Experimental Mapping of Polarization Dynamics induced by Optical Injection in VCSELs

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We carry out an experimental study of the dynamics induced in a VCSEL subject to injection of linearly polarized light orthogonal to the light emitted by the free-running VCSEL. We observe a very rich dynamics, such as multiwave mixing, frequency pulling, limit cycle followed by a period doubling route to chaos, and an inverse period doubling route from a chaotic regime. A detailed mapping in the plane of the optical injection parameters unveils a bistability between a limit cycle and an injection locked steady-state, as well as transitions from the locking to the unlocking region with and without Hopf bifurcation.

Introduction

Optical injection in semiconductor lasers has attracted much interest through the years and rich dynamics have been observed. Important applications of injection locking such as laser spectral narrowing [1], reduction of frequency chirp under modulation [2] or synchronization of arrays of slave lasers by a unique master laser [3] have been demonstrated. Recently, first experiments concerning polarization control in VCSELs through optical injection was reported by Pan *et al.* [4], demonstrating polarization switching accompanied by injection locking and bistability. Latter, Li *et al.* [5] have analyzed experimentally and theoretically the injection locking region and wave mixing effects when a VCSEL is subject to optical injection with the same polarization as that of the free-running mode, mapping the limits of the injection locking region in a frequency detuning versus injected power plane. Hong *et al.* [6] have carried out an experimental study of the dynamics of a VCSEL injected in the same polarization as that of the free-running mode, reporting four-wave mixing, polarization-resolved chaos, period doubling dynamics and limit cycle behaviour after stable injection locking. In this paper we report on the experimental mapping of polarization dynamics induced by optical injection of linearly polarized light orthogonal to the light emitted by the free-running VCSEL.

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). The polarization-resolved light versus current (LI) characteristic of our VCSEL at a substrate temperature of 20°C is showed in Fig. 1(a). The vertical polarization mode is the higher frequency mode (ν_H) and the horizontal polarization mode is the lower frequency mode (ν_L). Mode hopping behaviour is found in the type I polarization switching and the type II polarization switching is accompanied by a region of hysteresis.

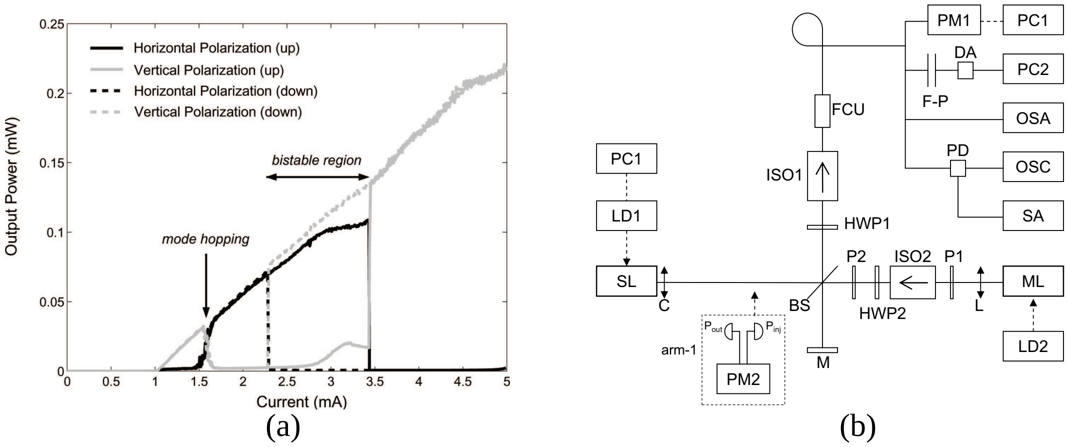

Figure 1: *(a) Polarization-resolved LI-curve for the upward and downward current scan at a substrate temperature of 20°C, (b) complete experimental setup.*

The light emitted by VCSEL (SL) is collimated by a lens (C). A non-polarizer 50/50-beam-splitter (BS) is used to guide the light to the detection branch. A half-wave plate (HWP1) turns the polarization of the light in order to detect the desired component (horizontal or vertical). An optical isolator of 36-40 dB attenuation (ISO1) prevents optical feedback from the Fiber Coupling Unit (FCU). An external cavity diode laser (TEC 100 Littrow) with total tuning range 845 nm to 855 nm is employed as a master laser (ML). The role of the polarizer P1 is to vary the injected power. The optical isolator ISO2 minimizes the perturbation of the master laser due to the slave laser light and its own light reflected by the VCSEL and the mirror (M). The function of the half-wave plate HWP2 is to correct the 45° light polarization rotation due to the optical isolator ISO2. The polarizer P2 is used 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. The box called arm-1 corresponds to a two-positions mobile stage that consists of two photodetectors connected to a power meter (PM2). When placed in the trajectory of the beams, they measure the averaged total power of the output light from the VCSEL (P_{out}) and the injected power (P_{inj}). A computer (PC2) has been used to display and record the spectrum of the light, being connected to the detector-amplifier (DA) of a Fabry-Pérot interferometer (F-P) model TL-300 with a Free Spectral Range (FSR) of 30 GHz and a Finesse >150. To measure frequency detunings of more than 30 GHz or simply to resolve the intrinsic ambiguity of the Fabry-Pérot (aliasing), we have used an Optical Spectrum Analyzer (OSA) model Ando-AQ6317B, with a consequent loss in resolution.

In Fig. 2 the frequency detuning defined as $\Delta\nu = \nu_{ML} - \nu_{SL}$ has been set to 2 GHz. A very weak injected power is needed to achieve polarization switching with injection locking (Fig. 2(b)). In Fig. 2(c) there is undamping of the relaxation oscillations ($f_{ro} \approx 3.4\ GHz$), which indicates limit cycle behaviour. For an increase of the injected power, more peaks appear (Fig. 2(d)) at multiples of the frequency of the side peaks in Fig. 2(c). Next, small features appear between the sharp peaks (indicative of period doubling dynamics) leading to a spectrum dominated by a broad pedestal in Fig. 2(e), indicative of chaotic dynamics. Moreover we observe that lasing in the normally depressed horizontal mode is strongly enhanced when the laser enters the chaotic regime. The aim of the inset of Fig. 2(f) is to show the disappearing features between the main peaks as we still increase the injected power after the region of chaos, which is indicative of inverse period doubling dynamics. For a further increase of power, all the peaks stretch and disappear except for the ones of the master laser and slave laser (which is pushed away towards lower values of frequency).

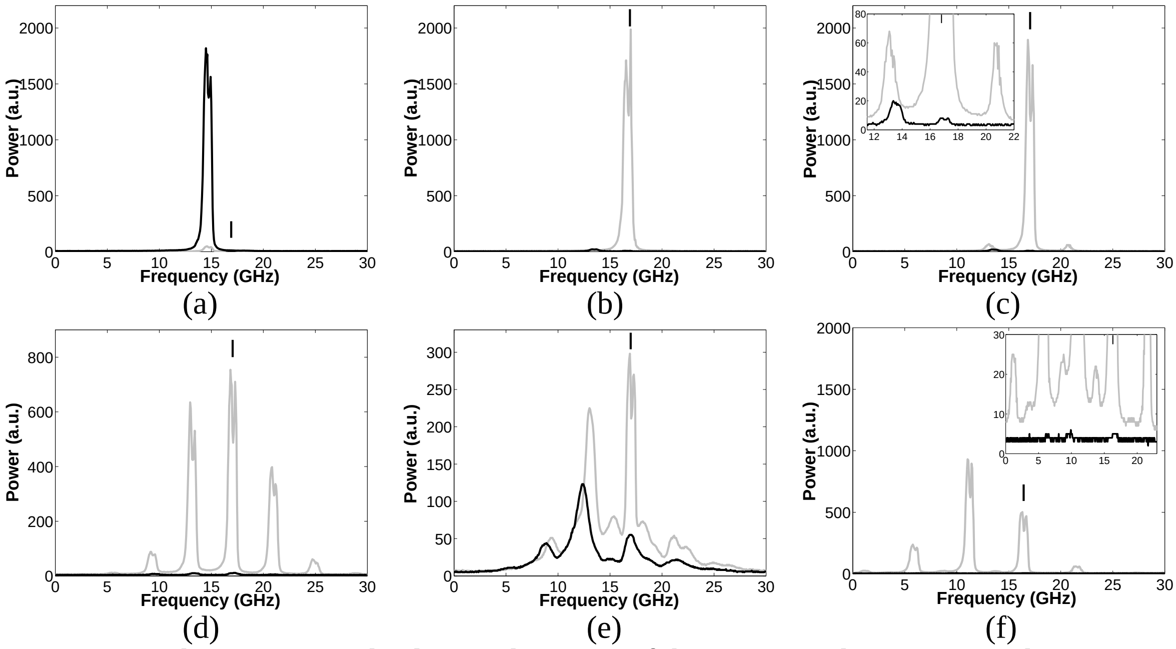

Figure 2: *Polarization-resolved optical spectra of the VCSEL subject to optical injection at a frequency detuning of 2 Ghz. The black (grey) line represents the horizontal (vertical) polarization. The injected power is: (a) 0 µW, (b) 1 µW,(c) 6 µW, (d) 16 µW, (e) 73 µW, (f) 140 µW. The small line marks the position of the master laser.* $I_{SL} = 1.9$ *mA and the substrate temperature is 20°C.*

By inspecting many dynamical scenarios similar to the one shown in Fig.2 but for different frequency detunings $\Delta\nu$ we carry out the mapping of polarization dynamics of the VCSEL biased at a constant injection current of 2.105 mA - see Fig.3. Some of our observations are as follows: In the bistable locking region B_1 the VCSEL can be either locked in frequency and polarization to the master laser (when entering from the stable locking region S_1) or unlocked (when entering from the left side of the mapping). In the bistable region B_3 the VCSEL can be lasing either in horizontal polarization (when entering from the left side of the map) or in vertical polarization (when entering from the right side of the map). Before crossing the blue line going rightwards (when injected power is increased) limit cycle behavior is found, i. e. a sustained time-periodic oscillation. The fact that this limit cycle coexists with an injection locked steady-state (when decreasing the injected power the limit cycle is not present) is interesting and never reported in VCSELs. The other type of limit cycle behaviour that we can find in our device corresponds to the red line and it is very common in lasers. It is a so-called *Hopf bifurcation* that appears getting out of the injection locking region (increasing the injected power).

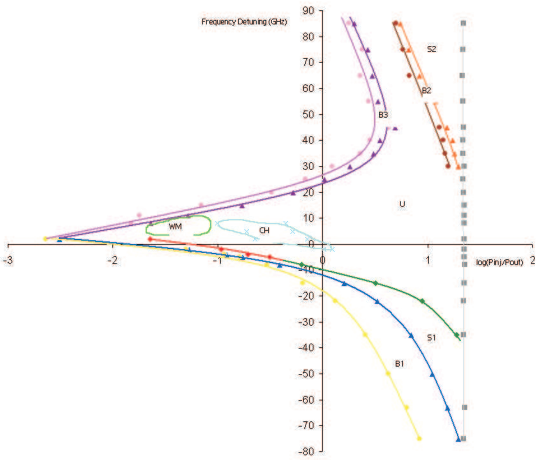

Figure 3: *Mapping of the dynamics.*

However, an unexpected result from our observations is that this behaviour is not present for all the transitions to an unlocking region; the green line represents a progressive unlock, where the VCSEL starts lasing gradually at a frequency (pushed proportionally to the injected power) which is different from that of the master laser. In the region labelled as wave mixing (WM), four-wave mixing and multiwave mixing can be found. The region labelled as CH corresponds to the chaotic dynamics shown in Fig. 2(e). When the injected power is increased for a large positive frequency detuning, first, polarization switching to the vertical mode without injection locking occurs (violet triangles) and afterwards, the suppression of the fundamental mode can be observed (orange triangles). On the way back, the fundamental mode appears again (brown circles) and recovers its horizontal polarization (pink circles) when injected power is decreased. That supposes the existence of a bistable locking region (B_2) and second injection locking region (S_2) in which the first order transverse mode of the slave laser locks in frequency and polarization to the master laser, and the fundamental mode is then suppressed.

Acknowledgements

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