The influence of extra carrier noise on vertical-cavity surface-emitting lasers

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We find experimentally that the relaxation oscillation (RO) peak in the relative intensity noise (RIN) of a semiconductor laser broadens by adding noise to the pump current. In our experiments we use a vertical-cavity surface-emitting laser. The broadening of the RIN peak with increasing carrier noise level is interpreted to be due to an increase of the non-linear gain saturation.

Introduction

In semiconductor lasers, spontaneous recombination of electrons and holes results in two types of noise contribution to the laser output field: spontaneous emission noise due to a fraction of spontaneously emitted photons ending up in the lasing mode, referred to as field noise, and carrier or inversion noise due to the discrete, random and instantaneous character of each recombination event, often also referred to as shot noise. Usually, it is only a small portion of the total spontaneous radiative recombination events that lead to a photon ending up in the lasing mode. These photons have random phases and hence lead to random fluctuations of the power and the phase of the field in the lasing mode. Another, much larger portion, of the randomly recombining carriers, decay from the positions in their respective energy states by non-radiative means, that is, without contributing a photon to the laser field. However, this does considerably alter the amount of carriers available for lasing, i.e. the inversion, and it is therefore quite surprising, as Henry showed [1, 2], and others confirmed later, [3, 4], that the carrier noise has no influence in the static properties of a cw-emitting semiconductor laser and has little influence in the dynamic properties. This has led to the general belief that carrier noise can be ignored in the analysis of semiconductor lasers [5, 6, 7].

Experimental results

In this section we will check up to what limit it is valid to neglect the contributions of the carrier noise in the modelling of a semiconductor laser. To that end, we will add low bandwidth (500 MHz) noisy carriers directly to the pump current of the VCSEL, which will additively contribute to fluctuations in the inversion. This is, to a certain extent, comparable to an increase in the diffusion strength of the Langevin force acting on the inversion in Eqs. (12)-(13) in [2]. The setup is sketched in Figure 1.
To probe the dependence of the laser features on carrier noise level, we measure the relative intensity noise (RIN) spectrum of the laser as a function of the noise strength.

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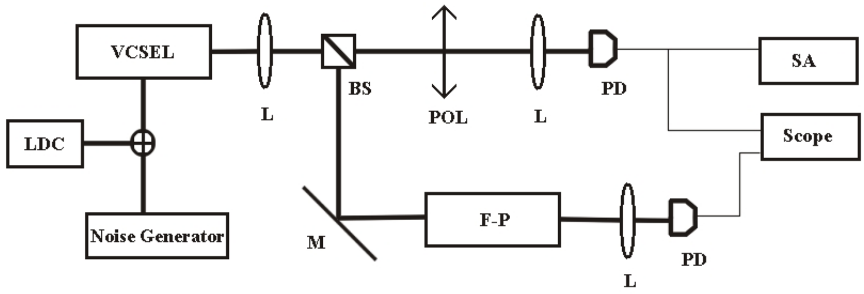

Figure 1: Scheme of the experimental set-up. VCSEL: thermally stabilized Vertical Cavity Surface Emitting Laser; L: collimating lens; BS: beam-splitter; POL: polarizer; M: mirror; PD: photodiode; FP: Fabry-Perot analyzer; LDC: laser diode controller; SA: spectrum analyser.

From the RIN-spectra in Figure 2 we can identify the relaxation oscillation (RO) peak, which changes both in position and shape as a function of the carrier noise strength. In general, we found that the RO peak shifts to lower frequencies, while the width of the peak increases with increasing noise strength. Also, the intensity noise below 500 Mhz is considerably enlarged due to the addition of the low bandwidth noise.

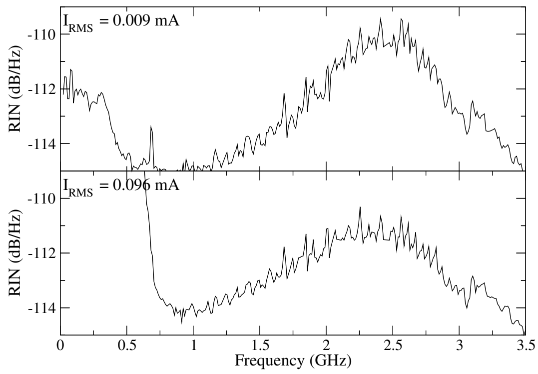

Figure 2: RIN spectra of the VCSEL under test at a constant current of 1.2 mA and at different carrier noise strengths.

The RIN spectra are fitted using the expression [8]:

$$RIN(\omega) = \frac{A\omega^2 + B}{(\Omega_{RO}^2 + \Gamma_{RO}^2 - \omega^2)^2 + 4\Gamma_{RO}^2\omega^2}. \quad (1)$$

From this we extract the relaxation oscillation damping rate Γ_{RO} and the relaxation oscillation frequency Ω_{RO}. A and B are fitting parameters that do not matter in the remainder of this work. All the measurements are done for current levels in the single polarization mode regime to minimize the effects of mode partition noise and to maximize the mode suppression ratio.

Figure 3 shows the extracted parameters as a function of the carrier noise amplitude at a bias current of 1.2 mA. It is clear that $\Omega_{RO}^2 + \Gamma_{RO}^2$ remains constant (within the error) with increasing noise strength, while Γ_{RO} increases more or less linearly with the carrier noise amplitude. At higher currents we observe similar trends, but the relaxation oscillation peak of these measurements lies outside the bandwidth of the signal detector ($\sim 3GHz$).

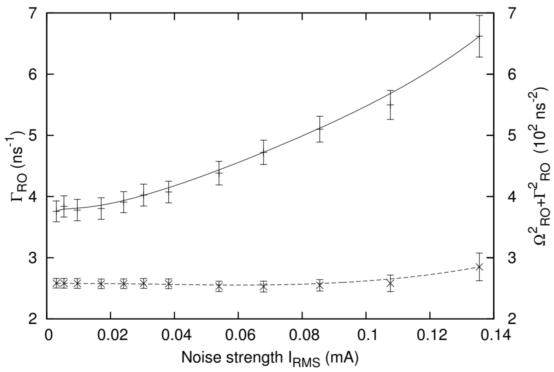

Figure 3: The relaxation oscillation damping rate Γ_{RO} (full) and $\Omega^2_{RO}+\Gamma^2_{RO}$ (dashed) as a function of the noise strength at a bias current of 1.2 mA.

During the experiments, we have also observed a broadening on the line width of the VCSEL when increasing the strength noise. While we can exclude thermal effects in the changes found in the RIN, we cannot do so for the increase found in the line width. The broadening of the line width remains as an open question.
Finally, we have checked for modifications to other operation characteristics of semiconductor lasers due to added carrier noise (output intensity, threshold current, . . .), but we have found no changes within the measurement error. In the next section, we will try to understand these phenomena following a rate equations analysis.

Modelling

In this section, we will use a rate equation approach to check analitically the effect of an extra current noise term added in the carrier equation. We consider the extra noise as being colored accounting for the fact that the noise generator is band-limited. The rate equations for photon $P(t)$ and carrier number $N(t)$ read as follows:

$$\dot{P(t)} = (G(t)-\gamma)P(t)+R(t)+F_P(t), \tag{2}$$

$$\dot{N(t)} = I(t)-G(t)P(t)-S(t)+F_N(t)+F_C(t), \tag{3}$$

where $G(t)$ is the gain net rate of stimulated emission, γ is the cavity loss rate, $R(t)$ is the spontaneous emission into lasing mode, $S(t)$ is the electron-hole recombination rate (both radiative an non-radiative) and $I(t)$ is the current. The Langevin noise sources $F_P(t)$ and $F_N(t)$ are noise sources accounting for the intrinsic noise. The colored noise on the current is modelled by $F_C(t)$.
Starting from equations (2)-(3), it is possible to find analytical expressions for the relaxation oscillation frequency and damping rate via linear perturbation analysis. Doing so, we find:

$$\Gamma_{RO} = \frac{1}{2}(\Gamma_N+\Gamma_P) = \frac{1}{2}(S_N+G_NP+G_PP+R/P), \tag{4}$$

$$\Omega^2_{RO}+\Gamma^2_{RO} = GG_NP+\Gamma_N\Gamma_P \approx GG_NP, \tag{5}$$

where $\Gamma_N = S_N+G_NP$ and $\Gamma_P = G_PP+R/P$ are the decay rates of n, p respectively; n, p being the small deviations from the steady-state values. The gain is expanded in a first

order approximation: $G(t) = G + G_N n - G_P p$, where G is the gain at steady-state and G_P accounts for the nonlinear reduction in gain (gain saturation) resulting from phenomena such as spatial hole burning [9].
If we recall that $\Omega_{RO}^2 + \Gamma_{RO}^2$ is constant, see fig. 3, we can infer from equation (5) that G and G_N are unaffected by the extra carrier noise. On the other hand, we experimentally find that the extra carrier noise modifies the damping rate. If we take a closer look to the right-hand side of equation (4), we can presume that the carrier noise modifies the nonlinear gain G_P since the other parameters show no measurable change.
Numerical simulations of eqs. (2)-(3) confirm the validity of our hypothesis. According to the experiments, the colored noise $F_C(t)$ only contributes to the RIN at low frequencies. No noticeable change in the shape of the RO peak is found unless we modify any of the input parameters. Again, the broadening of the RO peak is only achieved by increasing the nonlinear contribution to the gain.

Conclusions

In this contribution we present a systematic study of the effect of an extra current noise source added to the low-noise current injection source of a thermally stabilized VCSEL. We have checked the laser features when varying the injected noise level and report an interesting change on the shape and position of the relaxation oscillation peak in the relative intensity noise. We have also carried out an analytical study of a set of simple rate equations for a typical semiconductor laser. We can conjecture that the carrier noise is responsible for a change in the nonlinear gain due to spatial effects.

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