Dotted line is noise floor.

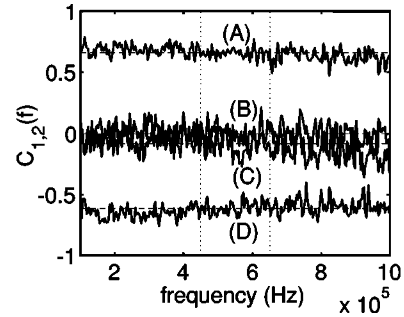

FIG. 3. Measured photon noise correlations at a 30 mA bias for the four bias configurations shown in Fig. 4, as a function of frequency. Dotted horizontal lines show the average over 450–650 kHz.

culated to be at least 100 times smaller than the shot noise level. To reduce noise pickup, everything up to and including the preamplifiers was placed in a properly grounded metal box. The absence of such noise was confirmed through a number of additional tests, including biasing the lasers in separate circuits and checking that their noise was uncorrelated.

Before the lasers' photon noise correlations were measured, the noise of each laser was measured between 450 and 650 kHz. Figure 2 shows the noise of both lasers plotted as a function of laser bias current, along with the noise floor of the measurement (dotted line). The lasers were both biased with a high impedance source. The noise metric used is the Fano factor, which is the ratio of the measured current noise power in the photodetector to the shot noise of the dc photodetector current. The shot noise of the photodetector current is calculated using the standard formula, $PSD_{\mathrm{shot}} \equiv 2qI_{\mathrm{dc}}$. The current noise of both lasers is well above shot noise. This is believed to be due to a combination of mode partition noise and mode hopping noise.[8] This explanation is consistent with the observed optical spectra, shown in the inset of Fig. 2, which shows several longitudinal modes of the laser with considerable power, especially at lower bias currents. An important consequence of the large amounts of noise is that the partition noise contributed by the photodetector's imperfect quantum efficiency is negligible. This means that the Fano factor of the photocurrent noise is very close to that of the incident photon noise, and also that the photon noise correlations are very well approximated by the current noise correlations.

The lasers' photon noise correlations were measured in four different configurations, labeled A–D and represented schematically in the insets of Fig. 4. In A, the two laser diodes are connected electrically in series, and biased with a low impedance (voltage-like) source. In practice, this low impedance is obtained by connecting the capacitor across the two diodes. Over the measurement frequencies the capacitor reduced the impedance seen by the lasers to below $10^{-3}\ \Omega$. In B, the lasers are electrically connected in series without the capacitor. Over the measurement frequencies, the impedance seen from the lasers is greater than 40 kΩ. This is much larger than the characteristic impedances of the lasers, and is a current-like bias. In C, the lasers are connected in parallel with the capacitor shunting them for a voltage-like bias. In D, the lasers are connected in parallel without the capacitor for a current-like bias.

The photon noise correlations in each of the four different bias configurations were measured as a function of the bias current. The correlation $C_{1,2}$ of the two noise signals was calculated in the frequency domain using the metric

$$C_{1,2}(f) \equiv \frac{CSD_{1,2}(f)}{\sqrt{PSD_1(f)PSD_2(f)}}. \quad (1)$$

This metric, defined in terms of the power spectral densities (PSDs) and the cross spectral density (CSD) of the two noise signals, is the square root of the standard coherence function. If the real part of the correlation $C_{1,2}(f)$ is taken, the resulting function has a simple interpretation: perfectly correlated signals have $C_{1,2}(f)=1$, and perfectly anticorrelated signals have $C_{1,2}(f)=-1$. The results of a sample measurement of $C_{1,2}(f)$ at a bias current of 25 mA are shown in Fig. 3.

The resulting real correlation spectrum was averaged over a fixed bandwidth (450–650 kHz) to obtain a single number characterizing the correlation of the photon noise of the lasers, and the procedure was repeated for different bias currents. The results are shown in Fig. 4.

It is apparent from Fig. 4 that over much of the bias range, the photon noise is strongly positively correlated when two lasers are biased in series with a low impedance, strongly negatively correlated for the case of two lasers biased in parallel with a high impedance source, and only weakly correlated for the other two scenarios. This can be understood as follows.

When photons are emitted from one laser in excess of the average rate, the carrier density in the active region of the laser experiences a corresponding drop. This in turn expresses a voltage across the junction,[9,10] which drives extra current into the laser through the bias circuit, restoring the carrier populations in the quantum well to what they were before the photons were emitted. In other words, the noise of the photon stream can be imprinted on the bias current, and the magnitude of this noise depends on the external impedance seen by the laser's junction.[2] When this bias current is shared with another laser, correlations in the photons emitted from the lasers are introduced.

For lasers whose stages are electrically coupled in series (cases A and B in Fig. 4), the photon noise correlations are positive, because when one laser pulls more than the average

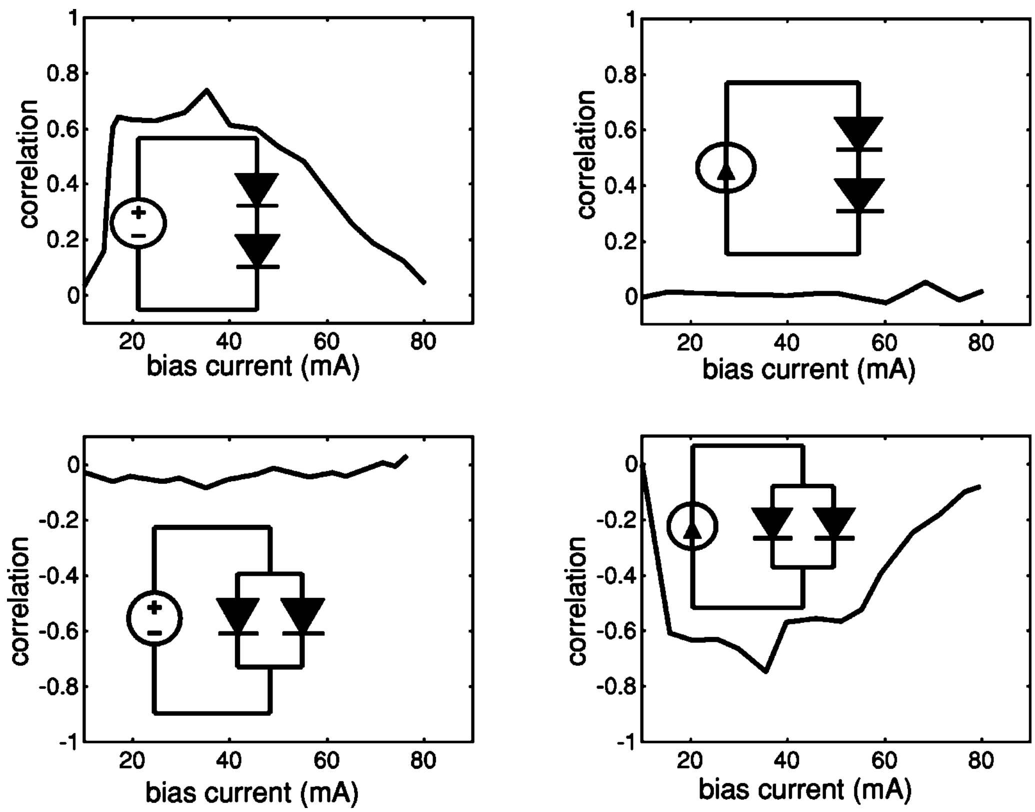

FIG. 4. Measured photon noise correlation as a function of bias for four distinct bias configurations. The threshold current for each laser was 15 mA.

amount of current from the bias source, the extra current must pass through the other laser. The size of the correlations displays a strong dependence on the impedance of the bias circuit seen by the lasers over the frequency range of interest. Impedances much larger than the impedance of the laser (current-like) will tend to suppress the noise correlation, since a voltage noise fluctuation across the active region of one laser will be unable to drive very much current through the large impedance of the bias circuit and through the other laser. This is the reason why the correlation in Fig. 4 is much larger in A than in B.

For lasers connected in parallel (cases C and D in Fig. 4), the correlations become negative. The intuition is that if one laser pulls more than the average amount of current from the bias circuit, it does so at the expense of the current through the other laser, giving rise to negative correlations in the emitted photon noise. Once again, the size of the correlations depends strongly on the size of the impedance of the bias circuit seen by the lasers over the frequency range of interest. This time, the correlations are suppressed when the impedance of the bias circuit is small (voltage-like), because the currents needed to restore a population fluctuation in one laser are shunted away from the other laser by the low bias impedance. This explains why the correlation in Fig. 4 is more negative in D than in C.

Measurements of the photon correlations between two circuit coupled semiconductor lasers have been presented. The noise on the bias current of the lasers is dominated by contributions from the lasers, not from thermal noise or from the external bias. The photon noise of the two circuit coupled lasers can become correlated by as much as 70% through their shared bias current, compared to the correlation of about 4% which was measured elsewhere for LEDs.[7] The lasers' photon noise shows large positive (negative) correlations when the lasers are connected electrically in series (parallel) with a small (large) source impedance. If the lasers are connected in series with a high impedance source, or in parallel with a low impedance source, the photon noise correlations are small. The magnitude of the correlations and their strong dependence on the impedance of the bias circuit suggest that the effects of the correlations should be included when modeling the noise figure of a cascade laser used in a communication link.

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