Polarization bistability induced by orthogonal optical injection in 1550-nm multimode VCSELs

Ana Quirce, José R. Cuesta, Angel Valle, Antonio Hurtado, Luis Pesquera, and Michael J. Adams

***Abstract*— We have analyzed experimentally the optical power polarization bistability induced in a long-wavelength multi-transverse mode vertical-cavity surface-emitting laser (VCSEL) under orthogonal optical injection. Bistability with very wide hysteresis cycles is measured for both the fundamental and the high-order transverse mode of the device. The shape of the associated hysteresis cycle is different for each of the two transverse modes. The power of the parallel polarized high-order (fundamental) transverse mode remains constant (gradually decreases) as the injected power is increased. Both powers suddenly drop to low levels at large values of the injected power. The squared shape measured for the input/output characteristic of the high-order transverse mode is of particular interest for obtaining good quality all-optical inversion and all-optical regeneration for use in optical telecommunication networks.**

***Index Terms*—All-optical switching, all-optical signal processing, optical bistability, polarization switching, optical injection, injection locking, vertical-cavity surface-emitting lasers (VCSELs), transverse modes.**

I. Introduction

ALL-OPTICAL signal processing using Vertical-Cavity Surface-Emitting Lasers (VCSELs) has been recently investigated for future all-optical photonic networks [1-8]. VCSELs are attractive for use in all-optical signal processing because of their low power consumption, compactness, low cost and small circular output beam. Optical injection in VCSELs has been used for obtaining all-optical memory [2-5], all-optical regeneration[6] and all-optical inversion [7-10]. Injection locking is also commonly employed to improve the performance of VCSELs without modifying their design [11-13].

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Emission in multiple transverse and polarization modes is usually found in VCSELs. The injection locking of VCSELs has been examined experimentally [14-20] and theoretically [21-22] in single and multi-transverse mode VCSELs taking into account the polarization additional degree of freedom. Polarization switching (PS) in VCSELs induced by optical injection has been obtained by using the so-called "orthogonal optical injection" in which linearly polarized light from an external laser is injected such that the polarization is perpendicular to that of the stand-alone VCSEL. PS in VCSELs using orthogonal optical injection has been mainly analyzed in devices that emit only in the fundamental transverse mode [14-19], [21]. Recent interest has also appeared in the transverse mode switching induced by optical injection [6-9], [22-23]. This interest has been mainly motivated by the all-optical signal processing functionalities associated with the switching of a high-order transverse mode induced by optical injection [1], [6-9]. Polarization bistability phenomena associated with PS have been reported in 850 nm [14-15] and 1550 nm [16-19] wavelength VCSELs. Analyses of the polarization bistability in multi-transverse mode VCSELs induced by orthogonal optical injection are scarce and only refer to 850 nm devices [22]. The corresponding analysis in 1550 nm-VCSELs is of interest for exploiting the multi-transverse mode character of these devices in all-optical signal processing and optical switching/routing applications in long-haul optical networks applications were 1550nm technology is dominant.

In this work we report an experimental study of the power-induced polarization bistability found in a 1550 nm multi-transverse mode VCSEL when subject to orthogonal optical injection. In contrast with previous experiments [7-8], [22] our solitary VCSEL emits in two transverse modes with the same linear polarization over the whole bias current range. Also the value of the frequency splitting between the orthogonal polarizations of each transverse mode is very large in comparison to those reported in [7-8], [22]. We mainly focus on an external light injected into the fundamental transverse mode in contrast to previous studies in which light was injected into a high-order mode [7-8]. We find optical bistability with very wide hysteresis cycles for both transverse modes. Wide hysteresis cycles are of particular importance for the potential development of low-cost, low-power, high-speed all-optical bistable memory elements. The shape of the hysteresis cycle depends on the transverse mode under consideration. Interestingly, the power of the parallel polarized high-order transverse mode remains constant as the optical injected power is increased until it suddenly drops to low levels. This kind of behaviour is of interest for obtaining good quality all-optical inversion and all-optical regeneration.

II. Experimental Setup

Experimentally, orthogonal optical injection is attained with the set-up presented in Fig. 1 of [24]. An all-fiber system has been used to inject the light from a tunable semiconductor laser into a commercially available quantum-well 1550nm-VCSEL (RayCan[TM]) via a three-port optical circulator. The optical power and the polarization of the externally injected signal were controlled by using a variable optical attenuator and a fiber polarization controller, respectively. An 85/15 fiber directional coupler divides the optical signal into two branches: the 85% branch is directly connected to the VCSEL whereas the 15% output is used to monitor the optical input power with a power meter. The reflected output of the VCSEL is measured by connecting an Optical Spectrum Analyzer (OSA) to the third port of the optical circulator. Note that the power measured at the OSA includes the power emitted by the VCSEL plus the reflection of the input light. The temperature of the VCSEL was held constant at 297 K for all the experiments.

Fig. 1(a) shows the experimentally measured L-I curve of the free-running VCSEL, showing a threshold current of I_{th} = 2.83 mA. The VCSEL begins to emit in the fundamental transverse mode with a linear polarization that we will call “parallel” polarization until its bias current, I_{bias}, reaches a value of 3.9 mA. Above that level the VCSEL also emits in a high-order transverse mode with the same linear polarization. Fig. 1(b) shows the optical spectrum of the VCSEL when I_{bias} = 5.5 mA. The two main peaks correspond to the parallel polarized fundamental and high-order transverse modes, located at the wavelengths of $\lambda_{f\|}$ = 1560.77 nm and $\lambda_{h\|}$ = 1558.69 nm, respectively. The orthogonal polarizations of the fundamental and high-order transverse modes are located at the wavelengths of $\lambda_{f\perp}$ and $\lambda_{h\perp}$, respectively. Orthogonally-polarized transverse modes are shifted 0.56 nm to the long wavelength side of the corresponding parallel modes. Parallel polarized emission in the two transverse modes is maintained over the whole bias current range.

III. Experimental Results

Fig. 2 shows experimental optical spectra when the VCSEL is subject to orthogonal optical injection. Several values of injected power, P_{inj}, and frequency detuning between the externally injected signal and the orthogonal polarized fundamental mode, $\Delta\nu = \nu_{inj} - \nu_{f\perp}$, were considered. The injected light that is reflected at the VCSEL cavity contributes to the peaks appearing at the wavelength λ_{inj}. For large and negative values of $\Delta\nu$ (see Fig. 2(a)), the power of the parallel polarized fundamental transverse mode, $P_{f\|}$, decreases as the value of P_{inj} increases. However, the behavior of the high-order mode is different because the power of the parallel polarized high-order transverse mode, $P_{h\|}$, remains constant as P_{inj} is increased.

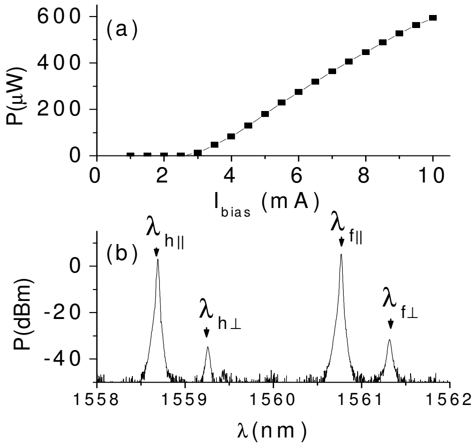

Fig. 1. (a) L-I curve and (b) spectrum of the free- running VCSEL (I_{bias}=5.5 mA).

The situation changes when P_{inj} = 1.81 mW because both, $P_{f\|}$ and $P_{h\|}$, suddenly drop to very low power levels. In this case, PS occurs together with injection locking and the VCSEL emits now all the power at the wavelength of the external signal and with orthogonal polarization. This evolution is also illustrated in Fig. 3(a-b) in which the values of $P_{f\|}$ and $P_{h\|}$ are plotted as a function of P_{inj}. The powers of the fundamental and first-order modes have been measured by finding the local maxima of their corresponding peaks in the optical spectra. These maxima are the values plotted in Fig. 3. $P_{f\|}$ decreases gradually whereas $P_{h\|}$ remains constant until a value of P_{inj} = 1.75 mW is reached. When P_{inj} > 1.75 mW, $P_{f\|}$ and $P_{h\|}$ decrease to very low power levels. PS and injection locking are then simultaneously obtained at P_{inj} = 1.75 mW. The insensitivity of the higher-order mode amplitude with respect to the injected power in the fundamental mode was already observed in a 850 nm VCSEL [20]. However the injected power was not enough to suppress the higher-order mode [20]. Fig. 3(a-b) illustrates the bistable character of the measured PS arising from the different behavior attained when P_{inj} is alternatively increased or decreased. Very wide hysteresis cycles are observed for both transverse modes as Fig. 3(a-b) shows. The hysteresis cycle observed for the input/output (I/O) power relationship of the parallel polarization of the fundamental mode (Fig. 3(a)) is similar to that observed in single transverse-mode VCSELs [19]. Nevertheless, the multi-transverse mode behaviour of the VCSEL adds new functionalities to our system. The squared shape with very high associated on-off contrast ratio between output states measured for the I/O power relationship of the parallel polarization of the high-order transverse mode ($P_{h\|}$ vs. P_{inj}) is of interest as it offers promise for obtaining good quality all-optical inversion and all-optical signal regeneration. The previous qualitative behaviour changes when λ_{inj} approaches $\lambda_{f\perp}$ as shown in Figs. 2(b) and 3(c-d). A gradual decrease of $P_{f\|}$ is also observed as P_{inj} increases until it suddenly drops to very low power levels at P_{inj} = 170 μW. In the other hand, $P_{h\|}$ shows two different behaviours: if P_{inj} is smaller (larger) than

170 µW, $P_{h\|}$ does not change (gradually decreases) with P_{inj}. No bistable behaviour is observed for this case. Additionally, optical spectra for a large and positive value of $\Delta\nu$ are shown in Fig. 2(c). In this case, $P_{f\|}$ gradually decreases as P_{inj} increases while $P_{h\|}$ remains constant and does not drop to low power levels when P_{inj} is further increased due to injected power limitations of our set-up.

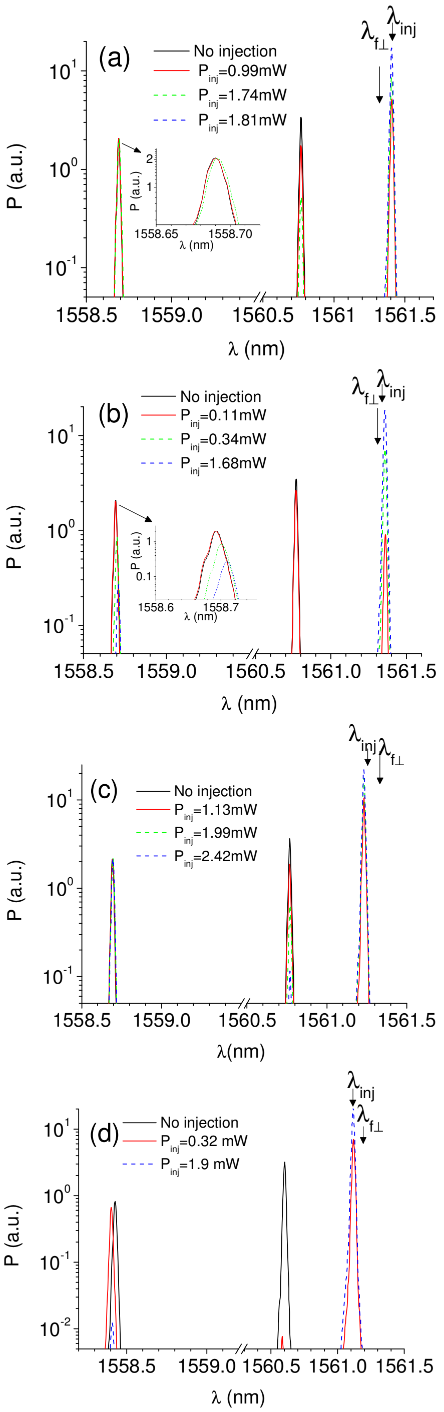

Fig. 2. (color online) Optical spectra for several values of injected power when (a) I_{bias} = 5.5 mA, $\Delta\nu$ = -10.75 GHz, (b) I_{bias} = 5.5 mA, $\Delta\nu$ = - 4 GHz, (c) I_{bias} = 5.5 mA, $\Delta\nu$ = 11.25 GHz, and (d) I_{bias} = 4.6 mA, $\Delta\nu$ = 5.5 GHz.

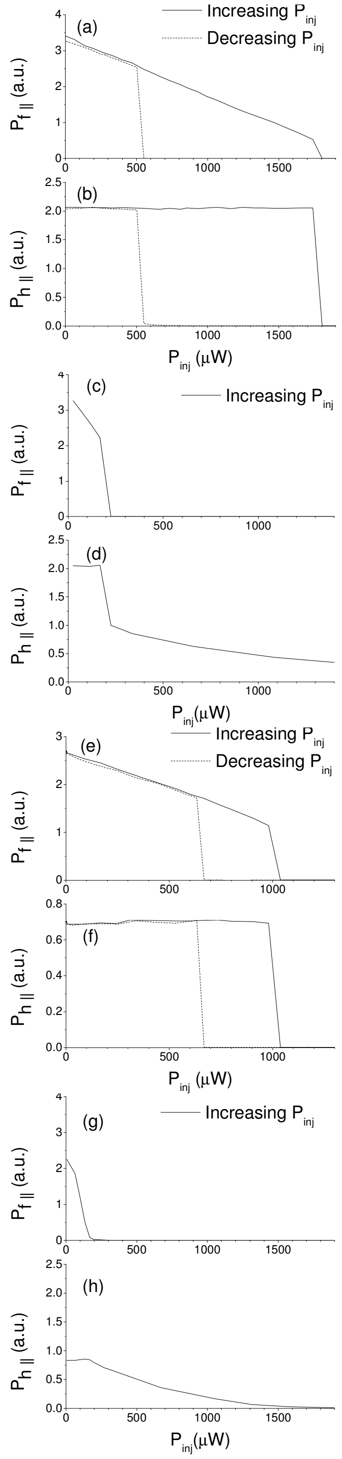

Fig. 3. I/O power characteristic for the output of the parallel polarized fundamental (upper row) and high-order (lower row) transverse modes. (a-b) I_{bias} = 5.5 mA, $\Delta\nu$ = -10.75 GHz, (c-d) I_{bias} = 5.5 mA, $\Delta\nu$ = -4 GHz, (e-f) I_{bias} = 4.6 mA, $\Delta\nu$ = -10.75 GHz, and (g-h) I_{bias} = 4.6 mA, $\Delta\nu$ = 5.5 GHz.

Fig. 3(e-f) shows respectively the I/O power characteristic when I_{bias} = 4.6 mA and $\Delta\nu$ = -10.75 GHz. The current-dependence of the behaviour is analyzed by comparing Fig. 3(e-f) with Fig. 3(a-b). In the former, PS with injection locking of both modes is observed at P_{inj} = 1.03 mW whereas in the latter a higher level of injected power P_{inj} = 1.80 mW is needed to obtain analogous behavior. Furthermore, the change of the bias current also affects the width of the bistable regions obtained for both transverse modes. The comparison of Fig. 3(e-f) with Fig. 3(a-b) shows that the width of the hysteresis cycle is larger at 5.5 mA than it is at 4.6 mA.

The situation found when $\Delta\nu$ is small and positive is illustrated in Fig. 2(d) and Figs. 3(g-h). These figures show that for this case the behaviour is similar to that observed when small and negative $\Delta\nu$ values are considered (see Fig. 2(b) and Figs. 3(c-d)). No bistability has been found for the conditions of Figs 3(g-h) either. Fig. 2(d) also shows that the fundamental and first order modes do not undergo polarization switching at the same injected power. When the injected power is 0.32 mW the fundamental mode exhibits polarization switching whilst the first order mode does not. The injected power must be increased significantly (see Fig. 2(d), P_{inj}=1.9 mW) for the first order mode to undergo polarization switching.

Frequency pulling/pushing phenomena can be observed in Fig. 2. A slight frequency pulling is observed in Fig. 2(a) as the injected power is increased. Insets with zooms of some peaks have been included in Figs. 2(a-b) for a better visualization of the phenomenon. A clearer frequency pulling is observed in the zoom of Fig. 2(b). Frequency pushing phenomenon is observed in the left part of Fig. 2(d) when $\Delta\nu$ is positive. However, similarly to what is observed in Figs. 2(a-b), a much smaller frequency shift appears in Fig. 2(c) when $|\Delta\nu|$ increases.

We illustrate in Fig. 4(a-b) for different values of applied bias current, the frequency detuning dependence of the injected power required for the suppression of the parallel polarized fundamental and high-order transverse modes, $P_{inj,f}$ and $P_{inj,h}$ respectively. We consider that $P_{f\|}$ and $P_{h\|}$ are suppressed when the Side Mode Suppression Ratio (with respect to the power emitted in the orthogonal polarization) is higher than 20 dB. Fig. 4(a-b) shows that, for large and negative frequency detuning, $P_{f\|}$ and $P_{h\|}$ drop at similar values of P_{inj}, and therefore $P_{inj,f} \sim P_{inj,h}$.

Those values correspond to the injected power at which the transition in the optical inversion characteristics occurs. As $\Delta\nu$ approaches to zero, $P_{inj,f}$ decreases until it reaches a minimum value at $\Delta\nu_f \sim 0$. Both $\Delta\nu_f$ and the minimum value of $P_{inj,f}$ change only slightly with I_{bias}. $P_{inj,h}$ also reaches a minimum value at $\Delta\nu_h < 0$. However, the behaviour of $P_{inj,h}$ is different since both $|\Delta\nu_h|$ and the minimum value of $P_{inj,h}$ increase as higher bias currents are applied to the VCSEL. Fig. 4(a-b) also shows that $P_{inj,f} \sim P_{inj,h}$ if $\Delta\nu < \Delta\nu_h$ and $P_{inj,f} < P_{inj,h}$ if $\Delta\nu > \Delta\nu_h$: the injected power required to suppress the parallel polarized fundamental mode is smaller (similar) than that needed to suppress the parallel polarized high-order mode when the frequency detuning is larger (smaller) than $\Delta\nu_h$.

The results measured when P_{inj} is increased or decreased are also included in Fig. 4(a-b). Both the fundamental and the high-order transverse mode powers exhibit bistable behaviour for large and negative values of $\Delta\nu$. Fig. 5(a-b) plots the measured hysteresis width, ΔP, as a function of $\Delta\nu$ corresponding to the curves included in Fig. 4(a-b). For large enough negative values of $\Delta\nu$, i) ΔP increases as $|\Delta\nu|$ increases, and ii) ΔP increases as I_{bias} increases (with a fixed $\Delta\nu$). However, only three different values of bias current have been considered in Fig. 5. Measurements for more values of bias current would be desirable to fully check the dependence on this magnitude.

Fig. 4(a-b) also describes the situation obtained for very large values of $\Delta\nu$, at which the wavelength of the optically-injected signal is close to the orthogonal polarized high-order transverse mode wavelength. Results are only plotted when I_{bias}=4.6 mA. $P_{inj,f}$ and $P_{inj,h}$ exhibit minimum values when $\Delta\nu$ is near 260 GHz which is the frequency separation between the parallel polarized fundamental and high-order transverse modes. Finally, Fig. 4(a-b) also states that i) $P_{inj,h} < P_{inj,f}$ and ii) the width of the hysteresis regions is very small.

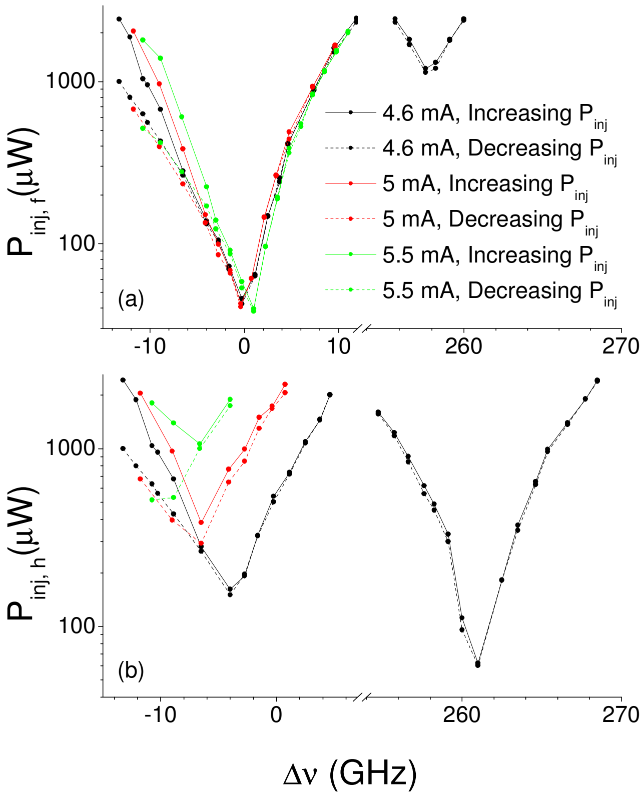

Fig. 4. (color online) Injected power required for suppressing the parallel polarized (a) fundamental and (b) high-order transverse mode versus the frequency detuning for three different levels of bias current. Results corresponding to increasing and decreasing the injected power are plotted with solid and dotted lines.

Our experimental results are in agreement with previous theoretical results contained in [21] and [22]. Two minimum values of injected power needed to obtain polarization switching of the total power have also been found in [22] for two different values of the frequency detuning: the first one corresponding to an optical injection wavelength near the orthogonally polarized fundamental mode resonant wavelength; and the second one appearing close to the frequency difference between the high-order and the fundamental transverse modes of the solitary VCSEL [22].

Our experimental results support that theoretical prediction. Also polarization switching and injection locking are attained with the same value of the injected power when the frequency detuning is negative [22]. In this way the experimental results shown in Figs. 2 and 3 support the theoretical model of Ref. [22].

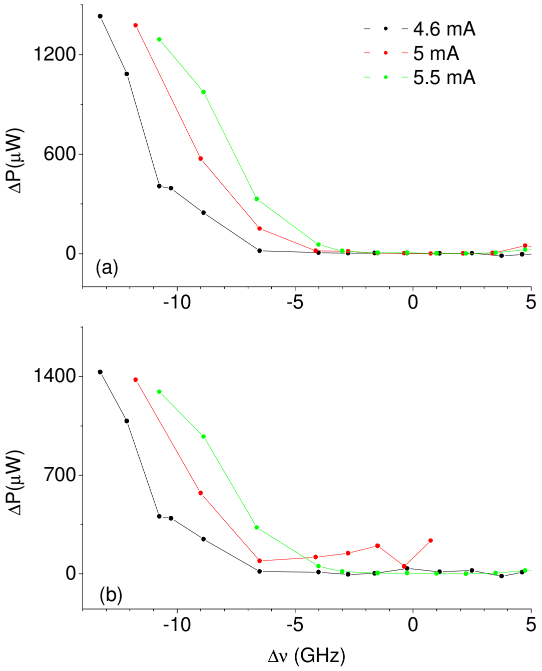

Fig. 5. (color online) (a-b) Hysteresis width corresponding to the data of Fig. 4 (a-b), respectively.

IV. Discussion & Conclusions

The potential of VCSELs for all-optical signal processing in future photonic networks has been recently demonstrated [1]. All-optical regeneration and all-optical inversion have been reported using optical injection to excite a high-order transverse mode of a VCSEL which in the absence of optical injection emits in the fundamental mode [1],[7]. The step-like transfer function useful for all-optical regeneration/inversion was obtained in those studies plotting the output power of the fundamental mode versus the injected power. In contrast with that work, our approach is to use optical injection for the suppression of the high-order transverse mode of a solitary multimode VCSEL. Our step-like transfer function is thus different as it is obtained considering the output power of the parallel polarized high-order transverse mode as a function of the injected power. Fig. 6 shows $P_{f\parallel}$, $P_{f\perp}$, $P_{h\parallel}$ and $P_{h\perp}$ as a function of P_{inj}. An example of our transfer function ($P_{h\parallel}$ vs. P_{inj}) is shown in Fig. 6(b). Furthermore, we have used a vertical logarithmic scale for a better comparison with the results reported in Ref. [1]. Our results are also obtained for similar frequency detuning values to that used in Fig. 15 of Ref. [1].

The nonlinearity of our transfer function improves previous results since its step-character is better defined: $P_{h\parallel}$ in Fig. 6(b) is constant if P_{inj}<1.75 mW, whereas in the results shown in Fig. 15 of Ref. [1] the output power decreased approximately 2 dB when the fibre input power was smaller than 3.4 mW. The width of the bistability window can be estimated by the ratio between the injected powers at which the downward and upward transitions occur, P_{down}/P_{up}. This ratio is 3.5 in our work (see Fig. 6) while in [1] (see Fig. 15 in that work) reduces to approximately 1.15). This result can be of interest for potential applications of our work in all-optical memories.

Similar switching powers (of the order of some mW) and extinction ratios (around 30 dBs) are found in our work and in Ref. [1]. Fig. 6(b) shows that the values of $P_{h\perp}$ are always very small. However, the values of $P_{f\perp}$ in Fig. 6(a) are large as they include the power emitted by the fundamental mode in the orthogonal polarization plus the reflection of the injected light at the VCSEL mirror, like in Ref. [19]. Fig. 6(a) also shows that another step-like transfer function is obtained when considering $P_{f\parallel}$ vs. P_{inj}. This transfer function has the advantage of a larger extinction ratio (more than 40 dB) but the disadvantage of having a gradual decrease (8 dB) when transiting from P_{inj} = 0 to 1.75 mW. The width of the hysteresis region associated to $P_{f\parallel}$ is larger than that found when considering single-transverse mode VCSELs subject to orthogonal optical injection [19] (P_{down}/P_{up}=2 when I_{bias}=2 I_{th} and $\Delta\nu$= -19 GHz).

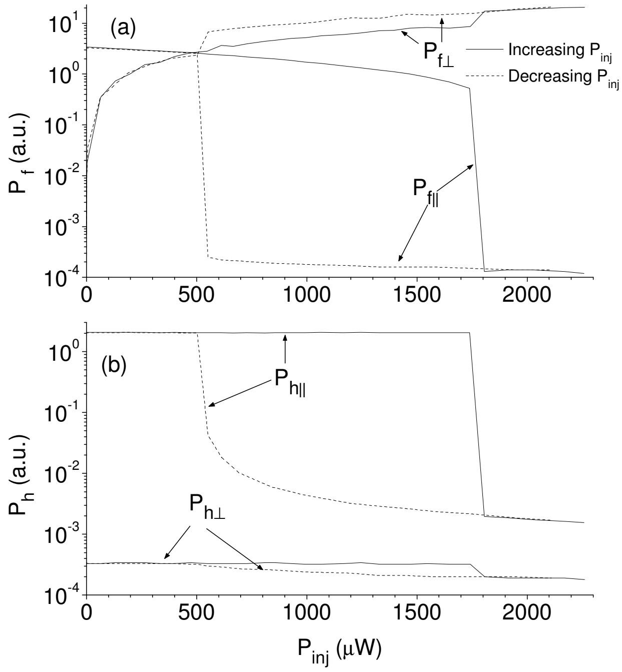

Fig. 6. Polarization-resolved I/O power characteristic for the output of the (a) fundamental and (b) high-order transverse mode. I_{bias} = 5.5 mA, $\Delta\nu$ = -10.75 GHz.

The bias current has been chosen large enough to assure multimode operation of the solitary VCSEL. The injected wavelength has been selected close to the resonant wavelengths corresponding to the orthogonal polarizations of the fundamental and high-order transverse modes of the device. In Figs. 4 and 5 we have considered a variety of values of bias current and injected wavelengths to identify the optimal operating conditions for all-optical inversion and bistability. Fig. 4 shows that the minimum injected power required for suppressing the parallel polarization appears near the zero frequency detuning. This means that the optimum injected power to achieve all-optical inversion is obtained when the injected wavelength is near the wavelength of the orthogonal polarization of the fundamental mode, as in Ref. [22]. Fig. 5 shows that, for a fixed negative frequency detuning, the hysteresis width increases as the bias current is increased, as in Ref. [19], which means that increasing the bias current is therefore suitable to achieve optimum all-optical memory operation.

We have reported the experimental observation of polarization bistability in each of the transverse modes of a 1550 nm multimode VCSEL when subject to orthogonal optical injection. We have studied in detail the injected power requirements for polarization bistability. We have also characterized the width of the associated hysteresis cycles as a function of the frequency detuning for three different values of bias current. In particular very wide hysteresis cycles have been obtained for both transverse modes when the frequency detuning has large and negative values. The multi-mode emission property of the VCSEL adds new functionalities to the system in comparison to previous studies in single transverse mode devices. A squared shape with very high on-off contrast ratio and very wide associated hysteresis cycle has been measured for the I/O power characteristic of the parallel polarized high-order transverse mode. This promising result offers potential for the use of multi-mode VCSELs operating at the very important telecom wavelength of 1550nm as low-cost and low-power consuming components for all-optical signal processing applications, such as all-optical inversion and all-optical signal regeneration, in long-haul optical networks.

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