Applied Physics Letters

Role of external cavity reflectivity for achieving polarization control and stabilization of vertical cavity surface emitting laser

Cite as: Appl. Phys. Lett. **90**, 031117 (2007); https://doi.org/10.1063/1.2431790
Submitted: 27 October 2006 . Accepted: 12 December 2006 . Published Online: 19 January 2007

Mikel Arizaleta Arteaga, Manuel López-Amo, Hugo Thienpont, and Krassimir Panajotov

AIP Publishing

APPLIED PHYSICS LETTERS **90**, 031117 (2007)

Role of external cavity reflectivity for achieving polarization control and stabilization of vertical cavity surface emitting laser

Mikel Arizaleta Arteaga[a] and Manuel López-Amo
Department of Electrical and Electronic Engineering, Universidad Pública de Navarra, Campus Arrosadía, 31006 Pamplona, Navarra, Spain

Hugo Thienpont and Krassimir Panajotov[b]
Department of Applied Physics and Photonics, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium

(Received 27 October 2006; accepted 12 December 2006; published online 19 January 2007)

The authors present the experimental results showing how the external mirror reflectivity affects the polarization properties of a vertical cavity surface emitting laser subject to optical feedback from an extremely short external cavity. The amplitude of modulation of the polarization switching current with the external cavity length is found to be proportional to the external mirror reflectivity, confirming its key role in achieving polarization control and stabilization of such lasers using optical feedback. Numerical simulations presented here show good agreement with experiments. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2431790]

Vertical cavity surface emitting lasers (VCSELs) possess many advantages over conventional edge emitting lasers, such as low threshold currents, circular beam profiles, and low cost. However, VCSELs suffer from a nonstable polarization. Small anisotropies introduced in the manufacturing process make VCSELs have two preferred orthogonal polarization directions of the fundamental transverse mode.[1,2] The two orthogonal linearly polarized (LP) modes have slightly different frequencies of operation and net gains that vary when changing the injection current and/or the temperature of operation, causing polarization switching (PS).[3,4] In order to avoid such polarization instabilities many different techniques based on introducing polarization dependent modal gain and/or loss have been proposed so far (see, for example, Refs. 5–7). Polarized and isotropic optical feedbacks from short and long external cavities are some of the techniques proposed to achieve polarization control or stabilization of VCSELs.[8–13] The increasing interest in using VCSELs as active micro-optic devices in applications such as optical interconnects, where they may be affected by optical feedback from external cavities of the order of tenths of micrometers, has driven the investigation towards shorter external cavities. In fact, isotropic optical feedback from an extremely short external cavity (ESEC) has been shown to cause periodic polarization switching between LP modes[14] and a modulation of the polarization switching current versus the external cavity (EC) length.[15,16] The uncontrollable frequency spacing between LP modes has been pointed out as the origin of such effects, and isotropic and polarized optical feedbacks from an ESEC have been proposed to stabilize and control polarization properties of VCSELs.[17] Indeed, polarization control and stabilization of a VCSEL by means of isotropic optical feedback from an ESEC have been recently demonstrated.[18] However, its applicability in VCSELs with short frequency spacing between LP modes is still under discussion. According to the theoretical model presented in Ref. 17, polarization stabilization could be achieved in practically every VCSEL by properly selecting the external mirror reflectivity, since an increase of the external mirror reflectivity is predicted to cause an increase of the net gain difference between the two LP modes.[17]

In this letter we present the experimental results showing how the external mirror reflectivity affects polarization switching modulation observed in Refs. 15 and 16 and how it may help to achieve polarization stabilization and control of VCSELs. We also carried out a comparison between such experimental results and numerical simulations calculated using model presented in Ref. 17, obtaining good agreement between them.

To perform the experiments we use an oxide-confined GaAs/InGaAs quantum well VCSEL, emitting at 1.005 μm, supplied by the University of Ulm. The VCSEL is made with a circular oxide aperture and shallow surface relief in order to enhance the current region of single transverse mode operation.[19] As a consequence the VCSEL emits in its fundamental transverse mode up to 1.75 times the threshold current. Although no special measures were taken to introduce polarization dependent gain/losses in the VCSEL, polarization of the light emitted by the laser is measured to be stable against injection current variations within the current operation range of the device. A more complete description of the laser is presented elsewhere.[18] The ESEC is made by placing a polarization maintaining optical fiber in front of the VCSEL, so that the cleaved face of the fiber acts as an external mirror with 4% power reflectivity. In order to vary the external mirror reflectivity we glue different aluminum mirrors at the fiber facet with index matching glue. The fiber and the VCSEL are mounted on a five axis translation stage and on a three axis piezoelectric controlled translation stage, respectively, which allows precise alignment of the fiber and the VCSEL. The EC length is changed by moving the VCSEL along the direction of light emission by means of one of the piezocomponents of its stage in steps of 20 nm and with a precision of 5 nm. However, due to the alignment of the charge coupled device camera with respect to the system VCSEL-external mirror, the absolute value of the EC length

[a]Electronic mail: mikel.arizaleta@unavarra.es
[b]Also at: Institute of Solid State Physics, 72 Tsarigradsko Chaussee Boulevard, 1784 Sofia, Bulgaria.

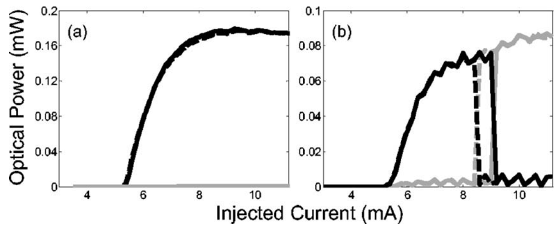

FIG. 1. Experimentally obtained polarization resolved *PI* curve of the VCSEL subject to isotropic optical feedback from an ESEC. The external mirror reflectivities are (a) 4% and (b) 14%. Gray (black) line represents the low (high) frequency LP mode, while solid (dashed) lines represent the two LP modes for slowly increasing (decreasing) the injection current (0.1 mA/s).

is known within 20 μm range (the resolution of the camera itself is 1 μm). In this way, the EC length reported in the following is somehow relative—the zero corresponds to an EC length smaller than 20 μm. The polarization resolved optical power is measured at the far end of the polarization maintaining optical fiber as in Ref. 16.

With no mirror glued at the front face of the fiber (external mirror reflectivity of 4%) and varying the voltage applied to the piezocomponent on which the VCSEL is mounted, we decrease the EC length in steps of 20 nm. At each EC length we vary the injected current (from 2 to 11.8 mA and back to 2 mA in steps of 0.2 mA) and measure the polarization resolved power versus current (*PI*) curve. In Fig. 1 we show two representative *PI* curves for external mirror reflectivities of 4% [Fig. 1(a)] and 14% [Fig. 1(b)]. The two represented modes correspond to the two fundamental transverse modes with orthogonal polarization. Due to the birefringence of the laser cavity these two LP modes have slightly different frequencies of operation and are, therefore, referred to the rest of the letter as the high and the low frequency LP modes. In the case of Fig. 1(a), similarl to the solitary case (without optical feedback), the VCSEL polarization is measured to be stable at any injection current above threshold independent of the EC length. If we increase the external mirror reflectivity to 14% and perform the same experiment [see Fig. 1(b)], two different kinds of polarization resolved *PI* curves are obtained. Depending on the EC length the VCSEL shows polarization switching from the high to the low frequency mode when increasing the injected current or a stable polarization operation as in the solitary case. The polarization switching, if present, does not occur at the same position when increasing and decreasing the injected current, describing a hysteresis (bistable) region [see Fig. 1(b)]. In order to better understand the effect of the optical feedback on the polarization properties of the VCSEL we map the bistable region on the plane EC length-injection current. Such mapping of bistability is measured for four different external mirror reflectivities (see Fig. 2). In this way Figs. 1(a) and 1(b) could be extracted as vertical cuts of Figs. 2(a) and 2(b) [Fig. 1(a) corresponds to cut A of Fig. 2(a) and Fig. 1(b) corresponds to cut B of Fig. 2(b)]. When the external mirror reflectivity is very low [see Fig. 2(a)] the only dependence on the EC length in the mapping is a modulation of the threshold current with half the wavelength of operation of the VCSEL.[20] Above threshold the emitting polarization mode does not depend on the EC length and the VCSEL exhibits the same polarization characteristics as in the solitary case (high frequency mode stable independent of

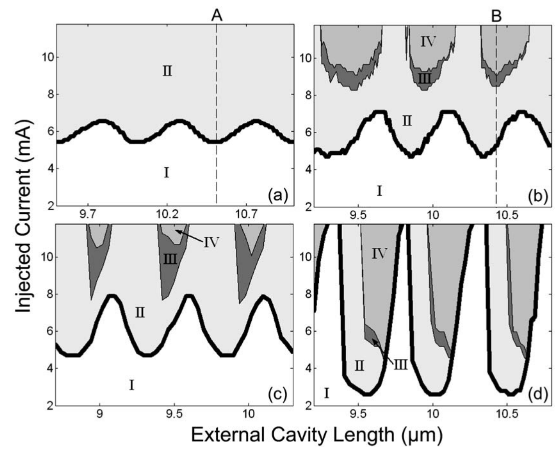

FIG. 2. Experimentally obtained mapping of bistability of a VCSEL subject to isotropic optical feedback from an ESEC. The external mirror power reflectivities are (a) 4%, (b) 14%, (c) 18%, and (d) 30%. A gray scale is used to distinguish between different zones. The darkest gray zone (zone III) between zones II and IV represents the bistable region. The thick black line represents the threshold current below which the laser is not emitting (zone I). On the other hand, in zone II (IV) the VCSEL is stable and emits in its high (low) frequency mode.

the injection current). When increasing the external mirror reflectivity to 14% the amplitude of modulation of the threshold current is increased. Moreover, within each period of modulation, we find a region of EC lengths where the VCSEL switches from the high to the low frequency LP mode when increasing the injection current [see Fig. 2(b)]. This PS occurs through a hysteresis region (bistable region) and as reported in Refs. 15 and 16 the current of PS is modulated with the EC length. If we keep on increasing the external mirror reflectivity, the threshold modulation and the bistable region modulation become deeper [compare Figs. 2(b)–2(d)]. At a certain level of the feedback strength [see Fig. 2(d)] the minima of the PS current modulation decrease below the threshold current and a region of EC lengths where the low frequency mode is stable at any injected current is found. Therefore, using isotropic optical feedback from a high enough external mirror reflectivity, polarization control and stabilization of a VCSEL of a common design are achieved. The experimentally deduced relation between the external mirror reflectivity and the minimum PS current is shown in Fig. 3(a) (please notice that with 4% reflectivity no PS is observed below 12 mA but it may occur above that current). The PS current modulation amplitude is inversely proportional to the minimum PS current.[15,16] However, the total amplitude of modulation of the PS current could not be measured since the maximum of such modulation falls above the range of current operation of the VCSEL. As mentioned previously the change of the external mirror reflectivity is

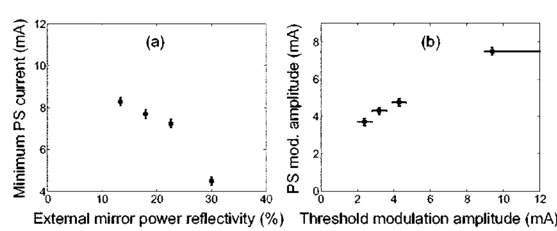

FIG. 3. (a) Measured minimum of the polarization switching current modulation vs the external mirror power reflectivity. (b) Measured polarization switching current modulation amplitude vs threshold modulation amplitude.

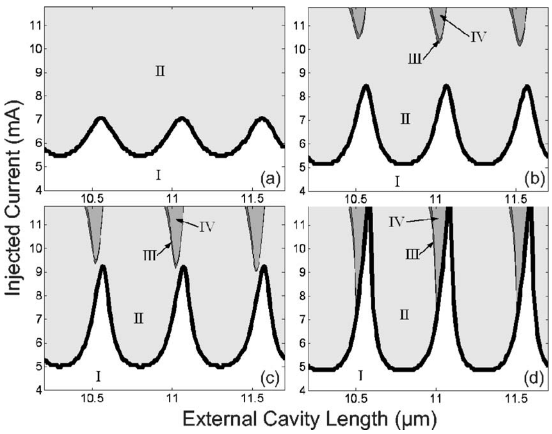

FIG. 4. Numerically obtained mapping of bistability with external mirror power reflectivities of (a) 4%, (b) 14%, (c) 18%, and (d) 30%. A gray scale is used to distinguish between different zones. The darkest gray zone (zone III) between zones II and IV represents the bistable region. The thick black line represents the threshold current below which the laser is not emitting (zone I). On the other hand, in zone II (IV) the VCSEL is stable and emits in its high (low) frequency mode.

performed by gluing a different aluminum mirror at the front face of the fiber, which implies a realignment of the system. In order to rule out an alignment difference as responsible for PS minima variation we check that by misaligning and realigning the system several times without changing the external mirror, the maximum coupled power at the end of the fiber remains constant. Moreover, since the threshold modulation amplitude is directly proportional to the feedback strength,[21] we can establish a relation between the PS modulation amplitude and the feedback strength [see Fig. 3(b)]. As it can be observed from Fig. 3(b), the PS current modulation amplitude increases when increasing the threshold current modulation amplitude by means of increasing the feedback strength.

In order to numerically model the ESEC-VCSEL system we use the model presented in Ref. 17. All the numerical results presented here are obtained using the same VCSEL parameters which are chosen to fit the solitary VCSEL polarization resolved *PI* curve (for the values of the parameters see Ref. 18). Figure 4 shows the numerically obtained mapping of the bistable region for four different external mirror reflectivities. As in the experiments, when the external mirror reflectivity is set to 4% only a modulation of the threshold current is observed and the polarization of the VCSEL is stable against current and/or EC length variations. Increasing the external mirror reflectivity, a region of stable low frequency mode emission (region IV in Fig. 4) and a very thin bistable region (region III in Fig. 4) appear in the mapping. The polarization switching current is modulated with the EC length as reported in Refs. 15 and 16 but only the lower part of the modulation curve stays within the plotted area. When the external mirror reflectivity is set to 30%, the minimum of the bistable region drops below the threshold current and polarization stabilization is achieved. Our model explains such phenomena as a result of an increase of the amplitude of modulation of the mirror losses of each LP mode with the increase of the external mirror reflectivity. Since the modulation of the losses is not in phase for the two LP modes due to the frequency difference between them, the amplitude of modulation of the net gain difference is also increased, leading to an increase of the PS modulation amplitude. This finally allows achieving polarization control and stabilization of the VCSEL.

Summarizing, our experimental results show that the amplitude of the modulation of the PS current versus the EC length of a VCSEL subject to isotropic optical feedback from an ESEC is proportional to the external mirror reflectivity. In such a way, selecting a high enough external mirror reflectivity, polarization control, and stabilization of a VCSEL is experimentally achieved. Numerical results presented are in good agreement with experiments. Therefore, small frequency spacing between LP modes that may prevent us from obtaining polarization stabilization with such technique could be compensated for by increasing the external mirror reflectivity. In such a way, optical feedback from an ESEC turns to be a generic approach to achieve polarization control and stabilization of VCSELs.

The authors acknowledge Rainer Michalzik and his coworkers at the Optoelectronics Department of the University of Ulm for providing the VCSELs, as well as the financial support of the Public University of Navarra, IAP "Photon" network of the Belgian government, FWO-Flanders, GOA and OZR of the VUB, and Project TEC-2004-05936-C02-01 of the MEC (Spain).

[1]C. J. Chang-Hasnain, J. P. Harbison, G. Hasnain, A. C. V. Lehmen, L. T. Florez, and N. G. Stoffel, IEEE J. Quantum Electron. **27**, 1402 (1991).
[2]A. K. Jansen van Doorn, M. P. van Exter, and J. P. Woerdman, Appl. Phys. Lett. **69**, 1041 (1996).
[3]K. D. Choquette, D. A. Richie, and R. E. Leibenguth, Appl. Phys. Lett. **64**, 2062 (1994).
[4]B. Ryvkin, K. Panajotov, A. Georgievski, J. Danckaert, M. Peeters, G. Verschaffelt, H. Thienpont, and I. Veretennicoff, J. Opt. Soc. Am. B **16**, 2106 (1999).
[5]D. Choquette and R. E. Leibenguth, IEEE Photonics Technol. Lett. **6**, 40 (1994).
[6]P. Debernardi, J. M. Ostermann, M. Feneberg, C. Jalics, and R. Michalzik, IEEE J. Sel. Top. Quantum Electron. **11**, 107 (2005).
[7]H. Uenohara, K. Tateno, T. Kagawa, Y. Ohiso, H. Tsuda, T. Kurokawa, and C. Amano, IEEE Photonics Technol. Lett. **11**, 400 (1999).
[8]P. Besnard, M. L. Chares, and G. Stephan, J. Opt. Soc. Am. B **16**, 1059 (1999).
[9]M. Sciamanna, K. Panajotov, H. Thienpont, I. Veretennicoff, P. Megret, and M. Blondel, Opt. Lett. **28**, 1543 (2003).
[10]T. H. Russell and T. D. Milster, Appl. Phys. Lett. **70**, 2520 (1997).
[11]P. Besnard, F. Robert, M. L. Chares, and G. Stephan, Phys. Rev. A **53**, 3191 (1997).
[12]Y. Hong, P. S. Spencer, and K. A. Shore, Opt. Lett. **29**, 2151 (2004).
[13]C. Masoller and M. S. Torre, IEEE J. Quantum Electron. **41**, 483 (2005).
[14]K. Panajotov, M. Arizaleta Arteaga, M. Camarena, H. J. Unold, J. M. Ostermann, R. Michalzik, and H. Thienpont, Appl. Phys. Lett. **84**, 2763 (2004).
[15]A. Valle, L. Pesquera, and K. A. Shore, IEEE Photonics Technol. Lett. **10**, 639 (1998).
[16]M. Arizaleta Arteaga, H. J. Unold, J. M. Ostermann, R. Michalzik, H. Thienpont, and K. Panajotov, IEEE J. Quantum Electron. **42**, 102 (2006).
[17]M. Arizaleta Arteaga, H. J. Unold, J. M. Ostermann, R. Michalzik, H. Thienpont, and K. Panajotov, IEEE J. Quantum Electron. **42**, 89 (2006).
[18]M. Arizaleta Arteaga, M. López-Amo, H. Thienpont, and K. Panajotov, Appl. Phys. Lett. **89**, 091102 (2006).
[19]H. J. Unold, S. Mahmoud, R. Jger, M. Grabherr, R. Michalzik, and K. Ebeling, IEEE J. Sel. Top. Quantum Electron. **7**, 386 (2001).
[20]A. Hsu, J.-F. P. Seurin, S. L. Chuang, and K. D. Choquette, IEEE J. Quantum Electron. **37**, 1643 (2001).
[21]J. H. Osmundsen and N. Gade, IEEE J. Quantum Electron. **19**, 465 (1983).