Thermal and current driven polarization modulation frequency response in VCSELs

Guy Verschaffelt, Jan Albert, Irina Veretennicoff, Jan Danckaert, Sylvain Barbay[2], Giovanni Giacomelli[2] and Francesco Marin[3]

Department of Applied Physics and Photonics (TW – TONA), Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium

[2] Istituto Nazionale di Ottica Applicata and INFM, Largo E. Fermi 6, 50125 Firenze, Italy

[3] Dept. Physics, Univ. Firenze and INFM and LENS, Largo E. Fermi 2, 50125 Firenze, Italy

We present an experimental study on the current driven polarization modulation properties of VCSELs. Some VCSELs exhibit a high-contrast polarization switch for a particular value of the pump current. When modulating the current around this value, we measure the critical modulation amplitude necessary to consistently enforce the polarization flips. The resulting frequency response curve has a shape characterized by time constants that are very long compared with the usual time scales of laser dynamics, and compatible with the measured thermal relaxation time. This study indicates that it is necessary to incorporate a temperature-dependent variable in realistic models describing the polarization behavior of these VCSELs.

Introduction

The polarization state of the light emitted by Vertical-Cavity Surface-Emitting Lasers (VCSELs) is not defined a priori by their structure. Nevertheless, VCSELs do actually emit linearly polarized light in one of two orthogonal linear polarization modes (PMs), which are usually oriented according to specific crystallographic directions. The two PMs have a frequency difference, which can vary between 1 and 40 GHz [1,2]. In some VCSELs, polarization switching (PS) between PMs is observed as the current is changed. During the past few years several experimental [3-8] and theoretical works [9-11] have aimed at understanding this effect. Roughly speaking, the different proposals for explaining the observed PS can be divided into two categories: those invoking slow (lattice) thermal mechanisms [3,5,6] and those relying on other, faster mechanisms [4,10,11]. The dynamical mechanism and the dominating time-scales of PS are not only interesting from a physical point of view, but also of great practical importance if one wishes to exploit the VCSEL's polarization properties for applications [12,13] where fast and controlled PS is required.

In this paper we present the first results of an experimental investigation of the current driven polarization modulation properties of VCSELs as a function of both the amplitude and frequency of modulation. We have studied different types of VCSELs (proton-implanted, air-post and oxide-confined), operating at different wavelengths (850 and 980nm) and presenting different types of switching (from the lower to the higher optical frequency mode with increasing current, called type II PS, and vice versa). The results are qualitatively analogous. For the sake of brevity we focus here on the results obtained on proton-implanted VCSELs from VIXEL Corporation. While the steady state characteristics of these devices and also some of the dynamical features have already been reported [5-7,14], the experimental study presented here is original and represents a critical testbench for the models describing the polarization features of VCSELs.

Measurement procedure and experimental results

Our gain-guided proton-implanted GaAs/AlGaAs quantum-well VCSEL operates around 850nm and exhibit a threshold current close to 7mA. The VCSEL shows type II PS in its single-transverse mode regime, while being operated under CW-conditions on the high frequency side of the gain maximum [6]. The switching current can be tuned over the entire current region of single transverse mode behavior, by applying a controlled amount of stress via a customized laser holder [7].

In our setup, the light emitted by the VCSEL is collimated with a lens and sent through a linear polarizer to select one of the two PMs. The polarization resolved intensity impinges on a 2-GHz bandwidth detector whose output signal is visualized on an oscilloscope. All the optical components are slightly misaligned to prevent optical feedback, which could cause extra instabilities in the VCSEL. The bias current generated by a stabilized current source and the modulation signal from a function generator are combined in a bias-T and subsequently sent through the VCSEL. Furthermore, the temperature of the VCSEL package is actively stabilized within few mK. The frequency responses of all the electronic components have been calibrated beforehand. Moreover, the overall amplitude response (from the signal generator to the laser current) was checked to be linear up to at least several hundreds of MHz.

When the VCSEL is biased close to the PS current, random mode hopping between the two orthogonally polarized fundamental modes occurs [15-17]. These stochastic hoppings, due to spontaneous emission and to the small differences pinning the polarizations, also show up in modulation experiments [14]. Indeed, while modulating around the switching current, PS occurs with a random delay (i.e. jitter). If this delay is longer than half the modulation period a polarization switch will be missed. We define a ‘successful’ modulation period as one where the laser undergoes the complete PS cycle.

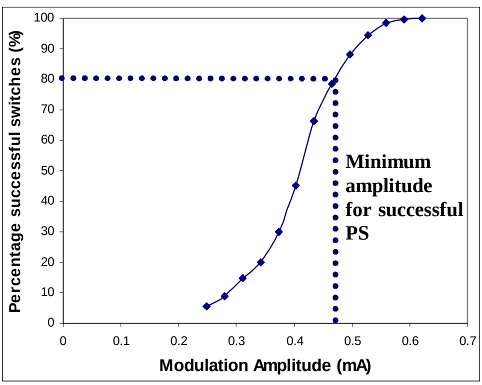

Fig. 1. Fraction of ‘successful’ cycles as a function of the modulation amplitude. The VCSEL is biased at a PS current of 9.85mA and modulated with a 200 kHz sinusoidal signal.

In our experiment we bias the laser at the PS point where the laser randomly jumps, spending on the average the same time in the two PMs. Then we apply a sinusoidal modulation current with varying amplitude and fixed frequency. In Fig. 1 we plot the measured fraction of successful periods as a function of the modulation amplitude. For low amplitudes there are only a small number of successful cycles, but this fraction rapidly grows as the modulation amplitude is increased: a narrow transition region (~ 0.5mA) leads to a regime of very effective current-driven PS. This effect can be easily understood if one assumes that he/she is modulating the current around the center of a hysteresis cycle: there is no PS if the modulation amplitude is smaller than the hysteresis width, and stable PS if it is larger. The stochastic effects smooth the edges of the hysteresis region, but the transition shown in Fig. 1 is still very sharp.

Based on Fig. 1, we define the minimum amplitude for current-driven polarization modulation as the amplitude yielding 80% successful modulation cycles. We have measured this minimum amplitude as a function of the modulation frequency. In Fig. 2

we plot the inverse of this minimum amplitude, as this yields a proper way to compare the PS frequency response with that of a standard first order system (see further). These measurements were performed for switching currents of 9.85mA and 10.3mA, corresponding to dwell-times of 10ms and 5s, respectively. We have chosen these high switching currents, as the associated long dwell-times minimize interference between the mode hopping phenomenon and switching induced by current modulation.

In Fig. 2 two regimes, separated by a cut-off frequency of about 90 kHz, can clearly be distinguished. Quite surprisingly, the minimum amplitude does not converge to a fixed value in the low frequency range, where there is a clear (albeit weak) monotonic decrease of the PS response with increasing frequency. Above 90 kHz the PS frequency response decreases drastically with increasing frequency. For higher frequencies (above 3 MHz), the measurements are disturbed by the large required modulation amplitude that drives the VCSEL from circa threshold up into the higher transverse mode regime. When we compare the experiments for different switching currents, we notice a vertical shift of the measured response curve that can be explained with a larger bistable region around the PS point for higher switching currents, but the overall shape of the frequency response of the minimum amplitude is not changed.

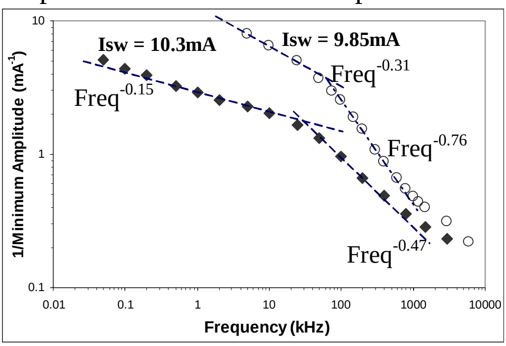

Fig. 2. PS frequency response for switching currents I_{sw} = 9.85 and 10.3mA.

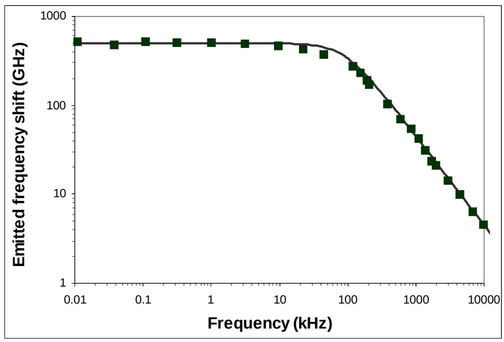

Fig. 3. Thermal frequency response measured at a bias current of 11.1mA and modulation amplitude of 0.1mA (filled squares) and fit to a first-order response function with a cut-off frequency of 90 kHz (solid line).

The PS cut-off frequency in VCSELs is much lower than what could be expected from the measured switching time of 10ns [8,14], and is also much lower than the one encountered in edge-emitting lasers (where 500 MHz PS has been reported [18]). The low cut-off frequency in VCSELs cannot be explained on the basis of existing models [9-11] that only take much faster time scales into account (such as photon and carrier lifetimes). Thermal properties are an obvious candidate for explaining this effect. To test this conjecture, we have evaluated the thermal response of the VCSEL with a scanning Fabry-Perot spectrum analyzer by measuring chirp ΔF of the emitted optical frequency as a function of the modulation frequency. The emitted optical frequency is indeed determined by the cavity resonance, which in its term depends on the lattice temperature of the laser cavity. For the measured frequency range, ΔF is mainly due to Joule heating. The result of this measurement is shown in Fig. 3. This thermal response corresponds very well to the transfer function of a linear first order system, given by:

$$\frac{\Delta F}{\Delta I} = \frac{A}{\sqrt{1+\left(f/f_0\right)^2}}$$

where f is the modulation frequency, f_0 is the cut-off frequency, A is a proportionality constant and ΔI is the current modulation amplitude, which is kept constant throughout the measurement. When we compare the PS and thermal characteristics, we notice two main differences. First, the polarization modulation response at low frequencies is not as flat as the thermal response. Secondly, in the high frequency region the PS frequency response does not decrease as fast as the thermal response curve. The origin of these differences requires further investigations. Nevertheless, both response curves show a cut-off frequency of about 90kHz, suggesting that thermal effects play an essential role in the PS phenomenon.

Conclusion

In conclusion, we have studied the current driven polarization modulation properties of an 850 nm VCSEL as a function of both amplitude and frequency of the modulation. The device exhibits a type II polarization switch. We measured the PS frequency response for different values of the switching current. This frequency response displays a clear cut-off of about 90 kHz that coincides with the measured thermal cut-off frequency of the VCSEL, suggesting that it is necessary to incorporate a temperature-dependent variable in the models in order to realistically describe the dynamics of PS in VCSELs. This can be done for instance by taking the temperature dependence of gain (material [3] and/or modal [5]) or losses [6] into account.

Acknowledgements

This research was supported in Belgium by the FWO, IUAP, GOA and the OZR of the VUB. GV and JD acknowledge the FWO (Fund for Scientific Research - Flanders) for their fellowships. The collaboration between the Brussels and the Florence groups was supported by EU programs COST268 and the RTN network VISTA (contract nr. HPRN-CT-2000-00034).

References

[1] A.K. Jansen van Doorn, M.P. van Exter, and J.P. Woerdman, Appl. Phys. Lett. 69, 3635 (1996).
[2] M.P. van Exter, A.K. Jansen van Doorn, and J.P. Woerdman, Phys. Rev. A. 56, 845 (1997).
[3] K.D.Choquette, D.A.Richie, and R.E.Leibenguth, Appl. Phys. Lett. 64, 2062 (1994).
[4] J. Martin-Regalado, J.L.A. Chilla, J.J.Rocca, P. Brusenbach, Appl. Phys. Lett. 70, 3350 (1997).
[5] K. Panajotov, et al., Photon. Technol. Lett. 10, 6 (1998).
[6] B. Ryvkin, et al., J. Opt. Soc. Am. B 16, 2106 (1999).
[7] K. Panajotov, et al., Appl. Phys. Lett. 77, 1569 (2000).
[8] M.B. Willemsem, M.P. van Exter, and J.P. Woerdman, Phys. Rev. Lett. 84, 4337 (2000).
[9] M. San Miguel, O. Feng, and J.V. Moloney, Phys. Rev. A 52, 1728 (1996).
[10] S. Balle, et al., Opt. Lett. 24, 1121 (1999).
[11] A. Valle, L.Pesquera, and K.S. Shore, Photon. Technol. Lett. 9, 557 (1997).
[12] K. Panajotov, et al., IEEE Photon. Technol. Lett. 11, 985 (1999).
[13] S. Barbay, G. Giacomelli, and F. Marin, Opt. Lett. 25, 1095 (2000).
[14] G. Verschaffelt, et al., and K. Gulden, Proc. of SPIE 3946, 246 (2000).
[15] G. Giacomelli, et al., Optics Commun. 146, 136 (1998).
[16] G.Giacomelli, F. Marin, and I. Rabbiosi, Phys. Rev. Lett. 82, 675 (1999).
[17] M.B. Willemsem, M.U.F. Khalid, M.P. van Exter, and J.P. Woerdman, Phys Rev. Lett. 82, 4815 (1999).
[18] A. Klehr, R. Müller, M. Voss, A. Bänwolff, Appl.Phys.Lett. 64, 830 (1994).