Proceedings Symposium IEEE/LEOS Benelux Chapter, 2000, Delft, The Netherlands

Experimental study of polarisation mode-hopping in single-mode VCSELs

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We present an accurate experimental characterisation of the dynamical properties of polarisation switching (PS) in single transverse and longtudinal mode vertical-cavity surface-emitting lasers (VCSELs). When a VCSEL is biased at its polarisation switching current, it mode-hops. The hopping frequency varies over several orders of magnitude depending on the relative difference between threshold and switching current. This behaviour is the trademark of a Kramers hopping system. We have performed a statistical experimental characterisation of the residence times of mode-hopping VCSELs for both proton implanted and oxide confined ones, and compared our results with theoretical predictions.

1. Introduction

Over the past years VCSELs (vertical-cavity surface-emitting lasers) have established themselves as the semiconductor lasers of the future for information technology applications. The secret of their success is low-cost mass manufacturability, combined with superior operation characteristics to their edge-emitting counterparts.

The cylindrical symmetry of the cavity is also the cause of near indeterminacy of the polarisation state of the emitted light. Due to the elasto- and electro-optic effect two linear polarisation modes are chosen – within the fundamental transverse mode – usually along [1 1 0] and [1 $\bar{1}$ 0]. Their stability differs only slightly and varies with the operation parameters. As a result some VCSELs show polarisation switching behaviour, which can be desirable or not, depending on the application. But whatever the motivation, a thorough understanding and characterisation of this effect is called for.

The experimental work presented here deals with the dynamical aspects of polarisation switching, and more precisely with what is generally called mode-hopping. When a VCSEL is biased at its polarisation switching current, the spontaneous emission noise causes random switching between the two modes. We look here at the typical time-scale involved, namely the dwell time or Kramers time (T_k), which is the average time of residence in one of the modes. From theory and earlier experiments [1], [2] we expect a variation over several orders of magnitude of this dwell time when the switching current is moved with respect to the threshold current.

In section 2 we give an overview of the theory, applied to a simple rate equation model. Section 3 summarises the experimental set-up as well as the obtained results. In section 4 we draw conclusions.

2.The two-well potential

In [4] we describe how a Langevin equation can be derived for a polarisation mode-hopping VCSEL. We use a simple intensity rate equation model for two nearly degenerate modes. Key ingredients are current dependent gain coefficients for the two modes (which cause the PS) and optical saturation (which cause a region of bistability around the PS point). When the carrier noise is neglected, we derive one dynamical equation for one of the modes [4], [5]:

$$\begin{aligned} \frac{dp_y}{dt} &= \frac{(\varepsilon_{sx}+\varepsilon_{sy}-\varepsilon_{xy}-\varepsilon_{yx})}{J}p_y^3+(2\varepsilon_{yx}-2\varepsilon_{sx}+\varepsilon_{xy}-\varepsilon_{sy}-\frac{G}{J})p_y^2 \\ &\quad +[(\varepsilon_{sx}-\varepsilon_{yx})J+G-\frac{2R_{sp}}{J}]p_y+R_{sp}+\widetilde{F}_y-\frac{\widetilde{F}_x+\widetilde{F}_y}{J}p_y \end{aligned} \tag{1}$$

ε_{ij} are optical saturation coefficients, $G(J)$ is the current dependent gain difference between the modes, J is the current pump and time has been reduced with respect to the carrier life-time (i.e. ns).

The deterministic part of this Langevin equation defines a two-well potential, as can be seen on Fig 1. First passage time calculations from one well to the other [**?**] allow to obtain the dwell-time in the case of a symmetric potential. In case of a symmetric potential the average residence times of both states are equal and given by [4]:

$$T_K = T_c \exp\left[\frac{K_p}{D}(\frac{I_{sw}}{I_{th}}-1)^3\right] \tag{2}$$

K_p and T_c are functions of the parameters, I_{sw} and I_{th} are switching and threshold current, and D is the variance of the noise terms. As from now we will refer to $(\frac{I_{sw}}{I_{th}}-1)$ as μ. Assuming that $D \backsim \mu$ Eq.(2) becomes

$$T_K = T_c \exp(K_p \mu^2) \tag{3}$$

The aim of the experiments described in the next paragraph is to verify this relation between T_K and μ.

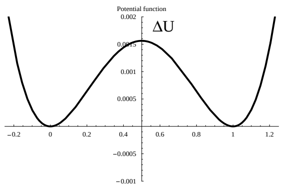

Figure 1: The symmetric bistable potential based on (1)

3. The experiments

For the measurements we used the set-up depicted in Fig 2. The temperature controller, the laser driver and the APD are in-house made components. The 1 GHz oscilloscope (Lecroy) has built-in functions for statistical analysis which allow for on-line measurement of the dwell-time as well as histograms of the mode-hopping. To tune the PS current with respect to the threshold current, the VCSEL is mounted in a self-made holder with which we can induce uniaxial strain in the VCSEL package.[6] By varying the strength and the direction of the strain we were able to tune μ between 0.15 and 0.8. When measuring T_K it is important that the two-well potential is symmetric. To maintain this symmetry a feedback loop was introduced.

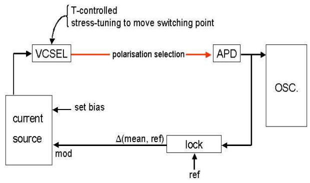

Figure 2: The set-up: APD = Avalanche Photodiode, OSC = Oscilloscope, the feedback loop feeds the difference of the mean of the APD signal with a reference value back to the current input of the VCSEL

We performed our measurements on two different types of VCSELs: a proton implanted one from VIXEL corporation, operating around 850 nm with a threshold of about 7 mA; and an airpost type VCSEL from CSEM, operating around 980 nm with a threshold of about 3.3 mA. In Fig 3 a & b we plot the measured dwell-times as a function μ.

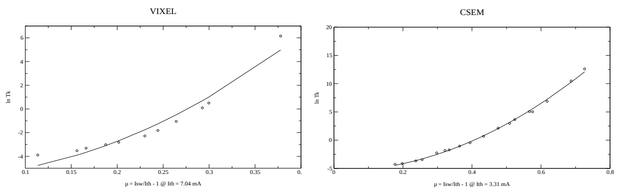

Figure 3: a & b - Dwell time as a function of μ; circles: measured ln T_k as a function of μ; full: fitted curve $\ln(T_k) = a + b\mu^2$ left (a) : proton implanted VIXEL-Corp VCSEL operating at 850 nm with $I_{th} = 7.04$ mA - fitting values $a = -5.7$, $b = 75.0$, with $\chi^2 = 3.937$ and a correlation coefficient of 0.976 right (b): airpost CSEM VCSEL operating at 980 nm with $I_{th} = 3.31$ - fitting values a=-5.5, b=33.4, with $\chi^2 = 0.986$ and a correlation coefficient of 0.9998

We fit the values with the expected expression:

$$\ln(T_k) = a + b\mu^2 \tag{4}$$

For the CSEM VCSEL we see a striking quality of the fit. The fitting parameter values are $a = -5.5$ and $b = 33.4$, with $\chi^2 = 0.986$ and a correlation coefficient of 0.9998. For the VIXEL-Corp. VCSEL the fit is not quite as good: $a = -5.7$ and $b = 75.0$, with $\chi^2 = 3.937$ and a correlation coefficient of 0.976. Puzzled by this difference, we repeated the fit, this time leaving the power in μ as a fitting parameter:

$$\ln(T_k) = a + b\mu^c \tag{5}$$

We obtain a best fit for $a = -3.94$, $b = 316.2$ and $c = 3.54$, with $\chi^2 = 0.034$ and a correlation coefficient of 0.9998. The new fit is shown on Fig 4. So far there is no theoretical model which predicts an order different from 2 in μ for the μ dependence of

T_k. When we use (5) to fit data of the CSEM VCSEL we get the following fitting values: $a = -5.04$, $b = 34.88$ and $c = 2.17$, with $\chi^2 = 0.679$ and a correlation coefficient of 0.9992. Within the measurement error this is not significantly better than the fit with (4).

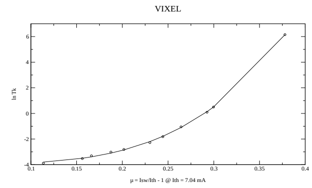

Figure 4: Dwell time as a function of μ; circles: measured lnT_k as a function of μ; full: fitted curve $\ln T_k) = a + b\mu^c$ proton implanted VIXEL-Corp VCSEL operating at 850 nm with $I_t h = 7.04$ mA - fitting values : $a = -3.94$, $b = 316.2$ and $c = 3.54$ with $\chi^2 = 0.034$ and a correlation coefficient of 0.9998

We checked the robustness of the fits to measurements errors and the influence of the exact value of the threshold current. We can conclude that the influence on the obtained results is negligible. Therefore,a measurement error cannot account for the unexpected power in μ. This matter will be object of further study.

4. Conclusions

In this work we have performed a thorough experimental study of the average time of residence in the two polarisation states of the VCSEL in its polarisation mode-hoping regime. The measurements to verify this relation were performed on both a proton implanted VCSEL and an airpost onė. The datapoints of the airpost VCSEL fit very well with the theory. For the proton implanted one the agreement is less clear, and the best fit is actually obtained for a power of 3.5 in the μ-dependence of T_k. This surprising result, which none of the existing theories can explain for the moment, will be the subject of further study.

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