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Polarization Modal Noise in Vertical-Cavity Semiconductor Lasers

Abstract

We have studied the polarization fluctuations and polarization modal noise in semiconductor VCSELs. The measurements include (polarization-resolved) optical spectra, intensity noise, correlated fluctuations in two polarization modes, and stochastic switching between these modes. Good agreement is found with a relatively simple model.

1 Introduction

The optical polarization of light emitted by Vertical Cavity Surface Emitting Lasers (VCSELs) is less stable and shows more dynamics than that of most other lasers. This has two reasons: (i) the high degree of rotational symmetry (round for proton-implanted VCSELs, square for some oxidized VCSELs) makes the two in-plane polarization directions nominally equivalent, and (ii) their small size makes quantum noise, due to spontaneous emission, relatively important. One striking consequence of this limited polarization stability is that many VCSELs switch their dominant polarization at a certain laser current. Furthermore, even at currents where only one polarization mode dominates the laser polarization is not stable, as the intensity in the other (much weaker) polarization mode fluctuates wildly. We have studied these polarization fluctuations with several experimental techniques and compared the results with a simple model.

Our model is valid for VCSELs that operate in the fundamental transverse mode, so that the (slowly-varying component of the) emitted optical field can be specified in terms of four variables: the optical phase φ_l, the intensity $I = |\mathbf{E}|^2$, and two Poincaré angles ϕ and χ that characterize the optical polarization, where ϕ $(0 \leq \phi \leq \pi)$ is the direction of the polarization ellipse and χ $(-\pi/4 \leq \chi \leq \pi/4)$ is the ellipticity angle. For practical VCSELs the output polarization is approximately linear, in a direction that we define to be the x-axis, so that:

$$\mathbf{E} \approx [\mathbf{e}_x - (\phi + i\chi)\mathbf{e}_y]\sqrt{I}e^{-i\varphi_l} . \tag{1}$$

We study the polarization dynamics in VCSELs via the natural fluctuations in the polarization angles ϕ and χ. The polarization dynamics is thus separated into a *(stochastic) diffusion*, due to noise, and a *(deterministic) flow*, due to possible polarization preferences. For VCSELs that operate not too close to the lasing threshold, the intensity I is relatively stable, and the polarization and intensity dynamics are almost decoupled.

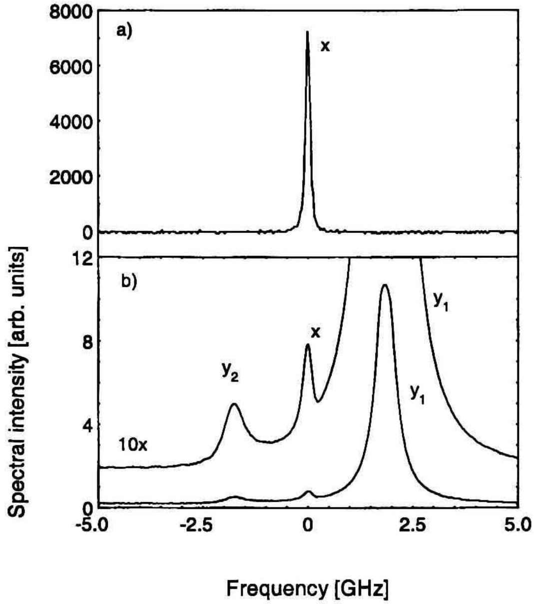

Figure 1: Optical spectra taken at: (a) the dominant x polarization, (b) close to the y polarization, showing the "nonlasing" peak y_1 and a weak polarization-type of four-wave-mixing peak y_2

2 Optical and intensity noise spectra

One way to study the polarization dynamics is via the polarization-resolved optical spectrum. The upper part of Fig. 1 shows the optical spectrum at the dominant (x) polarization, the lower part shows the spectrum in the almost orthogonal polarization (in the same units), with as little as 5×10^{-4} of the dominant polarization mixed in on purpose. The y-polarized light, which depends on the complex variable $\phi + i\chi$, is concentrated in a spectral line (y_1) that is shifted and broadened with respect to the x-polarized line and that can be associated with the "non-lasing" polarization mode. The shift or frequency difference between the two lines ($\approx$ 1.8 GHz in Fig. 1) is associated with birefringence. The broadening ($\approx$ 0.2 GHz in Fig. 1) is associated with a polarization-dependent gain difference of dichroism. Both comprise a linear and nonlinear part. The weak spectral line y_2 in Fig. 1 results from a polarization-type of four-wave-mixing. It can be used to quantify the mild preference for VCSELs to emit linearly polarized light, which results from (relatively fast) internal spin dynamics [1].

Another way to study the polarization dynamics is via the polarization-resolved intensity noise, as demonstrated in Fig. 2. The two curves denoted as ϕ and χ show the intensity noise spectrum as measured behind a polarizer oriented at 45° with respect to the x-axis, either without or with an additional $\lambda/4$-plate. These polarization projections mix x and y-polarized light and allows one to separately detect the dynamics of the polarization angles ϕ and χ. The ϕ and χ spectra peak around the birefringent frequency and have a width that is equal to the dichroism. The curves denote as x and y show the intensity noise after

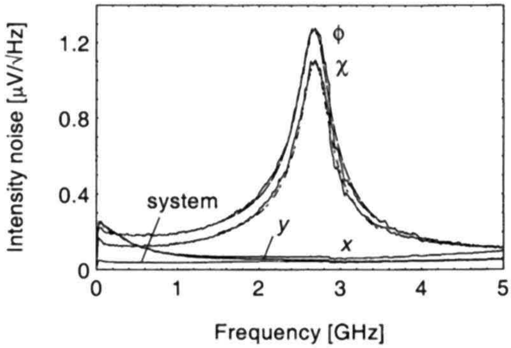

Figure 2: Intensity noise spectra, as measured behind a polarizer (i) at 45° with respect to the laser polarization (curves ϕ and χ (with additional $\lambda/4$-plate)), and (ii) aligned with the x or y-axes as defined by the dominant laser polarization.

projection on either one of the polarization modes. These noise spectra are almost identical, are strongly peaked around zero frequency, and have a width that is equal to the dichroism. The total intensity noise, as measured without any polarization projection, is generally small and peaks at the (relatively large) relaxation oscillation frequency. A tail of this peak is visible in the high-frequency intensity noise of the lasing mode (curve x).

3 Polarization modal noise

The noise spectra shown in Fig. 1 and 2 are a-typical in the sense that they belong to a VCSEL with relatively small birefringence. For the more common VCSELs, with a birefringence in the range of 10-20 GHz, the polarization evolution is fast enough to average out the nonlinear anisotropy, i.e., the intrinsic preference of VCSEL to emit linearly polarized. As a result, the four-wave mixing peak in Fig. 1 becomes too weak to observe (its magnitude scales with the inverse square of the birefringence), and the ϕ and χ spectra shown in Fig. 2 become essentially identical. This allows one to separate the polarization dynamics into a fast oscillation between ϕ and χ, and a much slower (and more interesting) evolution of the mode fraction $Y = I_y/I$, where I_y and I are the power in the nonlasing mode and the total power, respectively. For small mode fractions, Y exhibits "thermal-like" fluctuations [2] with an average amplitude

$$\langle Y \rangle = \langle \frac{I_y}{I} \rangle = \langle \phi^2 + \chi^2 \rangle = \frac{D}{\gamma}. \tag{2}$$

Typical values are $D = 10\ \mu s^{-1}$ for the diffusion rate, and $\gamma = 1\ ns^{-1}$ for the dichroism, making the average mode fraction $\langle Y \rangle$ about 1%.

The birefringence and dichroism change with current. In many VCSELs an increase in current leads to a reduction in dichroism, to an increase in polarization fluctuations, and finally to a switch of the dominant polarization. Polarization switches that occur at large currents often show hysteresis, whereas switches at lower current are of a stochastic nature

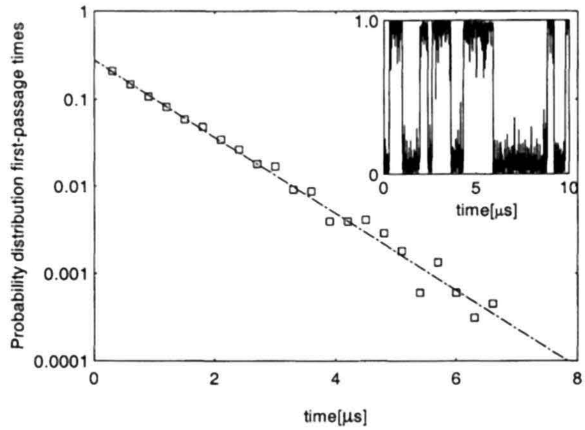

Figure 3: Distribution of average dwell times in one polarization mode for a VCSEL that spontaneously switches polarization.

(see inset of Fig. 3 for time trace of projected intensity). The random nature of this process is evident from the exponential probability distribution of the average dwell times in one of the two states, as shown in the body of Fig. 3. For this case (current 6.4 mA, corresponding to $\mu = 1.3$ time above threshold) the average dwell time was 1.0 μs [3].

Figure 4 shows how the average dwell-time for polarization switches changes by more than 7 orders of magnitude as a function of switch current, where the switching point was adjusted by modification of the VCSEL with an intense heating laser positioned $\pm$ 40 μm away from the device. The solid line is calculated on the basis of a simple Kramer's hopping model, with no adjustable parameters; the key parameters in this model, being the noise strength and the shape of the double well potential well, could be determined from independent measurements that gave the related diffusion rate D and dichroism γ, respectively.

4 Correlated modal fluctuations

Finally we again consider the polarization flucutions of a VCSEL outside the (relatively narrow) regime of polarization switches and wonder to what extent the intensity fluctuations in the x and y polarized mode are correlated, as quantified by the (real-valued) frequency-dependent correlation function

$$C_{xy}(\omega) \equiv \frac{Re\left(\langle \tilde{I}_x(\omega)\tilde{I}_y^*(\omega)\rangle\right)}{\langle|\tilde{I}_x(\omega)|^2\rangle^{1/2}\,\langle|\tilde{I}_y(\omega)|^2\rangle^{1/2}}$$

Figure 5 shows how the low-frequency component of C_{xy} changes with current, for a VC-SEL that switches polarization around 8-8.5 mA [4]. The intensity fluctuations in the two polarization modes show a strong anti-correlation, with the deviation from prefect anticorrelation ($C_{xy} = -1$) being proportional to the ratio of the low-frequency noise in the total intensity I and the mode fraction Y. Close to the switching point, where the dichroism is

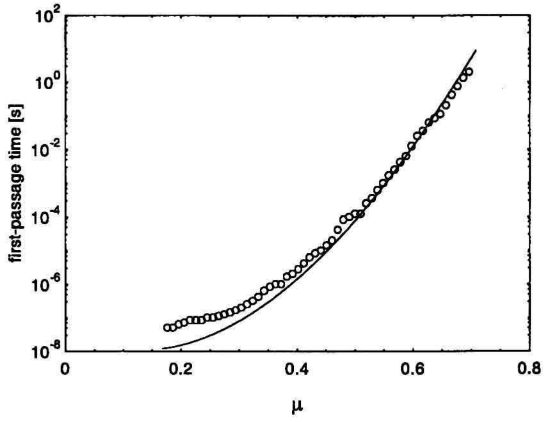

Figure 4: Average dwell time in each of the two polarization states as a function of the normalized pumping parameter $\mu = I/I_{th} - 1$. The dots are experimental data (obtained for a single VCSEL) and the curve is a theoretical fit.

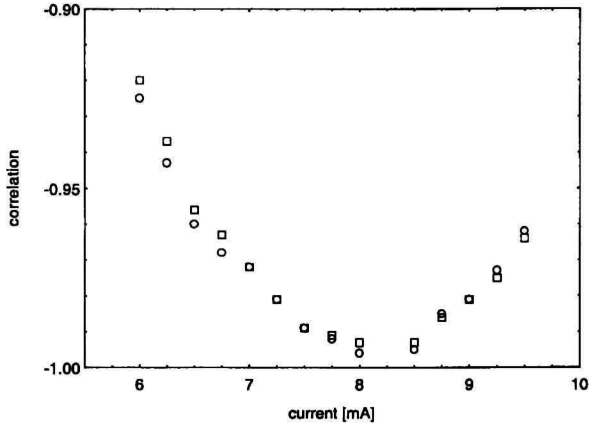

Figure 5: Low-frequency correlation C_{xy} as a function of current. Around a current of 8-8.5 mA, where the dominant laser polarization switches, the dichroism is smallest, the polarization fluctuations are strongest, and the correlation between the modal intensity fluctuations is largest.

small and the polarization fluctuations are large (large Y), the anti-correlation is strongest. The measurements presented in Fig. 5 support the earlier statement that the dynamics of the polarization mode fraction Y and the total intensity I are almost decoupled, as the squares and circles result from data analysis with and without the assumption of decoupling, respectively. A more quantitative discussion of this statement has allowed us to estimate the (limited) deteriorating effect of polarization mode partition noise on the possibility to obtain intensity squeezing.

References

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