Experimental study of Transverse Mode Selection in VCSELs induced by Parallel Polarized Optical Injection

A. Quirce, A. Valle, A. Hurtado, C. Giménez, L. Pesquera, and M. J. Adams

Abstract—Modal selection induced by parallel polarized optical injection is studied experimentally in a vertical-cavity surface-emitting laser (VCSEL) with emission in two transverse modes. We report that the selection of the fundamental transverse mode can be achieved when the two transverse modes have parallel polarizations. The selection of the fundamental mode is accompanied by locking of that mode to the optically injected signal for large enough values of the wavelength detuning between the fundamental mode and the externally injected signal. The injected power needed to induce modal selection grows as the VCSEL bias current is increased and exhibits a minimum with respect to the injection wavelength at a value $\lambda_{\min}$ that is slightly longer than the wavelength of the fundamental mode of the solitary VCSEL. We also report that the selection process exhibits a bistable behaviour when the wavelength of optical injection increases beyond $\lambda_{\min}$. The width of the observed bistable region grows linearly with the wavelength of the optically injected signal. Selection of the higher-order transverse mode is achieved when the optical injection wavelength is close to that of the higher-order transverse mode. The qualitative behavior associated with the selection of the higher-order mode is similar to that of the fundamental mode.

Index Terms—Optical injection, injection locking, transverse modes, vertical-cavity surface-emitting lasers (VCSELs).

I. INTRODUCTION

Optical injection in semiconductor lasers has undergone considerable research for many years [1]. Optical injection is a commonly employed technique to improve semiconductor laser emission characteristics [2-3]. Recent

interest in vertical-cavity surface-emitting lasers (VCSELs) subject to optical injection has emerged due to their excellent characteristics, including low threshold current, single-longitudinal-mode operation, compactness, low power consumption, low cost, and circular output beam [4-24]. Injection locking in VCSELs has been proven to reduce the frequency chirp [4] and the laser noise [6], and to increase the dynamic range [6] and the resonance frequency beyond 100-GHz [7]. An injection locked VCSEL has been used as a duplex transmitter/receiver [8] and also as a multifunctional device for performing format conversion and NRZ-data clock recovery [9]. Rich nonlinear dynamics can also be experimentally found in VCSELs subject to external optical injection [10-12]. Moreover, all-optical signal processing functions such as signal regeneration [5],[13-14], inversion [5],[15], buffer memory [16] and flip-flop [17] can be performed with VCSELs subject to appropriate optical injection. Recent experimental work has also demonstrated how optical injection can induce polarization switching [18-24] and transverse mode selection [5],[14-15],[25-27] in VCSELs. Most of the previous research [5],[14-15],[19-23],[26] has been reported for the 1550 nm wavelength region, making them relevant for applications in optical telecommunications. Some of the above mentioned applications [5],[14-15] are based on transverse mode selection in VCSELs induced by the external optical injection. The regions in which polarization and transverse mode switching occur, usually display bistable behavior [5], [15-17], [20-23] making these devices also suitable for all-optical flip-flop and buffer memory operation [16-17] for applications in all-optical signal processing and optical computing.

Emission in different polarization and transverse modes is usually found in solitary VCSELs. While the multitransverse mode emission is attributed to Spatial Hole Burning (SHB) effects [28-30], the polarization behavior of VCSELs can be influenced by a number of physical mechanisms [31-34]. Optical injection experiments have been usually performed using two different configurations. The first, corresponding to the seminal work by Pan [35], is known as the “orthogonal optical injection” configuration: linearly polarized light is injected with a polarization that is orthogonal to the linear polarization of the solitary VCSEL. The second is known as “parallel optical injection”, where both the optical injected

Manuscript received July 30, 2009. This work was supported in part by the Ministerio de Educación y Ciencia (MEC), Spain, under project TEC2006-13887-C05-02/TCM. The work of A.Hurtado was supported in part by the Ministerio de Educación y Ciencia (MEC), Spain, under the Programa de Becas Postdoctorales and by the European Commission, under the Marie Curie Intraeuropean Fellowships Programme.

A. Quirce, A. Valle, C. Giménez and L. Pesquera are with the Instituto de Física de Cantabria, Consejo Superior de Investigaciones Científicas (CSIC)-Universidad de Cantabria, E-39005 Santander, Spain. A. Quirce is also with the Departamento de Física Moderna, Univ. de Cantabria, Facultad de Ciencias, E-39005, Santander, Spain (Phone: (34) 942 201465. Fax: (34) 942 200935. E-mail: quirce@ifca.unican.es; valle@ifca.unican.es; pesquerl@ifca.unican.es)

A. Hurtado and M. J. Adams are with the School of Computer Science and Electronic Engineering, University of Essex, Wivenhoe Park, CO4 3SQ Colchester, U.K. (E-mail: ahurt@essex.ac.uk; adammm@essex.ac.uk)

signal and the VCSEL have parallel linear polarizations. In this configuration the injection locking dependence in single-transverse mode VCSELs on the injected power and frequency detuning is similar to that found in edge-emitting lasers [36]. Modal selection in multitransverse mode VCSELs has been obtained when using orthogonal [27] and parallel optical injection [25-26]. Theoretical analyses of that problem have also been performed for the cases of orthogonal [27] and parallel optical injection [37-40].

The selection process under parallel optical injection depends on the polarization of the transverse modes of the solitary VCSEL. Selection of the fundamental transverse mode has been reported when both modes are orthogonally polarized [25-26],[37-40]. However different experimental results have been obtained when the free-running VCSEL has two parallel-polarized modes. In particular, in Ref. [26] the selection of the fundamental mode was achieved, whereas in Ref. [25] that selection was not possible. Recent theoretical work [40] has shed some light on this discrepancy. In general, transverse mode selection can be attained when the two modes have parallel polarizations [40]. In that case the minimum injected power needed to select a transverse mode increases as the injection current is increased [40]. Theoretical simulations also show that the modal selection is favoured as the frequency of the injected light becomes smaller than the frequency of the mode to be selected [40].

In this work we have experimentally measured how parallel optical injection can select the fundamental transverse mode of a VCSEL emitting in two transverse modes with parallel polarizations. We show that the fundamental mode is selected over a wide range of optical injection powers and frequencies. Some of the theoretical predictions of Torre et al [40] are verified in our experiment. We have experimentally characterized the bistable behavior associated with transverse mode selection. Additionally, in the final part of this work we have shown that the selection of the higher-order transverse mode can also be achieved by using an appropriate optically injected signal. The paper is organized as follows. In Section II we describe the experimental set-up and the solitary VCSEL characteristics. Results concerning the fundamental transverse mode selection and its bistable behavior are described in Sections III and IV, respectively. A similar study for the selection of the higher-order transverse mode is presented in Section V. Finally, Section VI contains a summary and the conclusions.

II. EXPERIMENTAL SET-UP

Experimentally, parallel optical injection is achieved by using the set-up presented in Fig. 1. This set-up is based on the experiments of Refs. [20-21]. An all-fiber system has been developed in order to inject the light from a tunable laser (Tunics Plus-CL) into a quantum-well commercial VCSEL (RayCan, Co.) emitting around the wavelength of 1560 nm. The VCSEL bias current and temperature are controlled, respectively, by a laser driver (Thorlabs LDC200) and a temperature controller (Thorlabs TED200). The temperature was held constant at 297 °K during the experiments. The

output of the tunable laser is injected into the VCSEL via a three-port polarization-maintaining optical circulator (OC). Control of the power and polarization of the injected signal are

Fig. 1. Experimental set-up for parallel optical injection. VA: variable attenuator; OC: optical circulator; PC: polarization controller; FC: fiber coupler; PM: power meter; OSA: optical spectrum analyzer.

achieved by using a variable attenuator (VA) and a polarization controller (PC), respectively. A fiber coupler (FC) with a 98/2 split ratio and a power meter (PM) are used to monitor the optical power, P_{inj} , injected into the VCSEL. An Optical Spectrum Analyzer (OSA) with a resolution of 0.01 nm is included in the setup to perform spectral measurements. It is important to note that the spectrum measured at the OSA includes the power emitted by the VCSEL plus the reflection of the input light from the VCSEL cavity.

Fig. 2. Light-current characteristics of the multitransverse mode VCSEL.

We have first characterized the free-running VCSEL measuring its Light-Current (L-I) characteristics and the optical spectra for several values of bias current. Fig. 2 shows the L-I curve of our device, showing an experimentally measured threshold current (I_{th}) of 2.83 mA at 297 K. Optical spectra show that the VCSEL first emits in the fundamental

Fig. 3. Optical spectrum when P_{inj} is (a) 0, (b) 1.32 mW and (c) 1.49 mW. In this figure $\Delta\lambda=0.09$ nm and $I_{VCSEL}=4.9$ mA.

mode until its current reaches a value of $I_{VCSEL}=3.9$ mA. Exceeding that level the VCSEL also emits in a higher order transverse mode. This is illustrated in Fig. 3(a) which shows the optical spectrum of the VCSEL with an applied bias current of $I_{VCSEL}=4.9$ mA. The two main peaks appearing in the spectrum correspond to the fundamental transverse mode (located at the wavelength of $\lambda_f=1560.59$ nm) and to a higher-order transverse mode (at the wavelength of $\lambda_h=1558.5$ nm). We have checked that both modes are linearly polarized and have parallel polarizations for the values of current considered in this work. The two-mode emission is maintained over the whole VCSEL current range.

III. TRANSVERSE MODE SELECTION

To obtain modal selection, an optical signal is injected close to the wavelength of the fundamental transverse mode, λ_f . The polarization controller is adjusted to assure the parallel optical injection configuration. We characterize the optical injection by its strength, given by the value of the power entering into the VCSEL, P_{inj} , and by its wavelength, λ_{inj} . P_{inj} is obtained by multiplying the power measured at the PM by 49. When the optical injection is applied, a new peak appears at λ_{inj} in the optical spectrum. The magnitude of that peak increases as P_{inj} increases whereas the peaks appearing at λ_f and λ_h , corresponding to the fundamental and higher-order transverse mode, respectively, remain unchanged. This fact indicates that the peak appearing at λ_{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(b) where the optical spectrum is plotted when $P_{inj} = 1.32$ mW and $\lambda_{inj} = 1560.68$ nm, corresponding to an initial wavelength detuning of 0.09 nm ($\Delta\lambda = \lambda_{inj} - \lambda_f = 0.09$ nm) with respect to the fundamental mode. Two light sources contribute to the peak appearing at λ_{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 λ_f has clearly decreased its level with respect to the free-running case (please compare Figs. 3(a) and (b)). Injection locking is obtained for a slightly larger value of P_{inj} as shown in Fig. 3(c), where both peaks, located at λ_f and λ_h , disappear and the measured optical spectrum exhibits a single peak at the optical injection wavelength. Fig. 3(c) shows that the injection locking of the VCSEL's fundamental mode is accompanied by a suppression of the higher order transverse mode of more than 40 dB. For the detuning conditions considered in figs. 3(a-c) both phenomena, the locking and the selection of the fundamental mode occur simultaneously within the resolution of our variable attenuator.

We have measured the injected power needed to obtain the selection of the fundamental mode as a function of the bias current applied to the VCSEL, I_{VCSEL} . The results are

Fig. 4. Injected power required to achieve the fundamental transverse mode selection as a function of I_{VCSEL} . The selection is achieved above the squares and circles for $\Delta\lambda=0$ and $\Delta\lambda=0.05$ nm, respectively.

presented in Fig. 4 for two different values of initial wavelength detuning, $\Delta\lambda$. We consider that the selection of the fundamental mode is achieved if the power of the higher-order mode becomes smaller than the 5% of the total power without injection. The injected power, given in dBs, corresponds to the ratio between P_{inj} and the solitary VCSEL power.

For the two cases of detuning considered, $\Delta\lambda = 0$ and $\Delta\lambda = 0.05$ nm, the selection of the fundamental mode is attained for values of injected power higher than those represented respectively by the squares and circles included in Fig. 4. This indicates, in agreement with the theoretical results reported in Ref. [40] that for small values of current the selection of the fundamental mode by optical injection is possible. Also, as

predicted in Ref. [40], the minimum injected power needed to select the fundamental transverse mode increases as the VCSEL injection current increases. However, Ref. [40] also predicts that if P_{inj} is then further increased the VCSEL again would emit in two transverse modes. Our experimental results do not confirm this theoretical prediction. We believe that this is due to the high levels of optically injected power predicted to obtain again emission in two modes. These levels of input power could not be obtained in our experiments due to equipment limitation (in our setup the maximum available P_{inj} was around 4 mW).

In Ref. [25] it is experimentally reported that in the case of two parallel-polarized transverse modes, the VCSEL single-mode operation cannot be obtained via optical injection. These observations are quite different from our results and those of Ref. [26]. A possible reason behind such discrepancies could be the different injection rates in the i-transverse mode, κ_i ($i=f,h$ for fundamental and higher-order transverse mode, respectively) achieved in both experiments. We have theoretically shown in Ref. [40] that when $\kappa_f=\kappa_h$ the selection of the fundamental mode can be achieved by selecting a small enough VCSEL bias current. That is the situation that we have found in our experiment. However, Refs. [38, 40] also show that when the injection rate in the higher-order transverse mode is larger than that of the fundamental mode ($\kappa_h=2\kappa_f$) there are no values of injected power nor VCSEL bias current in which the fundamental mode is selected. This situation can be obtained if the injected beam has a larger spatial overlap with the higher-order transverse mode and could be the reason behind the results of Ref. [25].

Fig. 4 also shows that the value of P_{inj} required to obtain the selection of the fundamental mode decreases as the detuning, $\Delta\lambda$, is increased from 0 to 0.05 nm. In principle this result is in

Fig. 5. Injected power required to achieve the fundamental transverse mode selection as a function of $\Delta\lambda$ when $I_{VCSEL}=4.9$ mA. Results corresponding to increasing and decreasing P_{inj} are plotted with dotted and solid lines, respectively.

agreement with Ref. [40] since the modal selection is favoured

as the wavelength of the injected light becomes longer than the wavelength of the mode to be selected [40]. However, a more detailed analysis of this dependence over a wider range of detuning, $\Delta\lambda$, would be desirable to fully check the agreement. This analysis is performed in the following section.

IV. BISTABLE BEHAVIOR OF THE TRANSVERSE MODE SELECTION

In this section we measure the injected power required to obtain the fundamental mode selection as a function of the detuning, $\Delta\lambda$, for a fixed value of the VCSEL current. Two sets of results are presented in Fig. 5. The first set, shown with a dotted line, corresponds to the case of increasing the injected optical power, P_{inj} , from 0 until the maximum level is reached

Fig. 6. Hysteresis width as a function of $\Delta\lambda$ when $I_{VCSEL}=4.9$ mA.

($P_{inj}=3.92$ mW). Subsequently P_{inj} is decreased from that maximum until the zero level is reached again. Results corresponding to the selection when decreasing P_{inj} are plotted with a solid line in Fig. 5. We can observe that for $\Delta\lambda < \Delta\lambda_{min}=0.045$ nm, the P_{inj} required to achieve selection decreases as $\Delta\lambda$ increases. If the detuning is further increased above that value the power required for selection increases again. The existence of a wavelength (λ_{min}) for which the power required for the fundamental mode selection is minimum can be explained by the fact that the selection is associated with injection locking. As the wavelength of the injected signal is moved towards longer values of detuning with respect to the resonant wavelength of the VCSEL, the locking and hence the selection of the fundamental mode will require an increasing amount of injection power. The comparison between the dotted and the solid lines in Fig. 5 also shows that the process of transverse mode selection exhibits a bistable behaviour. A similar kind of bistability was obtained by Koyama [5] although in that case, in contrast to the results reported in this work, the optical injection was performed in the vicinity of the higher order transverse mode in order to select that mode.

Fig. 5 also shows the existence of three distinct regions in the plane of injected power versus initial wavelength detuning:

regions of stable locking, unstable locking and no locking. In the unstable locking region, for a fixed value of detuning, the VCSEL will only be locked to the externally injected signal if the injected power, P_{inj} is decreased from values inside the stable locking region. The bistable behaviour is much clearer when $\lambda > \lambda_{min}$ since the width of the hysteresis region increases significantly. Very wide hysteresis cycles can be obtained for larger values of wavelength detuning. Fig. 6 shows the width of the measured hysteresis cycles, ΔP_{inj} , as a function of the detuning. When $\lambda > \lambda_{min}$ a linear increase of the hysteresis width with the wavelength detuning is observed. However, when $\lambda < \lambda_{min}$, no bistable region is observed and hysteresis width vanishes.

V. SELECTION OF THE HIGHER-ORDER TRANSVERSE MODE

In this section we extend our study to the selection mechanism of the higher-order transverse mode, i.e., when the optical injection wavelength is close to that of the higher-order transverse mode. We now consider a wavelength detuning, $\Delta\lambda_h$, with respect to the higher-order transverse mode, $\Delta\lambda_h = \lambda_{inj} - \lambda_h$. Our results follow similar trends to those described in the previous sections. The selection of the higher-order transverse mode is achieved when λ_{inj} is near λ_h . We have checked that the selection is accompanied by locking of the higher-order mode to the optically injected signal for the same conditions of Fig. 3 ($I_{VCSEL}=4.9$ mA, and large enough positive detuning, $\Delta\lambda_h = 0.09$ nm). The qualitative evolution of the optical spectrum as P_{inj} is increased is very similar to that shown in Fig. 3. We also find that the injection locking and the higher-order transverse mode selection occur simultaneously. Fig. 7 shows the injected power required to obtain the higher-order mode selection as a function of $\Delta\lambda_h$. A comparison with Fig. 5 shows that the selection of the higher-order mode is obtained for larger values of the injected power. Similarly to Fig. 5, results corresponding to increasing and decreasing P_{inj} are shown. The qualitative trends associated with the selection of the higher-order mode are similar to those of the fundamental mode.

Fig.7. Injected power required to achieve the higher-order transverse mode selection as a function of $\Delta\lambda_h$ when $I_{VCSEL}=4.9$ mA. Results corresponding to increasing and decreasing P_{inj} are plotted with dotted and solid lines, respectively.

Fig. 8. Hysteresis width as a function of $\Delta\lambda_h$ when $I_{VCSEL}=4.9$ mA.

The injected power required for modal selection exhibits a minimum with respect to the injection wavelength at a value that is slightly longer than λ_h . The minimum appears at a wavelength detuning $\Delta\lambda_h = 0.05$ nm, very near to that found in Fig. 5. Fig. 7 also shows that the selection process exhibits a bistable behavior when $\Delta\lambda_h$ increases beyond 0.05 nm. The width of the bistable region increases with the wavelength of the optically injected signal. This is more clearly shown in Fig.8 where the hysteresis width has been plotted as a function of $\Delta\lambda_h$. Also a linear increase of the hysteresis width with the wavelength detuning is observed when $\Delta\lambda_h > 0.05$ nm. The comparison between Figs. 6 and 8 also shows that the hysteresis width is larger when considering the fundamental mode selection.

VI. SUMMARY AND CONCLUSIONS

In this contribution we have experimentally studied, for the first time to our knowledge, the selection of the fundamental transverse mode of a 1550nm-VCSEL induced by parallel optical injection. We have demonstrated that this selection is obtained for the VCSEL used in our experiments which is characterized by a free-running emission in two transverse modes both with parallel polarizations. In general the modal selection can be achieved in most classes of multimode VCSELs providing that the VCSEL bias current is small enough. However the selection process does not only depend on the class of VCSEL but also on the injection conditions, for instance on the spatial overlap between the injected beam and the transverse modes profiles. In fact, it has been shown theoretically in Refs. [38],[40] that the selection is not possible when the fundamental mode has a lower injection rate than that of the higher-order transverse mode, a situation that could be found for a larger spatial overlap between the injected beam and the higher-order transverse mode profile. For large enough positive wavelength detuning the selection of the fundamental mode is accompanied by locking of that mode to the optically injected signal. Future work will be devoted to the

simultaneous measurement of the selection and locking processes for different wavelength detunings and VCSEL bias currents. In this way the parameter regions in which selection and locking coincide will be determined. Preliminary theoretical results using the model of Ref. [40] show that for wavelength detunings and bias current similar to those considered in Fig. 3 the selection and injection locking occur simultaneously [41]. We have measured the injected power needed to select the fundamental mode as a function of the VCSEL current. In agreement with previous theoretical results [40], we have experimentally demonstrated that the selection of the fundamental mode by optical injection is possible for small enough values of bias current. We have also shown, again in agreement with the predictions of Ref. [40], that the injected power needed for modal selection grows monotonically as the VCSEL current is increased. However some of the theoretical predictions contained in that work, namely i) once the injected mode has been selected an increase of the injected power leads again to multimode operation, and ii) the selection of the mode is no longer possible if the current surpasses a certain value, could not be fully confirmed because they would require larger values of injection power than were available in our experimental set-up. The injected power needed for fundamental mode selection shows a minimum when measured as a function of the optical injection wavelength. The value of the wavelength, $\lambda_{\min}$, at which the minimum occurs, is 0.045 nm longer than the wavelength of the free-running fundamental mode of the VCSEL. The modal selection process induced by optical injection exhibits a bistable behaviour. Wide hysteresis cycles are attained when the wavelength of the optically injected signal is longer than $\lambda_{\min}$ and the width of the bistable region grows linearly as the wavelength of the injected signal is increased. Selection of the higher-order transverse mode is also achieved by using an optical injection of wavelength close to that of the higher-order transverse mode. The selection process shows similar trends to those observed in the fundamental mode selection.

REFERENCES

- [1] R. Lang, "Injection locking properties of a semiconductor laser", *IEEE J. Quantum Electron.*, vol. 18, no. 6, pp. 976-983, 1982.
- [2] G. H. M. van Tartwijk, and D. Lenstra, "Semiconductor lasers with optical injection and feedback", *Quantum Semiclass. Opt.*, 7, pp. 87-143, 1995.
- [3] E. K. Lau, L. Wong, and M.C. Wu, "Enhanced modulation characteristics of optical-injection locked lasers: a tutorial", *IEEE J. Sel. Top. In Quantum Electron.*, vol. 15, no. 3, pp. 618-633, 2009.
- [4] C. H. Chang, L. Chrostowski, and C. J. Chang-Hasnain, "Injection locking of VCSELs," *IEEE J. Sel. Top. In Quantum Electron.*, vol. 9, no. 5, pp. 1386-1393, Sep-Oct. 2003.
- [5] F. Koyama, "Recent advances of VCSEL Photonics", *J. Lightwave Technol.* Vol. 24, no. 12, pp. 4502-4513, Dec. 2006.
- [6] L. Chrostowski, X. Zhao, and C. J. Chang-Hasnain, "Microwave performance of optically injection-locked VCSELs," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pp. 788-796, Feb. 2006.
- [7] 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, April 2008.
- [8] G. Qing, W. Hofmann, M. C. Amann, and L. Chrostowski, "Optically injection-locked VCSEL as a duplex transmitter/receiver", *IEEE Photonics Technology Letters*, vol. 20, no. 7, pp. 463-465, 2008.
- [9] B. Zhang, X. Zhao, D. E. Parekh, Y. E. Yue, W. E. Hofmann, M. C. Amann, C. J. Chang-Hasnain, and A. E. Willner, "Multifunctional and reconfigurable 10-GHz operation of an optical injection-locked VCSEL", in *The Conference on Lasers and Electro-Optics (CLEO)*, (Optical Society of America, Washington, DC, 2009), paper CtuJ7, 2009.
- [10] Y. Hong, P. S. Spencer, S. Bandyopadhyay, P. Rees, K. A. Shore, "Polarization resolved chaos and instabilities in a VCSEL subject to optical injection", *Opt. Comm.*, vol. 216, pp. 185-189, 2003.
- [11] J. Buesa, I. Gatare, H. Thienpont, K. Panajotov, and M. Sciamanna, "Mapping of the dynamics induced by orthogonal optical injection in vertical-cavity surface-emitting lasers," *IEEE J. Quantum Electron.*, vol. 42, no. 2, pp. 198-207, Feb. 2006.
- [12] I. Gatare, J. Buesa, H. Thienpont, M. Sciamanna, and K. Panajotov, "Nonlinear dynamics accompanying polarization switching in vertical-cavity surface-emitting lasers with orthogonal optical injection", *Appl. Phys. Lett.*, 88, 101106, 2006.
- [13] T. Mori, Y. Sato, and H. Kawaguchi, "Timing jitter reduction by all-optical signal regeneration using a polarization bistable VCSEL," *J. Lightwave Tech.*, Vol. 26, No. 16, pp. 2946-2953, August, 2008.
- [14] Y. Onishi, F. Koyama, "All-optical regeneration using a vertical-cavity surface-emitting laser with external light injection", *IEICE Trans. Electron.*, vol. E87-C, no. 3, pp. 409-415, 2004.
- [15] Y. Onishi, N. Nishiyama, C. Caneau, F. Koyama, and C. E. Zah, "Dynamic behavior of an all-optical inverter using transverse-mode switching in 1.55 microns vertical-cavity surface-emitting lasers", *IEEE Photon. Technol. Lett.*, vol. 16, no. 5, pp. 1236-1238, 2004.
- [16] H. Kawaguchi, T. Mori, Y. Sato, and Y. Yamayoshi, "Optical buffer memory using polarization-bistable vertical-cavity surface-emitting lasers," *Japanese J. Appl. Phys., Express Lett.*, Vol. 45, No. 34, pp. L894-L897, September, 2006.
- [17] T. Mori, Y. Yamayoshi, and H. Kawaguchi, "Low switching-energy and high-repetition-frequency all optical flip-flop operations of a polarization bistable vertical-cavity surface-emitting laser," *Appl. Phys. Lett.*, Vol. 88, No. 10, art. 101102, 2006.
- [18] S. Bandyopadhyay, Y. Hong, P. S. Spencer, K. A. Shore, "VCSEL polarization control by optical injection," *J. Lightwav. Technol.*, vol. 21, no. 10, pp. 2395-2404, 2003.
- [19] K. H. Jeong, K. H. Kim, S. H. Lee, M. H. Lee, B. S. Yoo, and K. A. Shore, "Optical injection-induced polarization switching dynamics in 1.5 μ m wavelength single-mode vertical cavity surface emitting lasers", *IEEE Phot. Tech Lett.*, vol. 20, pp. 779-781, 2008.
- [20] A. Valle, M. Gomez-Molina, and L. Pesquera, "Polarization bistability in 1550 nm wavelength single-mode vertical-cavity surface-emitting lasers subject to orthogonal optical injection", *IEEE J. Sel. Top. In Quantum Electron.*, vol. 14, no. 3, pp. 895-902, 2008.
- [21] A. Hurtado, I. D. Henning, and M. J. Adams, "Two-wavelength switching with a 1550 nm VCSEL under single orthogonal optical injection", *IEEE J. Sel. Top. In Quantum Electron.*, vol. 14, no. 3, pp. 911-917, 2008.
- [22] A. Hurtado, I. D. Henning, and M. J. Adams, "Different forms of wavelength polarization switching and bistability in a 1.55 μ m vertical-cavity surface-emitting laser under orthogonally polarized optical injection", *Opt. Lett.*, 34, pp. 365-367, 2009.
- [23] A. Hurtado, I. D. Henning and M. J. Adams, "Wavelength polarization switching and bistability in a 1550nm VCSEL subject to polarized optical injection", *IEEE Phot. Tech. Lett.*, vol. 21, no. 15, pp. 1084-1086, 2009.
- [24] A. Quirce, A. Valle, L. Pesquera, "Very wide Hysteresis Cycles in 1550 nm-VCSELs subject to Orthogonal Optical Injection", *IEEE Phot. Tech Lett.*, to appear.
- [25] 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.
- [26] 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.
- [27] A. Valle, I. Gatare, K. Panajotov, and M. Sciamanna, "Transverse mode switching and locking in vertical-cavity surface-emitting lasers subject to orthogonal optical injection," *IEEE J. Quantum Electron.*, vol. 43, no. 4, pp. 322-333, Apr. 2007.

- [28] 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.*, vol. 27, no. 6, pp. 1402-1409, Jun., 1991.
- [29] 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.
- [30] A. Valle, J. Sarma, K. A. Shore, "Spatial hole burning effects on the dynamics of vertical-cavity surface-emitting semiconductor lasers," *IEEE J. Quantum Electron.*, vol. 31, no. 8, pp. 1423-1431, Aug. 1995.
- [31] K. D. Choquette, R. P. Schneider, K. L. Lear, and R. E. Leibenguth, "Gain-dependent polarization properties of vertical-cavity lasers," *IEEE J. Sel. Topics Quantum Electron.*, vol. 1, no. 2, pp. 661-666, Mar./Apr. 1995.
- [32] 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.*, vol. 33, no. 5, pp. 765-783, May 1997.
- [33] A. Valle, L. Pesquera, K. A. Shore, "Polarization behavior of birefringent multitransverse mode vertical-cavity surface-emitting lasers," *IEEE Photon. Technol. Lett.*, vol. 9, no. 5, pp. 557-559, May 1997.
- [34] B. Ryvkin, K. Panajotov, A. Georgievski, J. Danckaert, M. Peeters, G. Verchaffelt, 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. Amer. B*, vol. 16, pp. 2106-2113, 1999.
- [35] 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.*, vol. 63, pp. 2999-3001, 1993.
- [36] 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.*, vol. 32, no. 2, pp. 227-235, 1996.
- [37] 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.
- [38] M. S. Torre, C. Masoller, and K. A. Shore, "Numerical study of optical injection locking dynamics of vertical-cavity surface-emitting lasers", *IEEE J. Quantum Electron.*, vol. 40, no. 1, pp. 25-30, Jan. 2004.
- [39] M. S. Torre, A. Valle, and L. Pesquera, "Polarization and transverse mode behavior of VCSELs under optical injection," *Opt. Quantum Electron.*, vol. 38, pp. 445-465, 2006.
- [40] 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.*, in press.
- [41] M. Salvide, M. S. Torre, A. Valle, L. Pesquera, "Selection of transverse modes in VCSELs subject to optical injection", presented at the 94th Reunión Nacional de Física, Rosario, Argentina, Sept. 14-18, 2009.

A. Quirce received the Licenciada en Física (Ms. Sc.) degree from the Universidad de Cantabria, Spain, in 2008. She is currently working toward the PhD degree in Physics. Her current research interests are in the areas of dynamics of vertical-cavity surface-emitting lasers and optical injection effects in semiconductor lasers.

A. Valle was born in Reinosa, Cantabria, Spain, in 1965. He received the M. Sc. and Ph.D. degree in physics from the Universidad de Cantabria, Spain, in 1988 and 1993, respectively.

During 1994 and 1995, he was a postdoctoral fellow at the School of Electronic and Electrical Engineering at the University of Bath, England. In 1996 he joined the Instituto de Física de Cantabria (CSIC-UC). Since 1998 he has been lecturer at the Departamento de Física Moderna at the University of Cantabria, Spain. His research interests are in the areas of vertical-cavity surface-emitting lasers, noise and nonlinear dynamics of semiconductor lasers.

A. Hurtado was born in Madrid, Spain, in 1976. He received the Graduate degree in telecommunications engineering from the E.T.S. Ingenieros de Telecomunicación, Universidad Politécnica de Madrid, Spain, in 2001, and the PhD degree in photonic technology from the Universidad Politécnica de Madrid, in 2006, studying the optical bistability in semiconductor laser amplifiers.

Since 2007 he has been working at the Optoelectronics Research Group of the University of Essex (UK), firstly as a post-doctoral fellow and since 2009 as a Research Officer after being awarded a Marie Curie Intra-European Fellowship. His current research interests include semiconductor lasers, semiconductor laser amplifiers, laser's nonlinear dynamics, optical bistability, and optical switching devices.

C. Giménez is currently working toward the Licenciada en Física degree (Ms. Sc.) from the Universidad de Cantabria, Spain.

L. Pesquera was born in Vega de Infanzones, León, Spain, in 1952. He received the M.Sc. degree in physics in 1974 from the Universidad de Valladolid, Spain. He was a postgraduate fellow at the Université de Paris VI during 1977-1980. He received the Ph.D. degree in physics in 1980 from the Universidad de Cantabria, Santander, Spain.

In 1980 he joined the Departamento de Física Moderna of the Universidad de Cantabria. Since 1991 he has been Professor of Physics at the Universidad de Cantabria. In 1995 he joined the Instituto de Física de Cantabria (CSIC-UC). His research work started in the field of stochastic processes applied to Physics and he has made contributions to the foundations of quantum physics, fluctuations in nuclear reactors, disordered systems and laser physics. He is currently working on the modeling of noise and nonlinear properties of semiconductor lasers and their applications to optical communication systems.

M. Adams received the Ph.D. degree in laser theory from the University of Wales, Cardiff, U.K., in 1970. He was engaged in optoelectronics research and development with 15 years experience in industry (Plessey, BT), and 22 years in academia (University of Cardiff, University of Southampton, University of Essex, Colchester, U.K.). Since 1996, he has been a Professor at the University of Essex. His current research interests include semiconductor lasers, optical amplifiers, optical waveguides, optical bistability, semiconductor nonlinear optics and optical switching devices, and nonlinear dynamics of lasers. He is the author or coauthor of many articles published widely in the optoelectronics field over many years, including a standard text on optical waveguide theory and two books in semiconductor lasers and optical fibers for use in telecommunications.