# Transverse mode selection and injection locking in 1550-nm multimode VCSELs induced by optical injection

A. Quirce[1,2], A. Valle [1*], L. Pesquera[1], A. Hurtado[3], and M. J. Adams[3].

[1]Instituto de Física de Cantabria, CSIC-Universidad de Cantabria, Avda. Los Castros s/n, E-39005, Santander, Spain.

[2] Departamento de Física Moderna, Universidad de Cantabria, Avda. Los Castros s/n, 39005, Santander, Spain

[3]School of Computer Science and Electronic Engineering, University of Essex, Wivenhoe Park, CO4 3SQ, Colchester, United Kingdom

## ABSTRACT

An experimental investigation of the modal selection induced by optical injection in 1550 nm multitransverse-mode VCSELs is performed. The free-running VCSEL emits in two transverse modes that are linearly polarized in a direction referred as parallel. We consider the situation in which parallel polarized laser light is injected in the VCSEL in order to select its fundamental transverse mode. We analyze the dependence of the modal selection process on the wavelength detuning between the externally injected signal and the fundamental mode. The injected power needed to select the fundamental mode as a function of the wavelength detuning is measured for several values of the bias current. This injected power exhibits a minimum at a positive wavelength detuning. The curves obtained for different bias currents are very close for positive and large wavelength detuning, while they are very separated for smaller detuning. The selection of the fundamental mode can be obtained with a value of the injected power that changes only slightly with the bias current when the wavelength detuning is large and positive. These results indicate that operation at large and positive wavelength detuning is of interest in the long-distance single-mode fiber transmission of multimode injection-locked VCSELs because the selection of the fundamental mode is obtained with an injected power that is almost independent on the VCSEL bias current. Both, the minimum injected power and the wavelength detuning at which it appears increase with the VCSEL bias current. We describe the relation between transverse mode selection and injection locking by comparing the dependence of both phenomena on the wavelength detuning. Modal selection is accompanied by injection locking only for large and positive values of the wavelength detuning. For small detuning values, with the VCSEL biased with a low (high) current, the injected power required for modal selection is lower (higher) than that needed for injection locking.

**Keywords:** Semiconductor lasers, vertical-cavity surface-emitting laser (VCSEL), optical injection, injection locking, transverse modes.

## 1. INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELs) are very promising devices due to their inherent advantages in comparison with edge emitting lasers (single-longitudinal mode operation, low threshold current, circular output-beam profile, ease of fabrication of 2D arrays, compactness, wafer level testing, low cost, etc.) [1-2]. Injection locking in single-transverse mode VCSELs has been used to reduce the frequency chirp under modulation, to improve the laser intrinsic frequency response, and to increase the fiber transmission distance [3-6]. These advantages were firstly studied in edge-emitting semiconductor lasers [7-9]. Laser spectral narrowing and suppression of laser noise were demonstrated [8]. Optical injection is also of interest because it improves the performance of semiconductor lasers without modifying their design.

*e-mail: valle@ifca.unican.es; phone 34 942 201465; fax: 34 942 200935

Although VCSELs emit in a single-longitudinal mode, emission in multiple transverse and polarization modes is usually found in solitary devices [10-16]. Emission in multiple transverse modes is usually attributed to spatial-hole burning effects [10-12]. Directly modulated, multi-transverse mode VCSELs are extensively used in local and storage area networks due to their low cost and wide bandwidth [17]. Optical injection has been used in multimode VCSELs to enhance their modulation response [18]. Greatly enhanced transmission distance of multimode VCSELs over standard single-mode fiber using injection locking has been recently reported [19]. Transmission distance as high as 90 km was achieved at 10 Gb/s by frequency chirp inversion and higher order transverse mode suppression [19]. Suppression of higher-order transverse modes in VCSELs induced by optical injection has been studied from experimental [19-25] and theoretical [24-30] points of view.

Optical injection experiments in VCSELs have been usually performed using two different configurations. In the first one, linearly polarized external light is injected with a direction that is orthogonal to the linear polarization of the free-running VCSEL. This is known as "orthogonal optical injection" [31]. In such master-slave configuration, the sweep of the injected power for a fixed frequency detuning between the two lasers leads to a bistable switching of the VCSEL's polarization to the master polarization [31]. Bistable semiconductor lasers are expected to be key components for all-optical signal processing applications in future optical networks [2]. Additionally, optical injection in VCSELs is an attractive method to obtain nonlinear transfer functions which can be used for different aplications in optical computing and in optical communications [2]. All-optical signal processing functions such as signal regeneration or inversion can be performed using transverse mode selection in multimode VCSELs under appropriate optical injection [2]. In a different configuration, known as "parallel optical injection", linearly polarized light from an external laser source is injected parallel to the linear polarization of the solitary VCSEL [32]. Both, parallel [20-22] and orthogonal [23-25] optical injection have been used in experiments to suppress higher order transverse modes. Corresponding theoretical studies have been made for orthogonal [24-25] and parallel [26-30] optical injection configurations.

Recent experimental and theoretical work on higher order transverse mode suppression in VCSELs induced by parallel optical injection have focused on devices with emission in two transverse modes [23, 29-30]. The selection of the fundamental mode (and hence, the suppression of the higher order mode) has been achieved when the two transverse modes have parallel polarizations [23,29-30]. Analysis was given of the dependence of the modal selection on the wavelength detuning, $\Delta\lambda=\lambda_{inj}-\lambda_f$ , where $\lambda_{inj}$ is the optical injection wavelength and $\lambda_f$ is the wavelength of the fundamental mode. The injected power needed to induce modal selection exhibited a minimum, $P_{min}$, at a positive wavelength detuning, $\Delta\lambda_{min}$ [23,30]. It was theoretically shown that both $P_{min}$, and $\Delta\lambda_{min}$ increase with the VCSEL bias current [30]. A linear increase of $\Delta\lambda_{min}$ with the bias current was obtained [30]. The relation between the transverse mode selection and the injection locking was theoretically [30] and experimentally [23] obtained for large positive values of $\Delta\lambda$. In this case the selection was accompanied by locking of the fundamental mode to the optically injected signal [23,30]. However the relation between both phenomena was not explored for arbitrary values of the wavelength detuning.

In this work we perform an experimental study of the transverse mode selection in a 1550-nm two-transverse mode VCSEL subject to parallel polarized optical injection. In a previous experiment the dependence on $\Delta\lambda$ of the injected power needed to induce transverse mode selection was studied for just one value of the VCSEL bias current [23]. We extend our measurements to consider several values of the bias current. We obtain a similar dependence on the current to that observed in theory [30]. Our measurements show that both $P_{min}$, and $\Delta\lambda_{min}$ increase with the bias current. We also report the relation between the transverse modal selection and the injection locking properties of multi-mode VCSELs for arbitrary values of $\Delta\lambda$. We show that both phenomena occur simultaneously at the same level of injected optical power if large and positive values of $\Delta\lambda$ are considered. For small enough values of $\Delta\lambda$ the injected power required to select the fundamental transverse mode of the VCSEL is smaller (higher) than that needed for the occurrence of injection locking for low (high) enough levels of the bias current.

Our paper is organised as follows. In section II we describe our experimental setup. In section III we present the experimental results. Finally, in section IV a discussion and a summary are presented.

## II. EXPERIMENTAL SET-UP

Parallel optical injection is achieved using the experimental set-up shown in Fig. 1. This setup is based on those used in [33-35]. An all-fiber system has been developed in order to inject the light from a tunable external cavity laser diode (Tunics Plus-CL) into a commercially available quantum-well 1550nm-VCSEL (RayCan™) via a three-port polarization maintaining optical circulator. The bias current and the temperature of the device were controlled with a laser driver (Thorlabs LDC200) and temperature controller (Thorlabs TED200), respectively. The temperature of the VCSEL was held constant at 297 $^{o}$K for all the experiments. 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 98/2 fiber directional coupler was included in the setup to divide the optical signal from the tunable laser into two branches. The 2% branch was connected to an optical power meter to monitor the optical input power, while the 98 % branch was directly launched into the 1550nm-VCSEL. After the third port of the optical circulator a 50/50 coupler was connected in order to analyze the reflective output of the VCSEL in an Optical Spectrum Analyzer (OSA, ANDO AQ6317) and in an electrical RF signal analyzer (Anritsu MS2719B). A fast photodetector (PD, 9 GHz bandwidth) was connected before the RF analyzer in order to obtain the RF spectrum of the signal.

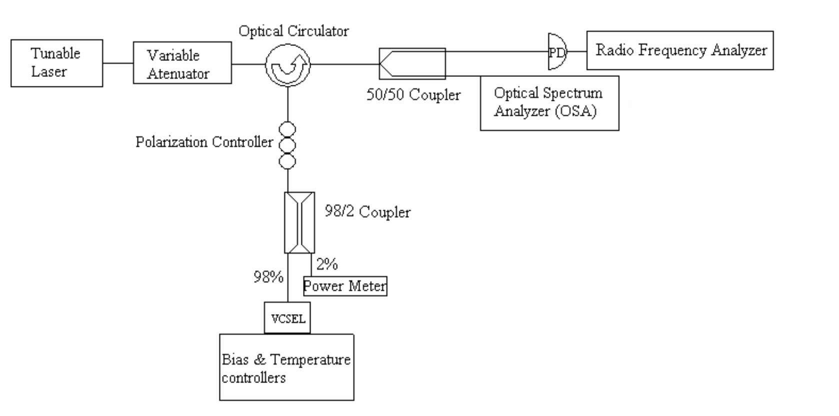


Fig. 1. Experimental set-up of parallel optical injection in a VCSEL.

Fig. 2(a) shows the L-I characteristics of the solitary device. This is the same device that was studied in [23]. The VCSEL begins to emit in the fundamental transverse mode with a threshold current of $I_{th}$ = 2.83 mA, measured at the temperature of 297 K. Linearly polarized emission in the fundamental transverse mode is observed until its bias current reaches a value of $I_b$=3.9 mA (1.4 times the threshold current). The direction of that polarization will be called "parallel" in this work. Above that bias current level the VCSEL also emits in a higher-order transverse mode. The higher-order transverse mode is also linearly polarized in the parallel direction. Fig. 2(b) shows the optical spectrum of the VCSEL at a bias current of $I_b$=4.9 mA. The two peaks, that correspond to the parallel polarized fundamental and high-order transverse modes, are located at the wavelengths of $\lambda_f$ = 1560.59 and $\lambda_h$ = 1558.5 nm, respectively. We have checked that both modes are linearly polarized and have parallel polarizations over the whole bias current range.

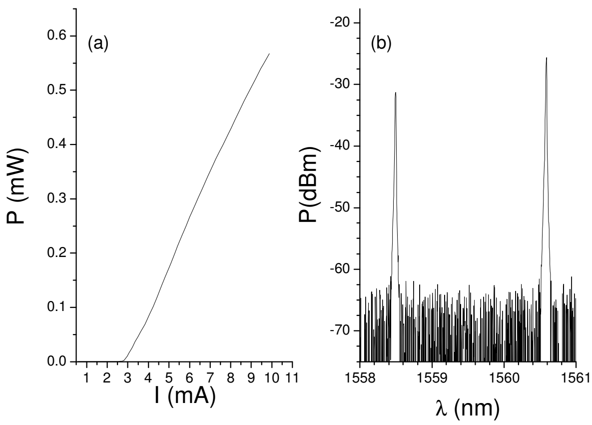


Fig. 2. (a) Light-current characteristics of the VCSEL without optical injection. (b) Optical spectrum of the free-running VCSEL ($I_b$=4.9 mA).

## III. EXPERIMENTAL RESULTS

In this work we consider a "parallel polarized optical injection" configuration in which linearly polarized light from a tunable external laser source is injected parallel to the linear polarization of the free-running VCSEL. The polarization controller is adjusted in order to assure the parallel optical injection configuration. The optical injection is characterized by its wavelength $\lambda_{inj}$ and by its strength, given by the value of optical power arriving at the VCSEL, $P_{inj}$. When the optical injection is applied, a new peak appears at $\lambda_{inj}$ in the optical spectrum. The magnitude of that peak increases as $P_{inj}$ increases whereas the peaks appearing at $\lambda_f$ and $\lambda_h$, corresponding to the fundamental and higher-order transverse mode, respectively, remain unchanged. This fact indicates that the peak appearing at $\lambda_{inj}$ is due to the tunable laser light that is reflected at the VCSEL cavity. The situation changes for larger values of $P_{inj}$ that are slightly below the value in which injection locking occurs. This is shown in Fig. 3(a) where the optical spectrum is plotted when $P_{inj}$ = 1.32 mW and $\Delta\lambda = \lambda_{inj} - \lambda_f$ = 0.09 nm. Two light sources contribute to the peak appearing at $\lambda_{inj}$: the tunable laser light that is reflected at the VCSEL and the fundamental mode of the VCSEL. This mode is contributing because the peak appearing at $\lambda_f$ has clearly decreased its level with respect to the free-running case (see Figs. 2(b) and 3(a)). Injection locking is obtained for a slightly larger value of $P_{inj}$ as shown in Fig. 3(b), where both peaks, located at $\lambda_f$ and $\lambda_h$, have disappeared and the measured optical spectrum exhibits a single peak at the optical injection wavelength. Fig. 3(b) shows that, for the detuning conditions considered in Fig. 3, both phenomena, the locking and the selection of the fundamental mode occur simultaneously. This result was already obtained both in theory [30] and in experiments [23].

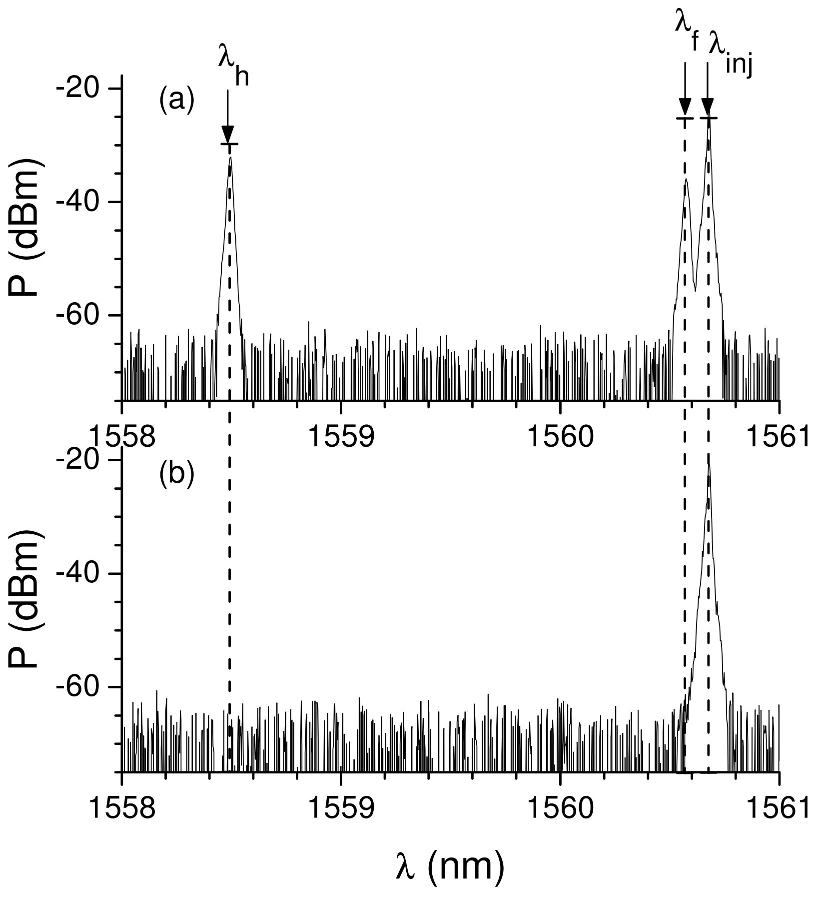


Fig. 3. Optical spectrum for the multimode VCSEL subject to parallel polarized optical injection when $P_{inj}$ is (a) 1.32 mW, and (b)=1.49 mW. In this figure $I_b$=4.9mA and $\Delta\lambda$= 0.09 nm.

Fig. 4 shows the injected power required for the selection of the fundamental transverse mode as a function of the wavelength detuning, $\Delta\lambda$, for several values of the bias current applied to the VCSEL. We have obtained these values by fixing the detuning and increasing the injected power from zero until a Side Mode Suppression Ratio (SMSR) of 20 dB is achieved. We have considered that the selection of the fundamental mode is obtained when the SMSR of the peak appearing at $\lambda_{inj}$ with respect to the peak appearing at $\lambda_h$ is equal or larger than 20 dB.

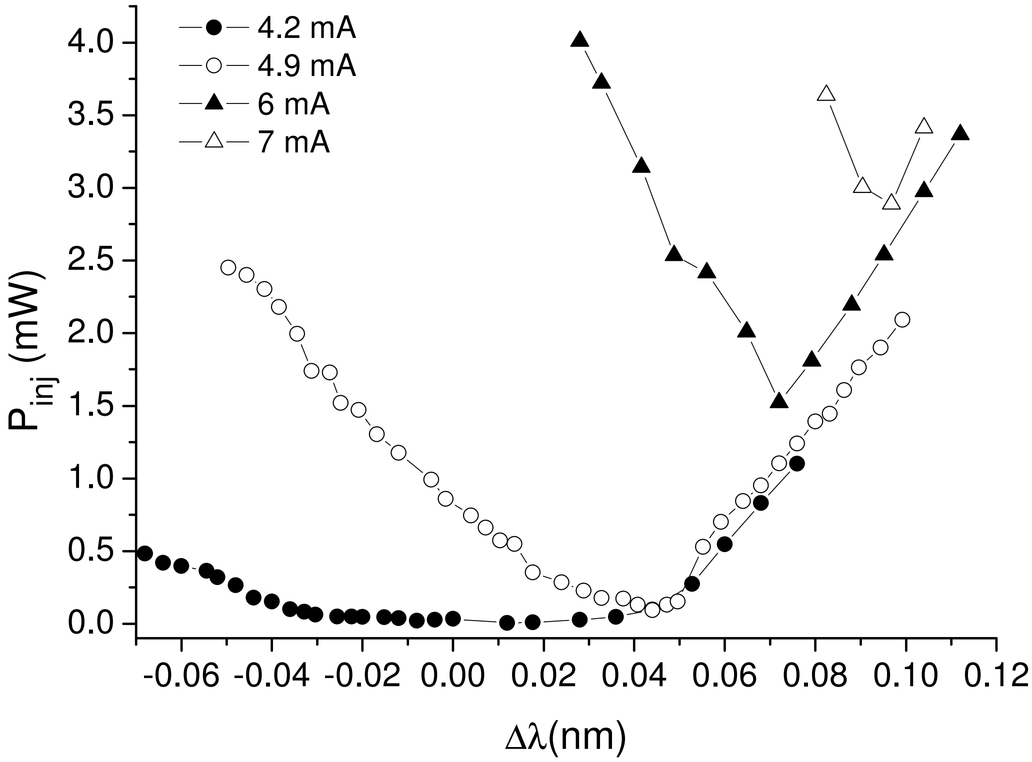


Fig. 4. Injected power required to achieve the fundamental transverse mode selection as a function of Δλ for several values of $I_b$.

The injected optical power required for modal selection exhibits a minimum, $P_{min}$, at a positive value of wavelength detuning, $\Delta\lambda_{min}$. Fig. 4 shows that this result holds for a wide range of $I_b$. It also generalizes our previous experimental findings that were obtained for just one value of the current ($I_b$=4.9 mA) [23]. Curves are more asymmetric around $\Delta\lambda_{min}$ as $I_b$ is decreased. Fig. 4 also shows that the curves are very close for positive and large wavelength detunings, while they are very separated for smaller $\Delta\lambda$. Both $P_{min}$ and $\Delta\lambda_{min}$ increase when increasing $I_b$. These experimental results are in agreement with the theoretical results of [30]. Both, the asymmetry of the curves and the positive value of $\Delta\lambda_{min}$ are due to the positive value of the linewidth enhancement factor, $\alpha$ [30]. In fact symmetric curves around $\Delta\lambda_{min}$=0 are obtained when $\alpha$=0 [30].

The fact that the curves in Fig. 4 are close for long injection wavelengths indicates that the selection of the fundamental mode can be obtained with a value of the injected power that changes slightly with the bias current when $\Delta\lambda$ is large and positive. This result is in agreement with previous theoretical results [30]. For instance, when $\Delta\lambda_{min}$ = 0.075 nm, $P_{inj}$ at which selection is obtained only changes from 1.10 to 1.64 mW when $I_b$ is varied from 4.2 to 6 mA. This is in contrast with the large variations obtained at smaller values of $\Delta\lambda$: when $\Delta\lambda_{min}$ = 0.028 nm, $P_{inj}$ at which selection is obtained changes from 0.027 to 4 mW when $I_b$ is varied from 4.2 to 6 mA. Our results indicate that operation at large and positive $\Delta\lambda$ is of interest in the long distance single-mode fiber transmission of multimode injection-locked VCSELs [19] because the selection of the fundamental mode is almost independent on the VCSEL bias current.

Fig. 5 shows the dependence of $P_{min}$ and $\Delta\lambda_{min}$ on $I_b$. Both quantities increase when increasing the bias current. A linear increase of $\Delta\lambda_{min}$ with the current was obtained in theory [30]. This means that if the fundamental mode has to be selected with the minimum injected power, an increase of the injected current must be accompanied by a linear increase of the wavelength of the optical injection [30]. A linear fit of our results is included in Fig. 5(b). The slope of the fit is $\Delta\lambda_{min} / \Delta I_b$ is 0.032 nm/m and its regression coefficient is 0.94. The low regression coefficient can be due to the large uncertainty in the determination of $\Delta\lambda_{min}$ for $I_b$=4.2 mA due to the wide plateau around the minimum value. Measurements for more values of $I_b$ are desirable to fully check the previous linear relationship.

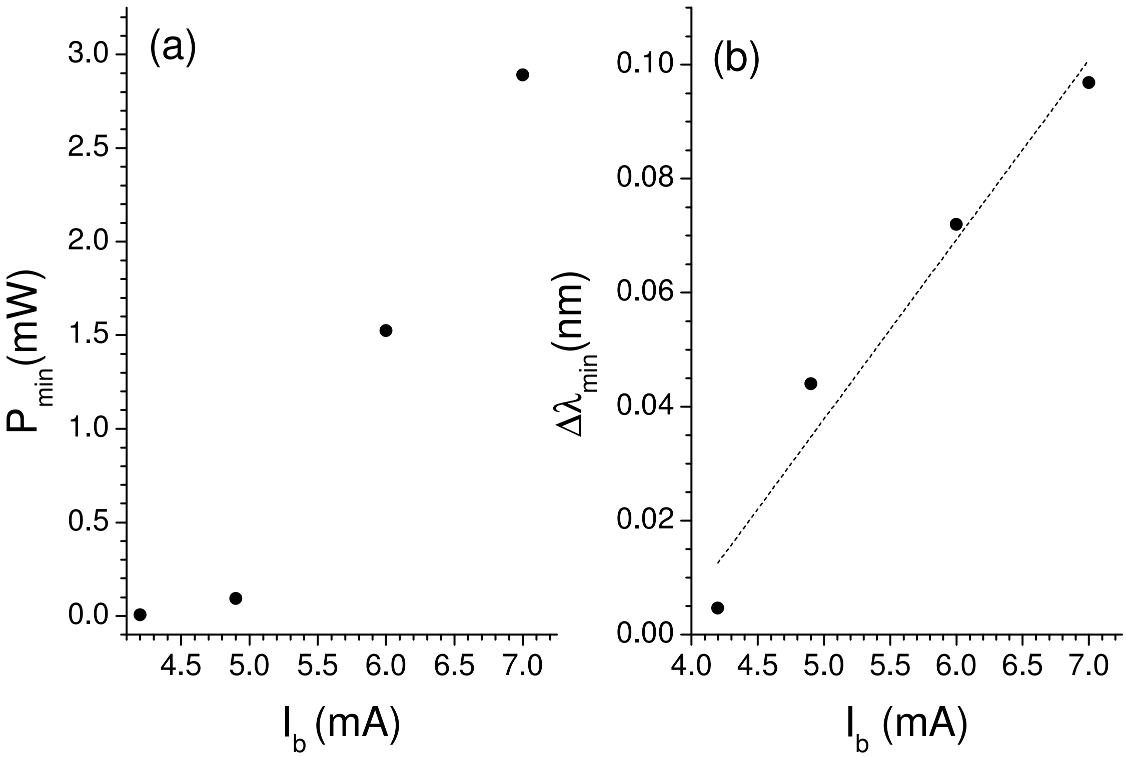


Fig. 5. (a) $P_{min}$ and (b) $\Delta\lambda_{min}$ values as a function of the bias current.

We have also studied the injection locking properties of the 1550 nm multimode VCSEL. Injection locking behavior has been characterized by using the RF spectrum of the total power. The transition to injection locking illustrated in Fig. 3(b) is characterized in the RF spectrum by a sudden decrease towards a flat shape. This is also the criterion that we have used to depict the stable locking region in [35]. Fig. 6 shows the injection locking diagrams in the plane of injected power versus wavelength detuning. These diagrams are depicted for the same values of the bias current considered in Fig. 4. The characterization of the locking behavior has been performed simultaneously with the characterization of the modal selection shown in Fig. 4. The values shown in Fig. 6 have been obtained by fixing the detuning and increasing the injected power from zero until its maximum value. The stable locking regime, where the wavelength of the fundamental mode follows the wavelength of the external signal, is obtained inside the curves shown in Fig. 6. Our results for the stable locking region are similar to those observed for single-transverse mode VCSELs subject to parallel optical injection [36]. The stable locking region is bounded on the long-wavelength side by the saddle-node bifurcation and on the short-wavelength side by the Hopf bifurcation [36].

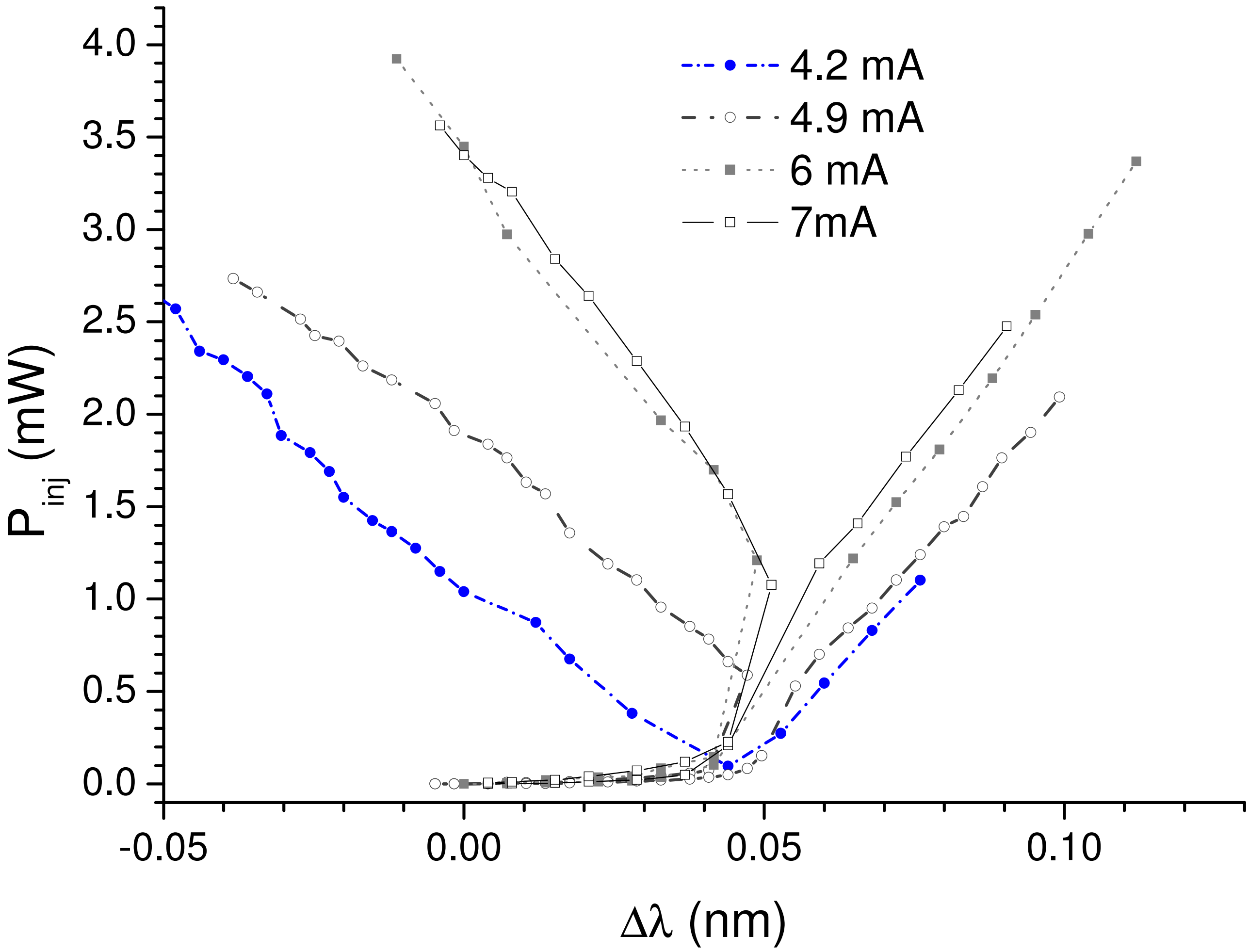


Fig. 6. Injected power required to achieve injection locking as a function of Δλ for several values of $I_b$.

Similarly to Fig. 4, locking curves are closer when $\Delta\lambda$ is large and positive than for smaller $\Delta\lambda$. For a fixed $\Delta\lambda$, the value of $P_{inj}$ at which the locking is obtained increases as $I_b$ is increased. This increase is smaller for large and positive values of $\Delta\lambda$. However the increase is similar for large values of $I_b$ because curves for $I_b$=6 and 7 mA become similar. We also note that results shown in Fig. 3 are not totally consistent with those reported in Figs. 4 and 6. Fig. 3(b) shows that the selection of the fundamental mode and locking is obtained at $P_{inj}$=1.49 mW when $\Delta\lambda$=0.09 nm. However, Figs. 3 and 6 indicate that both locking and selection are obtained at $P_{inj}$=1.75 mW for that value of $\Delta\lambda$. The reason for this small discrepancy is that the results shown in Fig. 3 were obtained in a similar set-up but with instruments [23] that were different to those used to obtain Figs. 4 and 6.

In Fig. 7 the relation between injection locking and modal selection is clarified when some of the results of Figs. 4 and 6 are superimposed. Fig. 7(a) shows that for small enough values of $\Delta\lambda$ ($\Delta\lambda<0.04$ *nm*), the injected power required to select the fundamental mode is smaller than that needed for injection locking. The opposite situation is observed when increasing the bias current. Fig. 7(b) shows that when the VCSEL is biased with 6mA, for small values of $\Delta\lambda$ ($\Delta\lambda<0.07$ *nm*) a larger $P_{inj}$ is required for modal selection than that needed for injection locking. Finally, Figs. 7(a) and 7(b) show that the selection of the fundamental mode is accompanied by locking of that mode to the injected signal for large enough values of detuning (Δλ>0.04 nm and Δλ>0.07 nm, for 4.9 and 6 mA bias currents, respectively).

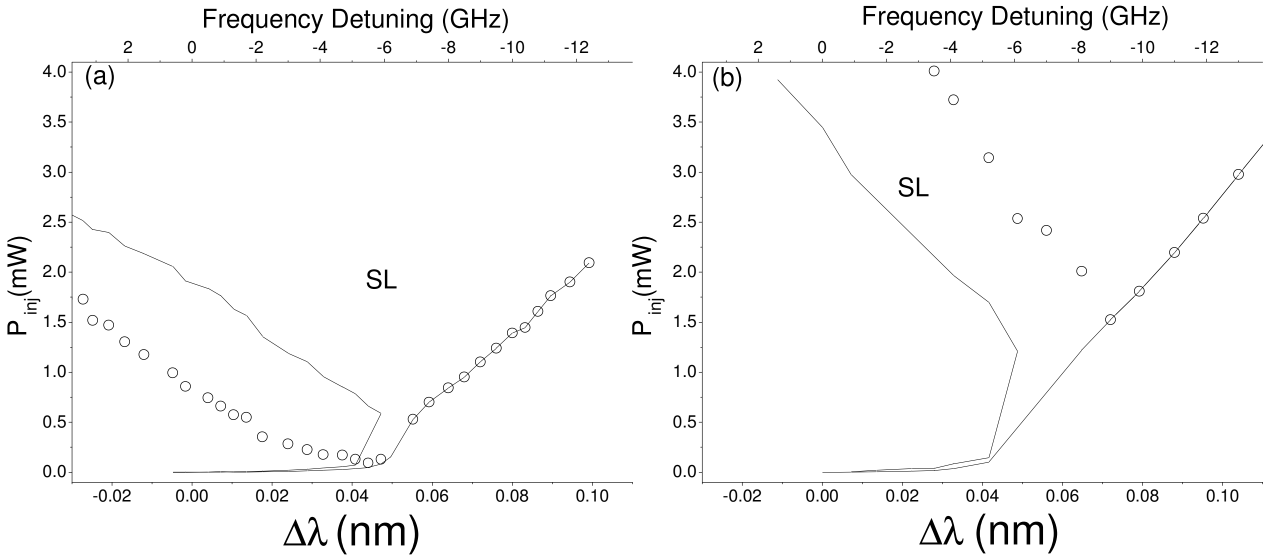


Fig. 7. Injection power required to achieve fundamental transverse mode selection (circles) as a function of wavelength detuning when the VCSEL bias current is (a) 4.9 mA, and (b) 6 mA. Injection locking diagrams are also depicted with solid lines.

## V. SUMMARY AND CONCLUSIONS.

To summarize, we have performed an experimental study of the transverse mode selection in a 1550-nm two-transverse mode VCSEL subject to parallel polarized optical injection. We have measured the injected power needed to select the fundamental mode as a function of the wavelength detuning for several values of the bias current. This power exhibits a minimum at a positive wavelength detuning value. The curves obtained for different bias currents are very close for positive and large wavelength detuning, while they are very separated for smaller detuning. The selection of the fundamental mode can be obtained with a value of the injected power that changes only slightly with the bias current when the wavelength detuning is large and positive. These results indicate that operation at large and positive wavelength detuning is of interest in the long-distance single-mode fiber transmission of multimode injection-locked VCSELs [19] because the selection of the fundamental mode is obtained with an injected power that is almost independent on the VCSEL bias current. Both, the minimum injected power and the wavelength detuning at which it appears increase with the bias current. Our results indicate that this wavelength detuning increases linearly with the bias current. This means that if the fundamental mode has to be selected with the minimum injected power, an increase of the injected current must be accompanied by a linear increase of the wavelength of the optical injection. We have experimentally investigated the relation between injection locking and modal selection for arbitrary values of the wavelength detuning. For small detuning values, with the device biased with a low (high) current, the injected power required for modal selection is lower (higher) than that needed for injection locking. Modal selection and injection locking occur simultaneously for large and positive values of the wavelength detuning. Our results are in qualitative agreement with recent theoretical investigations [30].

## ACKNOWLEDGEMENTS

The authors would like to thank Matías Salvide and Marita Torre from the Instituto de Física "Arroyo Seco", U.N.C.P.B.A. for fruitful discussions. The authors acknowledge support from the Ministerio de Ciencia e Innovación under project TEC2009-14581-C02-02 and from the Marie Curie Intra-European Fellowships for Career Development (IEF), European Commission.

# REFERENCES


[1] K. Iga, “Surface-emitting laser: its birth and generation of new optoelectronics field”, *IEEE J. Sel. Top. Quantum Electron*. 6, no.6 , 1201 (2000).

[2] F. Koyama, “Recent advances of VCSEL Photonics”, *J. Lightwave Technol*. 24, no. 12, pp. 4502-4513 (2006).

[3] C. H. Chang, L. Chrostowski and C.J. Chang-Hasnain, “Injection locking of VCSELs”, *IEEE J. Select. Topics Quantum Electron*. 9, no. 5, pp.1386-1393 (2003).

[4] L. Chrostowski, B. Faraji., W. Hofmann, M. C. Amann, S. Wieczorek and W. W. Chow, “40 GHz bandwidth and 64 GHz resonance frequency in injection-locked 1.55 µm VCSELs”, *IEEE J. Sel. Top. Quantum Electron*. 13, 1200-1208 (2007).

[5] E. K. Lau, X. Zhao, H. K. Sung, D.Parekh, C. J. Chang-Hasnain, and M. C. Wu, “Strong optical injection-locked semiconductor lasers demonstrating>100-GHz resonance frequencies and 80-GHz intrinsic bandwidths”, *Optics Express*, vol. 16, no. 9, pp. 6609-6618 (2008).

[6] X. Zhao, B. Zhang, L. Christen, D. Parekh, W. Hofmann, M. C. Amann, F. Koyama, A. E. Willner, and C. J. Chang-Hasnain, “Greatly increased fiber transmission distance with an optically injection-locked vertical-cavity surface-emitting laser”, *Opt. Exp*. 17, no. 16, 13785-13791 (2009).

[7] R. Lang, “Injection locking properties of a semiconductor laser”, *IEEE J. Quantum Electron*. 18, no. 6, pp. 976-983 (1982).

[8] G. H. M. van Tartwijk, D. Lenstra, “Semiconductor lasers with optical injection and feedback”, *Quantum Semiclass. Opt*. 7, pp. 87-143 (1995).

[9] E. K. Lau, L. Wong, and M.C. Wu , “Enhanced modulation characteristics of optical-injection locked lasers: a tutorial”, *IEEE J. Selec. Top. In Quantum Electron*., vol. 15, no. 3, pp. 618-633 (2009).

[10] C. J. Chang-Hasnain, J.P. Harbison, G. Hasnain, A.C. von Lehmen, L.T. Florez and N.G. Stoffel, “Dynamic, polarization and transverse mode characteristics of vertical cavity surface emitting lasers”, *IEEE J. Quantum Electron*. 27, no. 6, pp. 1402-1409 (1991).

[11] D. Vakhshoori, J. D. Wynn, G. J. Zydzik, M. Asom, K. Kojima, R. E. Leibenguth, and R. A. Morgan, “Top-surface emitting lasers with 1.9 V threshold voltage and the effect of spatial hole burning on their transverse mode operation and efficiencies”, *Appl. Phys. Lett*. Vol. 62, no. 13, pp. 1448-1450 (1993).

[12] A. Valle, J. Sarma and K.A. Shore, “Spatial hole burning effects on the dynamics of vertical-cavity surface-emitting laser diodes”, *IEEE J. Quantum Electron*. 31, no. 8, pp. 1423-1431 (1995).

[13] K. D. Choquette, R.P. Schneider, K.L. Lear and R.E. Leibenguth, ”Gain-dependent polarization properties of vertical-cavity lasers”, *IEEE J. Select. Topics Quantum Electron*. 1, no. 2, 661 (1995).

[14] J. M. Martín-Regalado, F. Prati, M. San Miguel and N.B. Abraham, “Polarization properties of vertical cavity surface-emitting lasers”, *IEEE J. Quantum Electron*. 33, no. 5, pp. 765-783 (1997).

[15] A. Valle, L. Pesquera, and K.A. Shore “Polarization behaviour of birefringent multi-transverse mode vertical-cavity surface emitting lasers”, *IEEE Photon. Technol. Lett.* 9, pp. 557-559 (1997).

[16] B. Ryvkin, K. Panajotov, A. Georgievski, J. Danckaert, M. Peeters, G. Verschaffelt, H. Thienpont and I. Veretennicoff, “Effect of photon-energy-dependent loss and gain mechanisms on polarization switching in vertical-cavity surface-emitting lasers”, *J. Opt. Soc. Am. B.* 16, 2106 (1999).

[17] D. Vez, S. Eitel, S. G. Hunziker, G. Knight, M. Moser, R. Hoevel, H. P. Gauggel, M. Brunner, A. Hold, and K. H. Gulden, “10 Gbit/s VCSELs for datacom: devices and applications”, Proc. SPIE 4942, 29 (2003).

[18] D. Parekh, X. Zhao, W. Hofmann, M. C. Amann, L. A. Zenteno, C. J. Chang-Hasnain, “Greatly enhanced modulation response of injection locked multimode VCSELs”, *Opt. Exp*. 16, no. 26, 21582 (2008).

[19] D. Parekh, B. Zhang, X. Zhao, Y. Yue, W. Hofmann, M. C. Amann, A. Willner, and C. J. Chang-Hasnain, “Long distance single-mode fiber transmission of multimode VCSELs by injection locking”, *Opt. Exp*. 18, no. 20, 20552-20557 (2010).

[20] Y. Hong, P. S. Spencer, P. Rees, K. A. Shore, “Optical injection dynamics of two-mode vertical-cavity surface-emitting semiconductor lasers,” *IEEE J. Quantum Electron*., vol. 38, no. 3, pp. 274-278 (2002).

[21] Y. Onishi, F. Koyama, N. Nishiyama, C. Caneau, and C. E. Zah, “Nonlinear optical input-output characteristics of 1.55 microns injection-locked vertical-cavity surface-emitting lasers,” *Appl. Phys. Lett.*, vol. 84, no. 17, pp. 3247-3249 (2004).

[22] A. Quirce, A. Valle, A. Hurtado, C. Giménez, L.Pesquera, and M. J. Adams, “Experimental study of transverse mode selection in VCSELs induced by parallel optical injection”, *IEEE J. Quantum Electron*. 46, no. 4, pp. 467-473 (2010).

[23] A. Quirce, J. R. Cuesta, A. Valle, A. Hurtado, L.Pesquera, and M. J. Adams. "Polarization bistability in long-wavelength multitransverse-mode VCSELs induced by orthogonal optical injection". Proc. SPIE 7720, 77201V (2010).

[24] A. Valle, I. Gatare, K. Panajotov, M. Sciamanna, “Transverse mode switching and locking in vertical-cavity surface-emitting lasers subject to orthogonal optical injection” *IEEE J. Quantum Electron*. 43, no. 4, pp. 322-333 (2007).

[25] K. Panajotov, I. Gatare, A. Valle, H. Thienpont and M. Sciamanna, “Polarization- and transverse-mode dynamics in optically injected and gain-switched vertical-cavity surface-emitting lasers”, *IEEE J. Quantum Electron*. 45, pp. 1473-1481 (2009).

[26] J. Y. Law, G. H. M. van Tartwijk, and G. P. Agrawal, “Effects of transverse mode competition on the injection dynamics of vertical-cavity surface-emitting lasers,” *Quantum Semiclass. Opt*., vol. 9, no. 5, pp. 737-747 (1997).

[27] M. S. Torre, C. Masoller, and K. A. Shore, “Numerical study of optical injection dynamics of vertical-cavity surface-emitting lasers”, *IEEE J. Quantum Electron*., vol. 40, no. 1, pp. 25-30 (2004).

[28] M. S. Torre, A. Valle, and L. Pesquera, “Polarization and transverse mode behaviour of VCSELs under optical injection”, *Optical and Quantum Electronics*. 38, pp. 445-465 (2006).

[29] M. S. Torre, A. Valle, and L. Pesquera, “Transverse mode selection in vertical-cavity surface-emitting lasers with optical injected signal,” *IEEE J. Quantum Electron*., vol. 46, no. 1, pp. 105-111 (2010).

[30] M. Salvide, M. S. Torre, A. Valle and L. Pesquera, “Transverse mode selection and bistability in vertical-cavity surface-emitting lasers induced by parallel polarized optical injection”, *IEEE J. Quantum Electron*., to appear.

[31] Z. G. Pan, S. Jiang, M. Dagenais, R.A. Morgan, K. Kojima, M.T. Asom and R.E. Leibenguth, “Optical injection induced polarization bistability in vertical-cavity surface-emitting lasers”, *Appl. Phys. Lett.* 63, pp. 2999-3001 (1993).

[32] H. Li, T.L. Lucas, J.G. McInerney, M.W. Wright and R.A. Morgan, “Injection locking dynamics of vertical cavity semiconductor lasers under conventional and phase conjugate injection”, *IEEE J. Quantum Electron*. 32, no. 2, pp. 227-235 (1996).

[33] A. Valle, M. Gomez-Molina, and L. Pesquera, “Polarization bistability in 1550nm wavelength single-mode vertical-cavity surface-emitting lasers subject to orthogonal optical injection”, *IEEE J. Sel. Top. Quantum Electron.* 14, no. 3, pp. 895-902 (2008).

[34] A. Hurtado, I. D. Henning, and M. J. Adams, “Two-wavelength switching with a 1550nm VCSEL under single orthogonal optical injection”, *IEEE J. Sel. Top. Quantum Electron*. 14, pp. 911-917 (2008).

[35] A. Hurtado, A. Quirce, A. Valle, L. Pesquera, and M. J. Adams, “Nonlinear dynamics induced by parallel and orthogonal optical injection in 1550 nm vertical-cavity surface-emitting lasers (VCSELs)”, *Opt. Exp*., vol. 18, no. 9, pp. 9423-9428 (2010).

[36] A. Hurtado, D. Labukhin, I. D. Henning, and M. J. Adams, “Injection locking bandwidth in 1550-nm VCSELs subject to parallel and orthogonal optical injection”, *IEEE J. Sel. Top. Quantum Electron*. 15, pp. 585-593 (2009).