Polarization Switching in Long-Wavelength VCSELs Subject to Orthogonal Optical Injection

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***Abstract*— Polarization switching (PS) appearing in long-wavelength vertical-cavity surface-emitting lasers (VCSELs) subject to orthogonal optical injection is investigated theoretically and experimentally. We have studied the injected optical power required for PS as a function of the frequency detuning between the injected light and the orthogonal linear polarization of the VCSEL. For a wide range of bias currents applied to the device, the injected power required for the occurrence of PS exhibited a minimum and a plateau with respect to the frequency detuning. The minimum (plateau) was found at negative (positive) frequency detuning. The bistable behavior of the polarization is described. Our experimental results confirm the theoretical predictions of Sciamanna and Panajotov. The levels of the minimum and the plateau were observed to increase as higher bias currents were applied to the VCSEL. A first theoretical and experimental observation of the disappearance and further appearance of PS when increasing the injected power in long-wavelength VCSELs is described. This situation is obtained for small levels of negative frequency detuning and for large enough values of applied bias current. A good overall qualitative agreement is found between our theoretical and experimental results.**

***Index Terms*— Injection locking, optical injection, polarization switching, vertical-cavity surface-emitting lasers.**

I. Introduction

OPTICAL injection in semiconductor lasers has been a subject of interest for many years [1]. External injection of light in a laser diode is a technique that is commonly employed to achieve optical bistability. This has attracted considerable attention due to its potential applications in all-optical signal processing, optical switching, and optical storage [2]. Recently, the unique features of a special type of semiconductor laser, the vertical-cavity surface-emitting laser (VCSEL) [3]–[11], has led to increased research interest in these applications. VCSELs have demonstrated many impressive characteristics, including low threshold current, single-longitudinal mode operation, and a circular beam profile [12]. Additionally, the possibility to fabricate large 2-D arrays of VCSELs makes these devices very attractive for optical interconnects. For short-haul datacom, 850-nm VCSELs have become the ubiquitous optical solution, while long-wavelength VCSELs are also attracting considerable research effort for use in single-mode fiber metropolitan area networks [3]. Optical injection in VCSELs has also been used for the reduction of the frequency chirp undermodulation [13] as well as for the improvement of the modulation response [14]. Although VCSELs are intrinsically single-longitudinal mode devices, they usually show complex polarization characteristics [15]–[20] and multi-transverse mode dynamics [15], [21]–[25]. The light emitted by a VCSEL is commonly linearly polarized along one of two orthogonal directions, and polarization switching (PS) between the two linearly polarized modes is often observed when the injection current or temperature is varied. Understanding and controlling the VCSEL polarization is crucial for their use in polarization-sensitive applications such as magnetooptical disks and coherent detection systems.

Optical injection strongly affects the transverse mode and polarization characteristics of VCSELs. In fact, optical injection induces transverse mode selection in VCSELs emitting in multiple transverse modes [26]–[31]. This selection can be achieved when two modes of the free-running VCSEL have parallel or orthogonal polarizations [28]–[31]. When the VCSEL is emitting in the fundamental transverse mode, stable injection locking has been observed when both the VCSEL and the externally injected light have parallel polarization [32]. A different configuration, usually called "orthogonal optical injection," was used by Pan *et al.* [33] to inject light into a single transverse mode VCSEL. In that configuration, linearly polarized light from a tunable laser source is injected orthogonally to the linear polarization of the free-running VCSEL. Switching from that polarization to the orthogonal polarization mode has been observed as the injected power increases [4]–[11], [33]–[40]. Optical bistability associated with PS has also been reported theoretically [4], [7], [8] and experimentally [5], [9]–[11], [33]–[42]. In the seminal work

Manuscript received May 25, 2010; revised July 13, 2010; accepted July 20, 2010. Date of current version December 30, 2010. This work was supported in part by the Ministerio de Ciencia e Innovación, Spain, under project TEC2009-14581-C02-02, and in part by the European Commission, under the Program FP7 Marie Curie Intra-European Fellowships Grant PIEF-GA-2008-219682. The work of M. S. Torre was supported in part by Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina, under Grant PIP-114-200801-00163.

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Digital Object Identifier 10.1109/JQE.2010.2061219

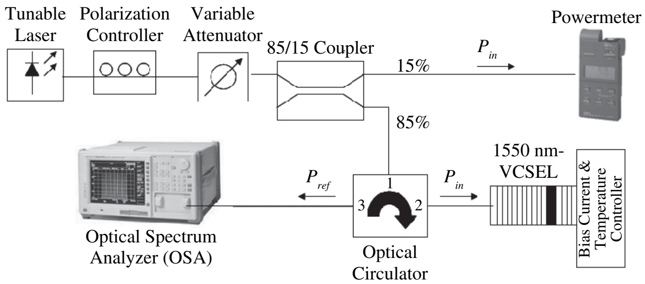

Fig. 1. Experimental setup for orthogonal optical injection in a VCSEL.

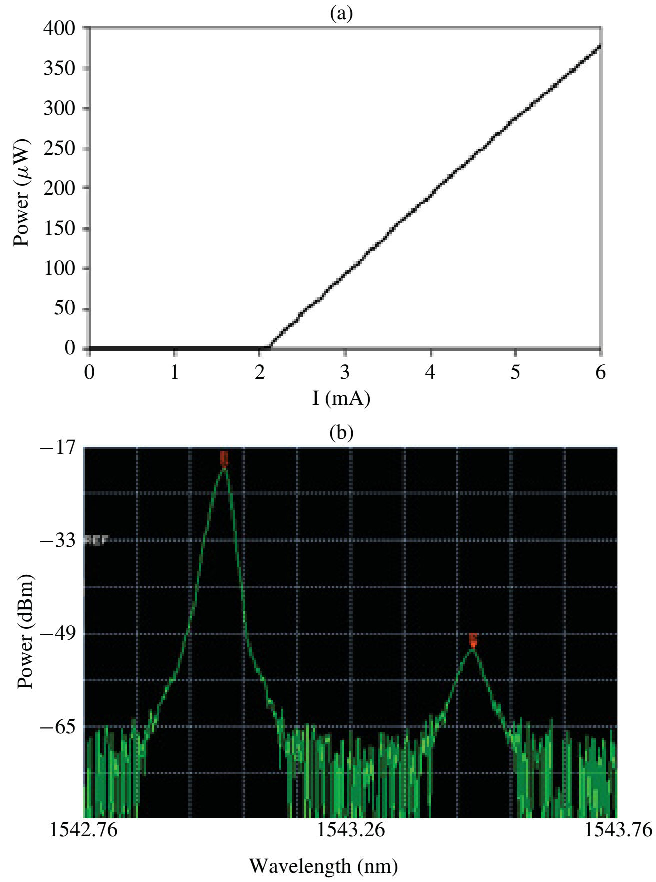

Fig. 2. (Color online.) (a) *L-I* Curve of the 1550-nm VCSEL. (b) Spectrum of the device biased with a current of 2.50 mA.

by Pan *et al.*, intensity polarization bistability was observed where hysteresis appeared in the polarization of the slave laser (SL) as the optically injected power was varied [33]. On the other hand, Kawaguchi *et al.* [42] kept the frequency and intensity of the trigger light constant and varied the bias current applied to the SL (which in fact changed the frequency detuning and the output intensity of the SL) to obtain PS and bistability.

This paper focuses on the dependence of the injected power required for PS with the frequency detuning between the externally injected signal and the orthogonally polarized mode of the VCSEL. We analyze this problem from a theoretical as well as an experimental point of view. We use the spin-flip model [16], [19] extended to account for orthogonal optical injection as in [4]. For a wide range of bias currents applied to the VCSEL, we show that the injected power required for PS exhibits a minimum and a plateau with respect to frequency detuning. The minimum appears in the region of negative frequency detuning, while the plateau occurs in the positive detuning range. These results confirm the theoretical predictions made by Sciamanna and Panajotov [4]. We extend their work by analyzing in detail the current dependence of the injected power required for PS vs. detuning curve. The values of the minimum and the plateau grow as the VCSEL current increases. We also report the experimental and theoretical observation of several windows in which PS does not appear as the injected power is increased, providing the VCSEL current is high enough. A previous observation of a window of PS disappearance was made in [5], [8]. A description of these windows is reported in the plane of injected power vs. frequency detuning and in that of injected power vs. VCSEL current. A good qualitative agreement is found between theory and experiments.

This paper is organized as follows. Section II gives a description of the experimental setup. In Section III, we present experimental results on the range of operating conditions for PS. Section IV is devoted to the description of the theoretical model, while in Section V we present our theoretical results. Finally, in Section VI, a discussion and summary are presented.

II. Experimental Setup

Orthogonal optical injection is achieved using the experimental setup shown in Fig. 1. This setup is based on the experiments of [9], [43]. An all-fiber system has been developed in order to inject the light from a tunable laser (Osics ECL) into a commercially available 1550-nm quantum-well VCSEL (RayCan Corporation). The bias current and the temperature of the device were controlled with a laser driver and temperature controller (ILX Lightwave LDC-3724B), respectively. The temperature of the VCSEL was held constant at 298 °K for all the experiments. In order to minimize the reflections at different FC/PC connectors, we have used index-matching gel in those connections. The optical power and the polarization of the externally injected signal were controlled using a variable optical attenuator and a fiber polarization controller, respectively. An 85/15 fiber directional coupler was included in the setup to divide the optical signal from the tunable laser into two branches. The first branch was connected to an optical multimeter (ILX Lightwave OMM-6810B) to monitor the optical input power, while the second one was directly launched into the 1550-nm VCSEL via a three-port optical circulator. The reflective output of the VCSEL was measured by connecting the third port of the optical circulator to an optical spectrum analyzer (ANDO AQ6317) with 0.01 nm resolution.

The free-running 1550-nm VCSEL emits in the fundamental transverse mode with a threshold current of $I_{th} = 2.05$ mA, measured at the temperature of 298 K [see Fig. 2(a)]. The VCSEL emits in a linear polarization which we will call the "parallel" (or "y") polarization. Fig. 2(b) shows that the lasing mode of the device with parallel polarization is located at the wavelength of 1543 nm when a bias current of 2.50 mA

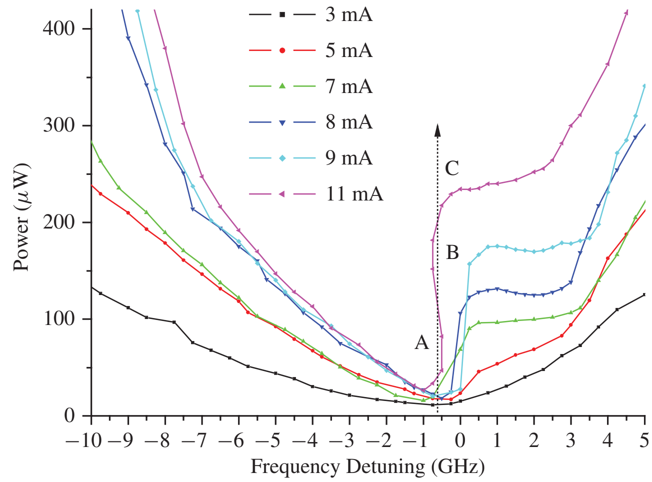

Fig. 3. (Color online.) Measured minimum injected power required for PS as a function of the frequency detuning for several values of the VCSEL current.

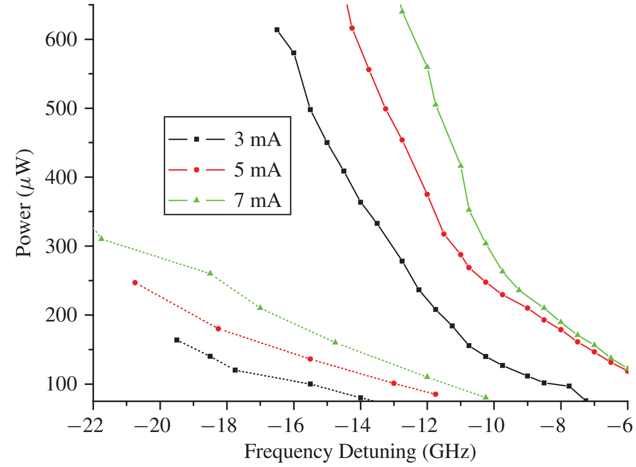

Fig. 4. (Color online.) Measured injected power required for PS as a function of the frequency detuning for several values of the VCSEL current. Results corresponding to increasing and decreasing the injected power are plotted with solid and dotted lines, respectively.

($I_{bias} = 1.22\ I_{th}$) is applied to the VCSEL. The emission in that polarization is stable and no PS is observed for any bias current above threshold. The second subsidiary mode has orthogonal (or "x") polarization and is shifted approximately 0.5 nm to the long-wavelength side of the lasing mode.

III. Experimental Results

We have measured the injected power required for PS as a function of the frequency detuning between the externally injected signal and the orthogonal polarization mode of the VCSEL, $\Delta\upsilon = \upsilon_{inj} - \upsilon_x$. These measurements are performed for several values of bias current applied to the device. Recently, Hurtado *et al.* [43] have studied the injection-locking properties of 1550-nm VCSELs subject to orthogonal optical injection. Theoretical and experimental injection-locking diagrams in the plane of frequency detuning vs. optical input power have been obtained for a single value of current, I_{VCSEL} [43]. Injection locking has been obtained when the side mode suppression ratio (SMSR, ratio between the power of the orthogonal and parallel polarizations) is higher than 30 dB [43]. The injected optical power P_{inj} required for PS has displayed an almost symmetric behavior with frequency and has shown a minimum near $\Delta\upsilon = -1$ GHz when the VCSEL is biased slightly above threshold ($I_{VCSEL} = 3$ mA) [43]. In our experiments, we also consider that the orthogonal optical injection induces a PS when SMSR > 30 dB.

Fig. 3 shows the injected power required for PS as a function of $\Delta\upsilon$ for different values of I_{VCSEL}. When I_{VCSEL} is small (3 mA) the results reported in [43] are recovered. Results obtained for $I_{VCSEL} = 5$ mA show that a plateau is being formed at positive $\Delta\upsilon$, while the minimum still appears at small negative values of $\Delta\upsilon$. As I_{VCSEL} is further increased (see the results for $I_{VCSEL} = 7, 8$, and 9 mA in Fig. 3), a wide plateau appears at positive values of $\Delta\upsilon$. A shallow local minimum appears at $\Delta\upsilon = 2$ GHz, close to the center of the previously described plateau. Therefore, for a wide range of I_{VCSEL}, the P_{inj} required for PS shows a clear minimum and a wide plateau for negative and positive values of $\Delta\upsilon$, respectively. These results confirm the theoretical predictions of [4]. The frequency location of the absolute minimum does not follow a clear trend: a fluctuation between $\Delta\upsilon = -1$ and -0.2 GHz is observed as I_{VCSEL} is increased. However, the optical power value of the absolute minimum grows as I_{VCSEL} increases (the minimum P_{inj} increases from 11.25 to 26.25 μW as I_{VCSEL} changes from 3 to 11 mA, as seen in Fig. 3), although some fluctuations are still clearly visible. On the other hand, the values of the optical power at the plateau increase as higher bias current are applied to the VCSEL. In addition, the results obtained for the largest applied value of I_{VCSEL} (11 mA) show new qualitative features. For positive frequency detunings, the plateau begins to disappear because P_{inj} becomes again an increasing function of $\Delta\upsilon$. More interestingly, the P_{inj} required for PS has an "S" shape for small negative values of $\Delta\upsilon$. This shape implies a novel behavior of the polarization in a detuning range spanning from -0.75 to -0.5 GHz. A new region appears in that detuning range, marked as region B in Fig. 3. In that region, PS to the orthogonal polarization is not observed. A vertical dotted arrow has been included in Fig. 3 to indicate the three different regions of distinct behavior of the polarization appearing as P_{inj} is increased when the device is biased with 11 mA. These three different regions are marked as regions A, B, and C in Fig. 3. In region A, PS from parallel to orthogonal polarization is obtained. Consequently, the orthogonal polarization dominates throughout this region. In region B, PS is no longer observed and the SMSR becomes smaller than 30 dB, reducing to levels of only around 10 dB. Nonetheless, throughout this region the orthogonal polarization is still dominant and no reverse polarization switching to the parallel polarization mode is observed. Finally, in region C, PS is observed and the orthogonal polarization becomes again the dominant one with SMSR > 30 dB. To the best of our knowledge, this is the first experimental observation of the existence of several regions of appearance and disappearance of PS in a VCSEL subject to orthogonal optical injection.

Fig. 4 shows the injected power required for PS vs. detuning when increasing and decreasing the injected power.

We find a bistable behavior of the polarization with wide hysteresis cycles. There is a non-monotonous dependency of the hysteresis width vs. the detuning, which is in agreement with the theoretical predictions of [4]. The hysteresis width increases as the frequency detuning becomes more negative, also in agreement with [4]. We have also obtained that for positive values of frequency detuning, $0 < \Delta\upsilon < 15$ GHz, no hysteresis was observed. The condition $0 < \Delta\upsilon$ corresponds to $\Delta w > \gamma_p$ in [4], where γ_p is the linear birefringence parameter and $\Delta\omega$ is the frequency detuning with respect to a frequency intermediate between that of the parallel and orthogonal polarizations. This result is in agreement with [4, Fig. 11], if $\Delta\omega < 45$ rad/ns. That figure also shows that the hysteresis width increases with $\Delta\omega$ when $\Delta\omega > 45$ rad/ns. That value approximately corresponds to the maximum detuning that has been reached in our experiments. In [4] (in our experiments) it corresponds to an injected frequency that is larger than the frequency of the orthogonal polarization for a value given by 0.27 (0.24) times the frequency difference between both polarizations. Further experimental work at larger frequency detunings would be interesting to fully check the theoretical predictions of [4].

IV. Model

Our rate equation model for the optically injected VCSEL is based on the model reported by San Miguel, Feng, and Moloney, also called spin-flip model (SFM) [16], [19]. The SFM assumes a four-level system in which electrons with different spins yield optical transitions with different circular light polarizations. We extended the SFM model to account for the injection of an external field with a polarization orthogonal to that of the free-running VCSEL [4], [7], [44], [45]. In our simulations, the parameters have been chosen such that the free-running VCSEL exhibits a stable and stationary y linearly polarized state. With these parameters, the frequency of the y polarized mode is higher than that of the x linear polarization ($\upsilon_y > \upsilon_x$). This is exactly the same situation measured for the VCSEL used in the experiments. We therefore choose to inject optically along the x direction in order to obtain PS from the y to the x linear polarizations. The rate equation model written in the frequency reference frame of the master laser is given by

$$\frac{dE_x}{dt} = \kappa(1+i\alpha)(DE_x + inE_y - E_x) - i(\gamma_p + \Delta\omega)E_x - \gamma_a E_x + \kappa_{inj}E_{inj} + \sqrt{\beta_{sp}}\xi_x \quad (1)$$

$$\frac{dE_y}{dt} = \kappa(1+i\alpha)(DE_y - inE_x - E_y) + i(\gamma_p - \Delta\omega)E_y + \gamma_a E_y + \sqrt{\beta_{sp}}\xi_y \quad (2)$$

$$\frac{dD}{dt} = -\gamma_e\left[D(1+|E_x|^2+|E_y|^2)\right] + \gamma_e\mu - i\gamma_e n(E_yE_x^* - E_xE_y^*) \quad (3)$$

$$\frac{dn}{dt} = -\gamma_s n - \gamma_e n(|E_x|^2+|E_y|^2) - i\gamma_e n(E_yE_x^* - E_xE_y^*) \quad (4)$$

where $E_{x,y}$ are the two linearly polarized slowly varying components of the field and D and n are two carrier variables.

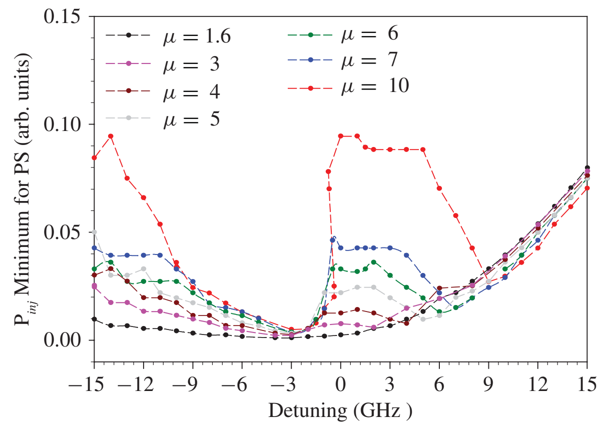

Fig. 5. (Color online.) Calculated minimum value of P_{inj} necessary to obtain PS as a function of the detuning $\Delta\upsilon$ for different values of injected current μ.

D accounts for the total population inversion between conduction and valence bands, while n is the difference between the population inversions for the spin-up and spin-down radiation channels. The internal VCSEL parameters are as follows: κ is the field decay rate, γ_e is the decay rate of D, γ_s is the spin-flip relaxation rate, α is the linewidth enhancement factor, μ is the normalized injection current, γ_a is the linear dichroism, and γ_p is the linear birefringence. The fluctuating nature of the spontaneous emission (with a fraction of spontaneous emission photons that goes into the laser mode of $\beta_{sp} = 10^{-6}$) is included in our calculations since $\xi_x(t)$ and $\xi_y(t)$ are complex Gaussian noise terms of zero mean and time correlation given by $\langle\xi_i(t)\xi^*{}_j(t')\rangle = 2\delta_{ij}\delta(t-t')$. We have integrated (1)–(4) by using the same numerical method for stochastic differential equations used in [46] with an integration time step of 0.1 ps.

The optical injection parameters are κ_{inj}, E_{inj}, and $\Delta\omega$, where κ_{inj} is the coupling coefficient, E_{inj} is the injected field amplitude, and $\Delta\omega$ is the detuning between the master and slave angular frequencies. We consider the case where the coupling coefficient coincides with the field decay rate ($\kappa_{inj} = \kappa$) for the ideal case of an effectively mode-matched injected input beam [19]. The $\Delta\omega$ parameter is defined as the difference between the angular frequency of the injected light ω_{inj} and the reference angular frequency ω_{ref}, intermediate between those of the x and y linear polarizations, i.e., $\Delta\omega = \omega_{inj} - \omega_{ref}$, where $\omega_{ref} = (\omega_x + \omega_y)/2$. The VCSEL parameters chosen for the simulations are: $\gamma_e = 1$ ns^{-1}, $\gamma_p = 192.1$ ns^{-1} $\gamma_a = 1$ ns^{-1}, $\gamma_s = 1000$ ns^{-1}, $\kappa = 300$ ns^{-1}, and $\alpha = 3$. With this parameter choice, the free-running VCSEL emits in the y linear polarization and does not show PS over the injected current range studied here. Also, the calculated value for the frequency difference between the y and x polarization modes ($\gamma_p/\pi = 61.1$ GHz) is close to the experimental value of 63 GHz.

V. Theoretical Results

In this section we will analyze the minimum injection power needed to obtain PS. We consider that PS occurs when the

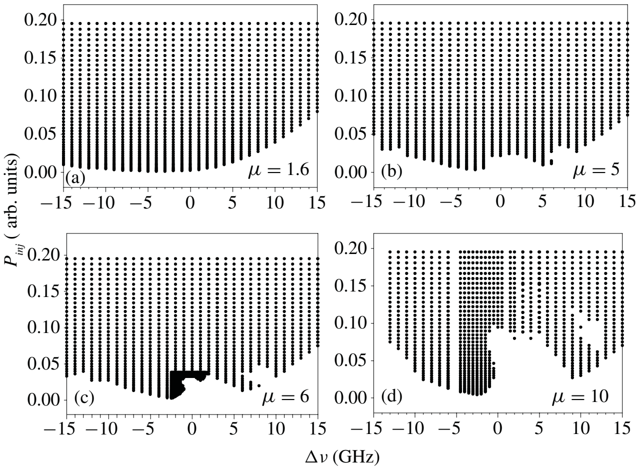

Fig. 6. Calculated injected optical power vs. detuning ($P_{inj} - \Delta\upsilon$ plane). A black point indicates the occurrence of PS for (a) $\mu = 1.6$, (b) $\mu = 5$, (c) $\mu = 6$, and (d) $\mu = 10$.

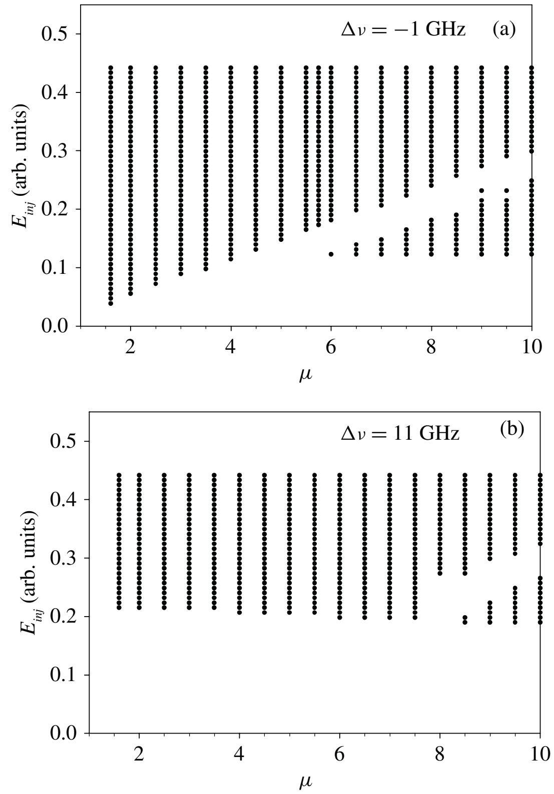

Fig. 7. Calculated injected electric field vs. normalized current ($E_{inj} - \mu$ plane). A black point indicates the occurrence of PS for (a) $\Delta\upsilon = -1$ GHz, and (b) $\Delta\upsilon = -11$ GHz.

SMSR $\geq$ 30 dB (the same criterion used in the experiments). Fig. 5 shows, for different values of bias current μ, the minimum values of $P_{inj} = E_{inj}^2$ needed to obtain PS as a function of the frequency detuning $\Delta\upsilon$ [calculated as the difference between υ_{inj} and υ_x, i.e., $\Delta\upsilon = (\omega_{inj} - \omega_x)/2\pi$]. We note a parabola-like dependence of the minimum P_{inj} as a function of $\Delta\upsilon$ for a normalized current of $\mu = 1.6$. The value of μ gives an approximate idea of the value of the current relative to the threshold current (the exact relationship between both quantities is given in [47]). The minimum P_{inj} appears at a negative value of detuning. For all analyzed bias currents, the injected power needed for PS exhibits an absolute minimum value P_{min} appearing at a frequency detuning of $\Delta\upsilon_{min} = -3$ GHz ($\Delta\upsilon_{min}$ does not depend on the bias current). The theoretical value of P_{min} increases as μ increases.

When $\mu \geq 3$, a plateau with some fluctuations begins to develop for positive values of the frequency detuning. The values of the optical power at those plateaus grow as μ increases. Fig. 5 also shows that a second minimum value of injected power for the occurrence of PS also appears at larger positive frequency detuning. The value of this second minimum as well as the frequency detuning at which it appears grows as μ increases.

For the largest value of the bias current, our experimental results indicated that the P_{inj} required for PS had an "S" shape for small negative values of $\Delta\upsilon$. In order to compare our theoretical results with the experimental measurements, we will not only focus on the minimum value of P_{inj} required for PS as in Fig. 5 but also consider numerous values filling the $P_{inj} - \Delta\upsilon$ plane to theoretically evaluate whether windows exist where PS is not observed.

The black dots in the $P_{inj} - \Delta\upsilon$ plane shown in Fig. 6 indicate, for a given value of $\Delta\upsilon$, the value of injected power P_{inj} required for the occurrence of PS. For a current of $\mu = 1.6$ [Fig. 6(a)], the minimum values of P_{inj} needed for PS show the same parabolic dependence observed in Fig. 3. The uniform filling above the parabolic curve means that, once PS is obtained, increasing P_{inj} does not produce any further PS. The situation is different when larger values of bias current are considered. Fig. 6(b) shows calculated results for $\mu = 5$. A small window appears in the $P_{inj} - \Delta\upsilon$ plane at around $\Delta\upsilon = 6$ GHz, $P_{inj} = 0.017$, in which no PS is observed. The existence of windows where PS is no longer observed is much more obvious when even higher values of μ are considered. Fig. 6(c) shows that, for small negative values of $\Delta\upsilon$, the P_{inj} required for PS exhibits an "S" shape with a window appearing centered at $P_{inj} = 0.022$ for -1.4 GHz $\leq \Delta\upsilon \leq -1$ GHz, where PS is no longer observed. The "S" shape is clearer when the current increases, as can be seen in Fig. 6(d) because of the range of P_{inj} values in which there are no PS increases: it is 0.05 (0.015) at $\Delta\upsilon = -0.5$ GHz ($\Delta\upsilon = -1$ GHz) when $\mu = 10$ ($\mu = 6$). This is exactly the same behavior observed in the experiments (see Fig. 3) for the case of an applied bias current of 11 mA. Fig. 6(c) and (d) also shows that the window that appeared in Fig. 6(b) around 6 GHz has evolved to an "island" (surrounded by dots where PS occurs) located at larger values of $\Delta\upsilon$. Therefore, for large enough values of μ, two different windows appear in the $P_{inj} - \Delta\upsilon$ plane (at negative and positive frequency detuning) where PS is not found. The evolution of both windows can be better understood with the help of Fig. 7. The black dots in the $E_{inj} - \mu$ plane in Fig. 7 indicate for a given value of μ the E_{inj} value for PS to occur. The first region without PS, appearing at $\Delta\upsilon = -1$ GHz, is shown in Fig. 7(a) as the tilted white band beginning at $\mu = 6$. The level of E_{inj} needed for the appearance of this region increases as μ grows. However, the width of this region does not depend on μ. This is consistent with the increase of the injected power range as the current increases observed in Fig. 6(c) and (d) because $P_{inj} = E_{inj}^2$. The same trends are observed for the second region without PS, as illustrated in Fig. 7(b) for $\Delta\upsilon = 11$ GHz. Fig. 7(a) and (b) also show the coexistence of both regions when $\mu > 8$.

VI. Discussion and Conclusion

In general, a good qualitative agreement has been found between theory and experiments on the conditions for the occurrence of PS in a 1550 nm-VCSEL under orthogonal optical injection. In agreement with our experimental measurements, the theoretical value of P_{min} increases as I_{VCSEL} grows. Additionally, both the experimental and theoretical values of $\Delta\upsilon_{min}$ are negative. However, the experimentally measured value of $\Delta\upsilon_{min}$ does not follow a clear trend with I_{VCSEL}, whereas the theory predicts a constant value for $\Delta\upsilon_{min}$. This theoretical result may be consistent with our experimental observations since the measured fluctuations could be due to thermal effects. Both experimental and theoretical results show that plateaus appear at positive values of $\Delta\upsilon$. In both cases, the value of the optical power at the plateau increases as a higher bias current is applied to the VCSEL. However, the experimental results show that a shallow minimum can appear at the center of the plateau, while a plateau with some fluctuations and a more defined minimum are obtained by using our theory. We have also found, both in experiments and in theory, the existence of windows where the PS disappears. The latter has been observed for the highest current considered and for small negative values of $\Delta\upsilon$. However, the experimental results have not confirmed the theoretical predictions of the existence of similar windows also for positive values of $\Delta\upsilon$. Future work will be devoted to extract the working parameters of our 1550-nm VCSELs, following the approach of [48], in order to improve the theoretical description of our experiments. We also note that the stability in the different regions of operation has been recently experimentally analyzed [49]. Regions in which the VCSEL is pulsing are identified in the injected power–frequency detuning plane [49]. A theoretical description of those regions seems useful for certain applications.

In summary, we have studied theoretically and experimentally the PS appearing in 1550-nm VCSELs subject to orthogonal optical injection. Our VCSELs are characterized by a large value of their birefringence parameter and by a linearly polarized emission over the whole current range. We have investigated the injected power P_{inj} required for PS as a function of the frequency detuning, $\Delta\upsilon$. For a certain range of VCSEL current, the injected power for PS exhibits a minimum and a plateau with respect to frequency detuning. The minimum appears at negative frequency detuning, whereas the plateau appears at positive detuning. Our experimental results confirm the theoretical predictions of [4]. Our theoretical calculations extend previous analysis [4] by considering the bias-current dependence of the injected power required for the PS vs. detuning curve. The injection power levels at the minimum and at the plateau increase as higher bias current are applied to the VCSEL. For the highest current applied to the VCSEL, we have described the existence of regions in which an increase of the injected power produces the disappearance and further appearance of PS. We have found these regions, both in experiment and theory, when the frequency detuning is negative and small, in agreement with previous studies [5], [8]. A theoretical description of these regions has been performed in the injected power–frequency detuning ($P_{inj} - \Delta\upsilon$) and the injected field–VCSEL current ($E_{inj} - \mu$) planes. Numerical simulations also predict the existence of similar regions located at large positive frequency detuning. Bistable behavior of the polarization is also found experimentally. Our experimental results confirm the non-monotonous dependence of the hysteresis width vs. detuning, in agreement with the theoretical predictions of [4]. A good overall qualitative agreement has been found between our theoretical and experimental results.

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