Very wide Hysteresis Cycles in 1550 nm-VCSELs subject to Orthogonal Optical Injection

A. Quirce, A. Valle, and L. Pesquera

Abstract—**A first experimental observation of three different types of frequency-induced polarization bistabilities in 1550-nm single transverse and polarization mode VCSELs subject to orthogonal optical injection is described. The hysteresis width of the bistable region that appears at longer wavelegth detunings increases as the injected power or the VCSEL current increase. Very large hysteresis widths are obtained. Those widths are more than seven times larger than previously reported widths.**

***Index Terms*—Optical injection, vertical-cavity surface-emitting laser (VCSEL), optical bistability, polarization switching.**

I. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) are very promising light sources for all-optical signal processing due to their inherent advantanges (low threshold current, circular output-beam profile, ease of fabrication of 2D arrays, low cost, etc.) [1]. Optical injection in VCSELs is an attractive method to obtain bistable behaviour and nonlinear switching which can be used for the previously mentioned applications [1-9]. Polarization switching and optical bistability have been reported in VCSELs subject to orthogonal optical injection [2-9]. In that configuration linearly polarized light from a tunable laser source (master laser, ML) is injected orthogonally to the linear polarization of a free-running VCSEL. Switching from that polarization to the orthogonal polarization mode is observed as the injected power increases [2-9]. “Pure-frequency polarization bistability”, that is the bistability found in the VCSEL when changing the ML wavelength with a fixed ML power, has been found in experiments [3], [5], [7], [10] and analyzed from a theoretical point of view [4], [10]. Experiments with 1550 nm VCSELs have been recently performed [5-8] due to the potential of these devices for their use in optical interconnects, optical switching and optical signal processing at that important telecommunication wavelength. When 1550 nm VCSELs are biased slightly above threshold bistable behavior in the orthogonal polarized mode is found when the detuning between the wavelength of the master laser, λ_{ML}, and the wavelength of the orthogonal polarized mode, $\lambda_{\perp}$, $\Delta\lambda=\lambda_{ML}-\lambda_{\perp}$, is positive [7]. Hysteresis widths are smaller than 2 GHz for the considered VCSEL currents, I_{VCSEL} (smaller than 1.3 times the threshold value, I_{th}) [7]. Optical bistability in the orthogonal polarized mode has been observed for both the positive and negative detuning range when the 1550 nm VCSEL is biased well above threshold [5]. Typical hysteresis widths around 5 GHz were found for a VCSEL biased at four times threshold.

In this work we perform an experimental study of the bistable behaviour of a 1550 nm wavelength single-mode linearly polarized VCSEL when subject to orthogonal optical injection. In our experiment the injected power is increased well above the values considered in Ref. [5]. Our results show, for the first time, that three bistable regions can be observed. We show that the hysteresis width of one of those bistable regions significatively increases as the injected power or the applied bias current increase. Measured values of that hysteresis width can go beyond 37 GHz. Those values are much larger than previously reported widths [3], [5], [7].

II. EXPERIMENTAL ARRANGEMENT

Experimentally, the orthogonal optical injection is achieved by using the setup presented in Fig. 1. This setup is based on the experiments of Refs. [5], [7]. An all-fiber system has been developed in order to inject the light from a tunable laser into the VCSEL. A quantum-well commercial VCSEL (RayCan) that emits around 1536 nm has its bias and temperature controlled. Temperature was held constant at 297 ^{o}K during the experiments. The free-running VCSEL emits in the fundamental transverse mode with I_{th}=1.62 mA. The VCSEL emits in a linear polarization, that we will call the “parallel” polarization, along the whole current range. The orthogonal polarization is suppressed 38 dB for a VCSEL current, I_{VCSEL}, of 6 mA, and it is shifted 0.48 nm to the long wavelength side with respect to the dominant one. Further

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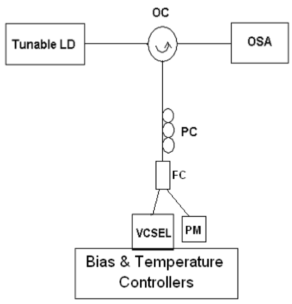

Fig. 1. Experimental set-up of orthogonal optical injection in a VCSEL. OC: optical circulator; PC: polarization controller; FC: fiber coupler; PM: power meter; OSA: optical spectrum analyzer.

details of this VCSEL, like the L-I curve and optical spectrum, can be found in Ref. [5]. The output of the tunable laser is injected into the VCSEL via a three-port polarization maintaining optical circulator (OC). The control of the polarization injected into the VCSEL is achieved by using a polarization controller (PC). An optical spectrum analyzer (OSA) is used to perform spectral and power measurements. A fiber coupler (FC) with a 2/98 split ratio and a power meter (PM) are used to measure the injected power that arrives at the VCSEL, P_{inj}.

III. RESULTS

In our previous work we showed that as λ_{ML} is scanned near $\lambda_\perp$ with fixed injection power, P_{inj}, the VCSEL exhibits two successive polarization switchings (PS) with two bistable regions in such a way that pure frequency-induced polarization bistabilities were found (see Fig. 4 of Ref. [5]). In our present setup we have been able to significatively increase P_{inj} by using all the elements with the same type of fiber connectors (FC/APC). The consideration of larger values of P_{inj} changes the behaviour obtained in Ref. [5] as it can be seen in Fig. 2, where the output power of the orthogonal polarization, $P_\perp$, is plotted as a function of the wavelength detuning, $\Delta\lambda$. Two bistable regions (corresponding to PS from the parallel to the orthogonal polarization and viceversa, marked with I and II in Fig. 2(a), respectively) similar to those obtained in Ref. [5] appear in Fig. 2(a). Both bistable regions can be described in a theoretical way by using a model that takes into account the lasing transitions between the spin sublevels of the conduction and valence bands of a quantum-well semiconductor [4]. In fact, Ref. [10] shows that the experimental dependence of the width of both hysteresis cycles on P_{inj} is similar to the obtained theoretically with the model of Ref. [4]. We also observe that a new third bistable region appears at longer $\Delta\lambda$. That third bistable region is the one marked with III in Fig. 2. That bistable region was also found in Ref. [7] but no observation of the simultaneous presence of those three bistable regions was done in that work. For the first time to our knowledge, we measure the width and depth of that third bistable region as a function of P_{inj} and of the bias current, I_{VCSEL}. Fig. 2 shows that both the width and depth increase as

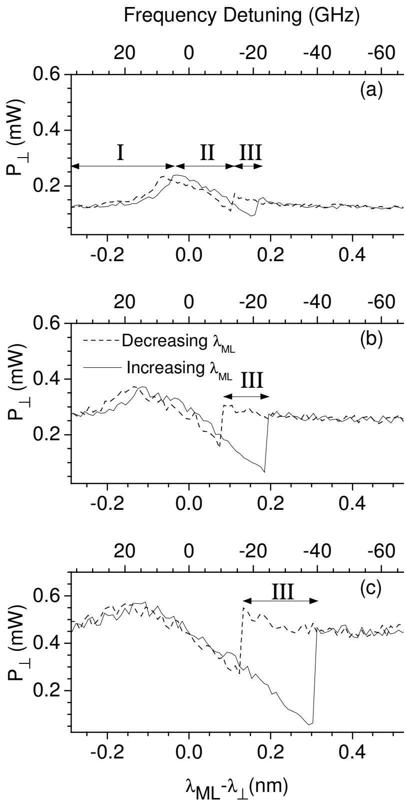

Fig. 2. Output power in the orthogonal polarization vs the wavelegth detuning when increasing (solid lines) and decreasing (dashed lines) λ_{ML} for injection powers (a) P_{inj}=0.75 mW, (b) P_{inj}=1.5 mW, and (c) P_{inj}=2.7 mW. In this figure I_{VCSEL}=4mA and $\lambda_\perp$=1534.74 nm.

P_{inj} increases. Anticlock-wise, clock-wise, and anticlock-wise responses are obtained as the wavelength detuning increases, as it is shown in Figs. 2(a) and (b). However, Fig. 2 (c) shows that the first two bistable regions that appear at lower λ_{ML} are not well defined when P_{inj} is large. In that situation the power of the VCSEL becomes a small fraction of the injected power. Those bistable regions are then hidden due to the larger influence of the fluctuating character of the power reflected by the VCSEL cavity.

Measurements of the output powers in the orthogonal and parallel, $P_\parallel$, polarizations, and of the total reflected power in both polarizations, P_{total}, as a function of the wavelength detuning have also been performed. Those measurements were obtained by substituting the optical circulator by another circulator that does not maintain the polarization. Fig. 3 shows the results for I_{VCSEL}=4 mA and two different values of P_{inj} Measurements of $P_\parallel$ and $P_\perp$ show qualitative behaviors similar to the one observed in Ref. [7] but with a much wider hysteresis cycle in the long wavelength bistable region due to our larger value of I_{VCSEL}. For instance, the 0.22 nm wide hysteresis cycle shown in Fig. 3 (b) is more than 15 times wider than the widest cycle reported in Ref. [7]. Fig. 3(a) shows that $P_\parallel$ displays clock-wise and anticlockwise responses as λ_{ML} increases. The ratio between $P_\parallel$ when decreasing and increasing λ_{ML} can be very large (around 40 dB at $\Delta\lambda$=0.45 nm in Fig. 3 (a)). We show in Fig. 3 (d)-(f) that the same

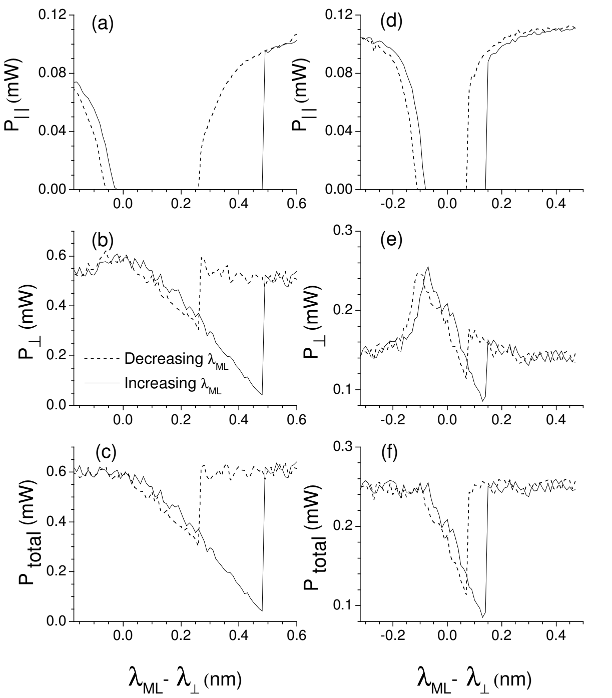

Fig. 3. Output power in the (a), (d) parallel polarization, (b), (e) orthogonal polarization, and (c), (f) total power, vs wavelength detuning when increasing (solid lines) and decreasing (dashed lines) λ_{ML}. Parts (a)-(c), and (d)-(f) correspond to P_{inj}=3.7 and 0.75 mW, respectively.

responses are obtained when decreasing P_{inj}, situation in which the three bistable cycles in $P_{\perp}$ are clearly defined. A wide bistable region at the same $\Delta\lambda$ also appear for P_{total}. The decrease of $P_{||}$ as λ_{ML} increases compensates the maximum observed in $P_{\perp}$, in such a way that P_{total} has no longer a maximum at negative wavelength detunings, as it is shown in Fig. 3.

The third bistable region becomes wider as the VCSEL current increases, as shown in Fig. 4, where the frequency width of that region has been plotted as a function of I_{VCSEL}. Hysteresis cycles are very wide: their width is larger than 20 GHz when I_{VCSEL} > 1.3 I_{th} and P_{inj}=3.7 mW. We note that a qualitatively similar hysteresis cycle appears when no current is applied to the VCSEL. That means that the origin of this third bistability lies in the passive cavity although Fig. 4 shows that the width is largely affected by the active operation of the device. We think that the aspect of the passive cavity that is responsible for the third form of bistability is the dispersive nonlinearity [8].

In conclusion, we have performed an experimental investigation of 1550 nm single transverse and polarization mode VCSEL subject to orthogonal optical injection. We have observed three different regions of bistability. The origin of the first two regions lies in the physical processes that determine the polarization of the VCSEL as an active device. A third bistability region, with a different physical origin to the one of the first two regions, appears at longer wavelength

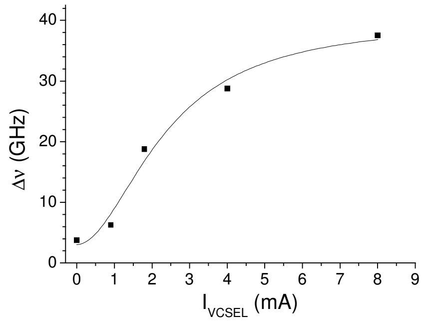

Fig. 4. Frequency width of the hysteresis cycle as a function of I_{VCSEL} when P_{inj}=3.7 mW. Squares represent experimental data.

detunings. We have shown that the frequency width of the third bistable region significatively increases as the injected power or the VCSEL current increase. Those frequency widths can go beyond 37 GHz, that is a value more than seven times larger than previously measured values [3], [5], [7]. Further theoretical work will be performed to obtain a model able to explain the three forms of bistability.

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