Experimental study of polarization switching and polarization mode hopping induced by optical injection in VCSELs

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We subject a VCSEL which exhibits type II polarization switching in the range of fundamental transverse mode operation to injection of laser light with orthogonal linear polarization. We report on the observation of bistable polarization switching under optical injection with and without injection locking. We have identified a frequency detuning - injection power range in which the first order transverse mode locks in frequency and polarization to the master laser, with the fundamental transverse mode being suppressed. Furthermore, we show that it is possible to induce polarization mode hopping in a VCSEL which emits in a stable polarization, as well as to stabilize the polarization of mode hopping solitary VCSEL.

Introduction

The vertical-cavity surface-emitting laser (VCSEL) has emerged as a very interesting device for high performance optical telecommunication systems, owing to its numerous advantages with respect to the conventional edge-emitting lasers. Its polarization properties are also of significant interest: the emitted light is linearly polarized (LP) but unlike edge-emitting lasers, its direction may not remain stable as we modify the operating conditions such as the temperature or the injection current. The polarization instability typically consists of a polarization switching (PS) between the two orthogonal LP modes [1, 2]. Recently, a lot of attention has been paid to the polarization dynamics of VCSELs when they are subject to a delayed optical feedback [3], i.e. when part of the emitted light is injected back to the laser cavity. However still little is known about the polarization properties of VCSELs subject to optical injection from another laser. In this paper, we complement the pioneering experimental work by Pan *et al.* in which the authors show that the injection of LP light orthogonal to that of the free-running VCSEL can force the slave VCSEL to lock in frequency and polarization to the master laser [4]. We show that optical injection may induce a bistable PS and injection locking in a large range of frequency detunings, and may induce or stabilize a polarization mode hopping regime.

Experimental results

In our experiment, we use an oxide-confined AlGaAs/GaAs quantum well VCSEL emitting at 845 nm fabricated at the Optoelectronics Department of the University of

Ulm (Germany). Figure 1 (a) shows the polarization-resolved light versus current (LI) characteristic of our VCSEL at a substrate temperature of 20°C. The vertical (horizontal) polarization mode is the higher (lower) frequency mode. A type I PS occurs around 1.6 mA and is accompanied by a polarization mode hopping behavior. It is followed by a type II PS with a region of hysteresis. Our experimental setup is detailed in Fig. 1 (b). Our master laser (ML) is an external cavity diode laser (TEC 100 Littrow) with a total tuning range 845 nm to 855 nm. A non-polarizing 50/50 beamsplitter (BS) is used to guide the light to the detection branch. A half-wave plate (HWP2) allows detecting the desired polarization (horizontal or vertical). An optical isolator (ISO2) prevents back reflections from the fiber coupling unit or the fiber facets. A second optical isolator (ISO1) including two polarizers P3 and P4 prevents optical feedback from the master laser. The polarizer P1 is used to vary the optical injection strength. The half-wave plate HWP1 and the polarizer P2 help to improve the linearity of the polarization of the master laser light and to ensure that the polarization of the injected light is orthogonal to the polarization of the free-running VCSEL. A computer (PC1) has been used to display and record the optical spectrum, being connected to the detector-amplifier of a Fabry-Pérot interferometer (FP) with a free spectral range (FSR) of 30 GHz and a finesse > 150. To measure large frequency detunings, we have used an optical spectrum analyzer (OSA) Ando-AQ6317B. Time-traces of the polarized intensities are analyzed with the combination of 4 GHz photodiode and digital oscilloscope Tektronix CSA 7404.

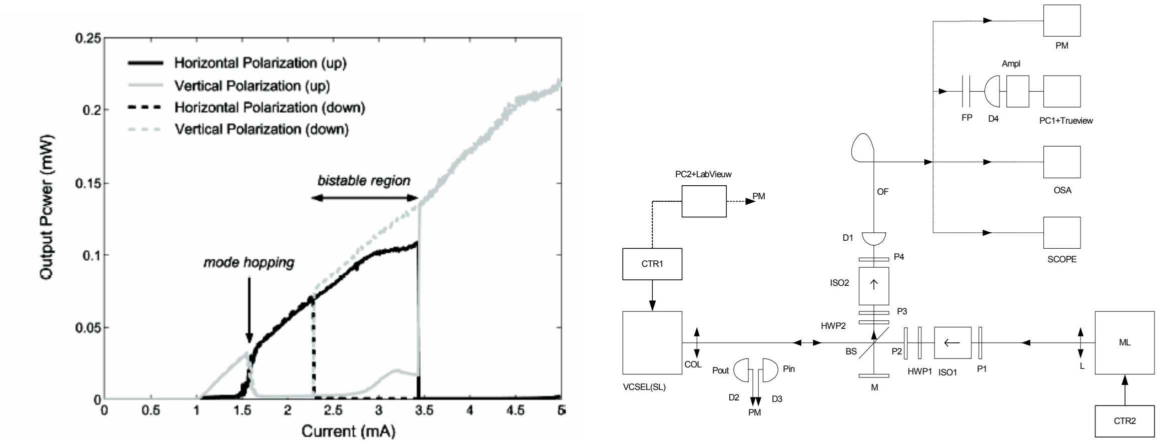

Figure 1: *(a) Polarization-resolved LI-curve for the upward and downward current scan at a substrate temperature of 20°C, (b) complete experimental setup.*

Figure 2 shows PS induced by optical injection, for three different values of the frequency detuning $\Delta\upsilon = \upsilon_{ML} - \upsilon_{SL}$ corresponding to different values of the slave injection current (but still in between the two PS points). The free-running slave VCSEL emits in the horizontal polarization (x, black) but an increase of the injected power (with vertical polarization) makes the VCSEL switching to the vertical polarization (y, gray). When decreasing back the injection strength, we observe a hysteresis region accompanying the optical injection induced PS. The width of the hysteresis increases with the increase of $|\Delta\upsilon|$. These results are in agreement with previous observations by Pan *et al.* [4] on a type I PS VCSEL. Moreover, since our VCSEL is also type II switching, we can test the optical injection effect also when the slave VCSEL is biased in the bistable region close to 2.6 mA. In this case, we observe that the increase of the injected power still makes the VCSEL switching from horizontal to vertical direction but the slave VCSEL keeps the vertical polarization even when decreasing the optical injection strength back to zero.

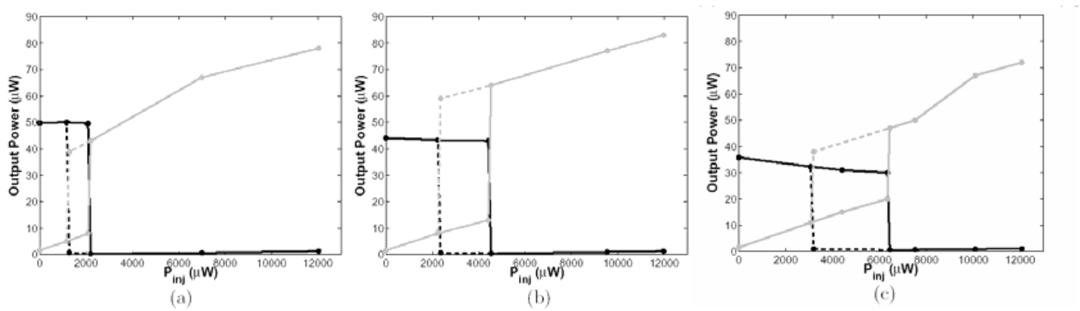

Figure 2: *Hysteresis loops of the output power in the two directions of polarization versus injected power for three different values of frequency detuning: (a) -24 GHz, I_{SL} = 2.074 mA; (b) -31 GHz, I_{SL} = 1.931 mA; (c) -45 GHz, I_{SL} = 1.8 mA. The black (grey) line represents the horizontal (vertical) polarization. The solid (dashed) line represents the upward (downward) injected power scan.*

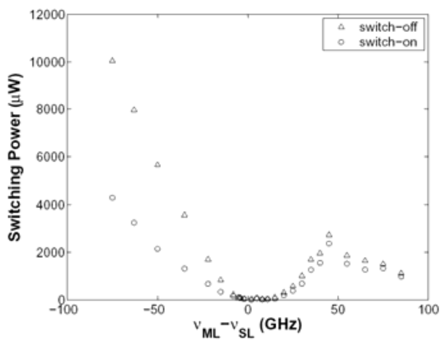

Figure 3: *Switching power as a function of the frequency detuning, at a bias current of 2.105 mA.*

Figure 3 shows the evolution of the hysteresis region due to optical injection for a wider range of frequency detuning. The bias current is set to I_{SL}=2.105 mA, so that the free-running VCSEL operates out of the bistable region. The change of the detuning value is obtained by tuning the master laser and always optimizing injection conditions. The switch-off and the switch-on powers refer respectively to the external injected power at witch the free-running polarisation mode switches off and on. For frequency detunings less than 45 GHz, we obtain results similar to those of Pan *et al.* [4].

However, for higher values of the positive frequency detunings, we observe a change of the slope of the switching power vs. $\Delta\upsilon$ curve. For such large positive detuning values, the slave VCSEL exhibits an injection locking of the first order transverse mode into the master laser frequency and polarization. The fundamental transverse mode is then completely depressed. Moreover, by contrast to previous studies, we have found a bistable PS for both positive and negative detunings. Finally, in our experiment, PS is achieved through injection locking only for negative values of frequency detuning (actually for $\Delta\upsilon < 2$ GHz), in contrast to the reports of Ref. [4].

As a last point, we analyze how optical injection may induce polarization mode-hopping in an otherwise polarization stable VCSEL; see Fig. 4. The free-running VCSEL is biased at a current of 2.105 mA and its dynamics is steady with emission in the horizontal, LP fundamental transverse mode. The frequency detuning is fixed at 39 GHz. For the injection strength corresponding to (a), the VCSEL has switched to the vertical, LP fundamental transverse mode. A further increase of the injected power excites the horizontal mode, which competes with the vertical mode through a polarization mode hopping regime (b)-(e). The duty cycle (percentage of the time in which the VCSEL emits in the horizontal polarization) depends on the injection strength. For large values of injected power, the VCSEL is stabilized back into the vertical polarization. It is worth noting that, on the other hand, optical injection may also stabilize a VCSEL which otherwise exhibits mode hopping: by biasing the slave VCSEL close to the type I PS point (1.756 mA), the VCSEL exhibits a mode hopping but an increase of the injected power with vertical polarization leads to stabilization of the VCSEL into the vertical LP mode.

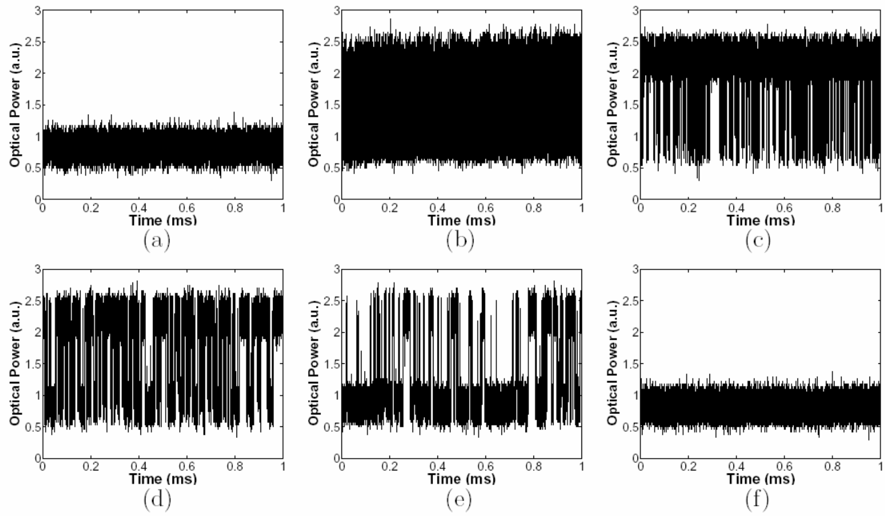

Figure 4: *Mode hopping induced by optical injection. I_{SL}=2.105 mA, $\Delta\upsilon$ = 39 GHz, the substrate temperature is 20°C, horizontal polarization detection. Injected power (duty cycle): (a) 2254 µW (0%), (b) 3673 µW (29%), (c) 4228 µW (82%), (d) 4413 µW (62%), (e) 4514 µW (30%), (f) 4689 µW (0%).*

Conclusions

In summary, we have reported on bistable polarization switching, injection locking, and mode-hopping regime induced by optical injection in VCSELs. Our results motivate further detailed theoretical and experimental studies of the polarization dynamics.

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