

Injection Locking and Polarization Switching in a 1550-nm VCSEL under Parallel Optical Injection

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ABSTRACT:

We report an experimental study of the injection locking regime and the polarization switching in a single mode Vertical-Cavity Surface-Emitting laser (VCSEL) under parallel optical injection when we inject around the parallel polarization frequency of the solitary VCSEL. We have analyzed the results for high and low injected values of the power. Also we have analyzed the effect of decreasing and increasing the frequency detuning for a fixed value of the injected power. Different bistable behaviors have been observed depending on the value of the injected power.

Key words: Vertical-Cavity Surface-Emitting Lasers (VCSELs), polarization switching, injection locking, parallel optical injection, bistability.

1.- Introduction

Vertical-Cavity Surface Emitting Lasers (VCSELs) are promising devices due to their excellent characteristics like low threshold current, single-longitudinal mode operation, compactness, low power consumption, low cost and circular output beam [1].

Optical injection in semiconductor lasers has undergone considerable research for many years [2]. Optical injection is a commonly employed technique to improve semiconductor laser emission characteristics [3-4].

Although VCSELs are intrinsically single-longitudinal mode devices, they usually show complex polarization characteristics [5]. The light emitted by the VCSEL is typically linearly polarized along one of two orthogonal directions, and polarization switching (PS) between the two orthogonal polarizations can

be observed when temperature or current are changed. Optical injection is also a technique used to achieve PS [1], [6-8]. Parallel optical injection consists in injecting linearly polarized light from an external laser whose polarization is parallel to the linear polarization of the solitary VCSEL.

Most of the experimental work concerns orthogonal optical injection. However, very recently, in Qader [8] the role of the frequency of the suppressed polarization in the PS is analyzed for both types of optical injection. Nonlinear dynamics using parallel optical injection in 1550-nm VCSEL has been studied in [9]. Moreover, the injection locking diagrams in the plane of frequency detunings versus injected power has been measured for both, orthogonal and parallel optical injection [10].

In this work, we investigate the injection locking (IL) and the polarization switching (PS) regimes in a single mode VCSEL under parallel optical injection around the parallel polarization frequency of the free running VCSEL. Bistability for both regimes have been studied. The results are analyzed for high and low injected power as a function of the frequency detuning ($\Delta\nu$). We define $\Delta\nu$ as $\Delta\nu = \nu_{inj} - \nu_{||}$, where ν_{inj} and $\nu_{||}$ are the frequencies of the optical injection and the parallel polarization of the free-running VCSEL, respectively.

2.- Experimental setup

The parallel optical injection is achieved using the all-fiber experimental setup shown in Fig. 1. The light from a tunable laser (TL) (master laser) is injected into a commercial 1550-nm VCSEL (RayCan) via a three-port optical circulator. The bias current and the temperature of the VCSEL are controlled with a laser driver (Thorlabs LDC200) and temperature controller (Thorlabs TED200), respectively. During all the experiments the temperature and the bias current are held constant at 298K and 3.043 mA, respectively.

The first polarization controller (PC1) is adjusted to assure the parallel optical injection configuration. A second polarization controller is connected to a polarization beam splitter (PBS) to select the parallel and the orthogonal polarizations, which are analyzed by power meters (PM) or a high-resolution optical spectrum analyzer (BOSA). The signal observed in the parallel polarization includes the reflection of the optical injection at the VCSEL mirror.

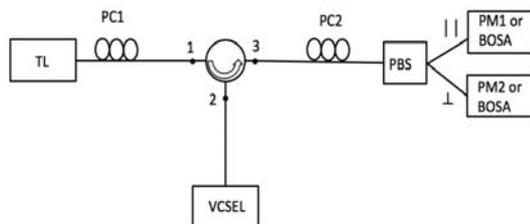


Fig. 1: All-fiber setup: (TL) Tunable Laser, (PC1) and (PC2) polarization controller 1 and 2, respectively, (PBS) Polarization Beam Splitter, (PM1) and (PM2) Power meter 1 and 2, respectively, (BOSA) High-resolution Brillouin Optical Spectrum Analyzer.

3.- Results for high injected power

Our VCSEL operates in a single transverse mode with a threshold current of 1.66 mA at 298K. The VCSEL emits in a linear polarization that we will call the “parallel” polarization. Fig. 2 shows the optical spectrum for the parallel polarization of the free-running VCSEL that emits at 1540.88 nm wavelength for a bias current of 3.043 mA. The orthogonal polarization (>30 dB weaker than the parallel polarization) is shifted 0.23 nm to the short wavelength side ($\lambda_c = 1540.65$ nm). It means that the birefringence of the VCSEL is 28.75GHz.

We characterize the optical injection by its strength given by the value of the power measured in the port 2 of the optical circulator. In this section the injected power is $P_{inj} = 1.159$ mW.

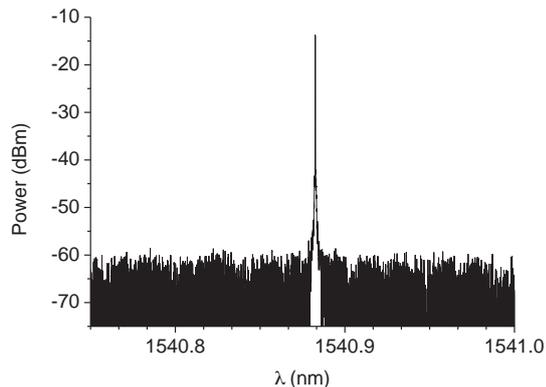


Fig. 2: Optical spectrum of the parallel polarization of the solitary VCSEL when the temperature is 298K and the bias current is 3.043 mA.

3.1.- Decreasing master laser's frequency (ν_{inj})

We consider that PS happens when the suppressed orthogonal polarization of the VCSEL starts to emit at 20 dB above the noise level. Also we consider that IL appears when the parallel polarization of the VCSEL emits at the frequency of the injected signal. Fig. 3 shows that periodic dynamics is observed for a frequency detuning of 4.66 GHz. Note that from now on, the zero value of the frequency in all the optical spectra has been chosen to correspond to the parallel polarization of the free-running VCSEL. Besides, only the parallel polarization is represented in the optical spectra unless otherwise stated. We have checked that the power in the opti-

cal spectra corresponding to the orthogonal polarization is negligible in most of the cases.

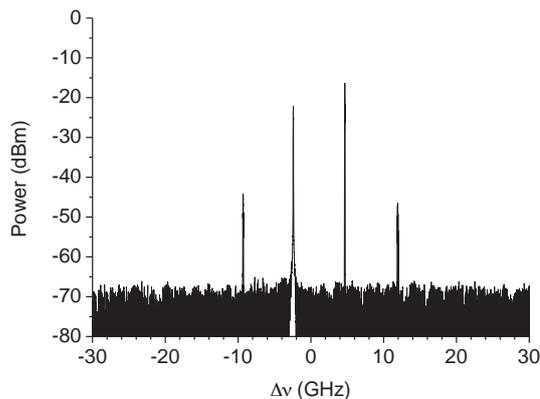


Fig. 3: Optical spectrum of the parallel polarization when the detuning is $\Delta\nu=4.66$ GHz.

As we decrease the frequency of the master laser for a fixed injected power, the system approaches the injection locking regime. When $\Delta\nu=-1.58$ GHz, the parallel polarization mode of the VCSEL becomes stably locked to the frequency of the master laser (ML). Fig.4 (a) shows the optical spectrum for the injection locking regime when $\Delta\nu=-4.11$ GHz. Only one peak at the frequency of the ML appears in the optical spectrum. The injection locking regime is maintained until $\Delta\nu=-12.05$ GHz. At this frequency detuning, PS happens simultaneously with the unlocking of the VCSEL as we can see in the optical spectrum of Fig. 4(b). The orthogonal polarization (in blue color) is excited and IL is not found for the parallel polarization (in black color). We can see that two peaks at two different frequencies appear in the optical spectrum for the parallel polarization, corresponding to the reflection of master laser light and the free-running VCSEL, respectively (the small peak in black color that appears close to 33 GHz is due to imperfect separation of polarizations in our PBS). The PS regime continues until $\Delta\nu=-15.01$ GHz. For lower frequencies of the master laser, only the peaks corresponding to the ML and the VCSEL appear in the optical spectrum and the orthogonal polarization is suppressed.

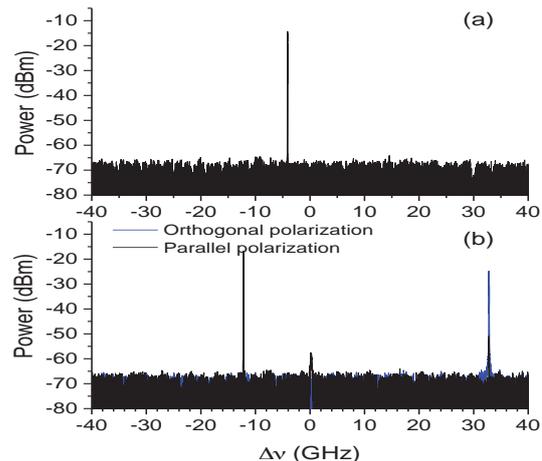


Fig. 4: Optical spectra when the detuning is (a) $\Delta\nu=-4.11$ GHz and (b) $\Delta\nu=-12.05$ GHz. Blue (Black) color represents the orthogonal (parallel) polarization.

3.2.- Increasing master laser's frequency (ν_{inj})

In this section, we analyze the bistability when the frequency of the master laser increases and for the same value of injected power, $P_{inj}=1.159$ mW. Bistable behaviour is found: the IL regime happens from $\Delta\nu=-17.96$ GHz to $\Delta\nu=0.04$ GHz. It means that now, the IL happens for a wider range of frequencies of the master laser. PS does not appear in this case.

4.- Results for low injected power

In this section we analyze the results obtained for the injection locking and PS regimes, for a fixed and low injected power of $P_{inj}=65.30\mu$ W.

4.1.- Decreasing master laser's frequency (ν_{inj})

As in the section 3.1, as we decrease the frequency of the master laser, injection locking and PS are found for low injected power. The injection locking regime is found from $\Delta\nu=-0.86$ GHz to $\Delta\nu=-4.88$ GHz. Before the injection locking, periodic dynamics is observed as we can see in Fig. 5(a) for a $\Delta\nu=-0.59$ GHz. Decreasing more the frequency of the master laser until $\Delta\nu=-3.27$ GHz, Fig. 5 (b) shows that injection locking is achieved similarly to Fig. 4 (a).

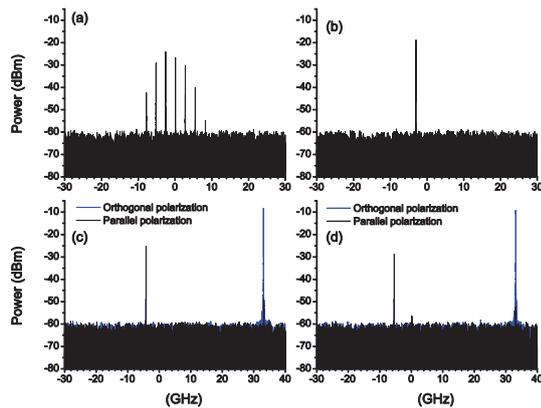


Fig. 5: Optical spectra when the detuning is (a) $\Delta\nu = -0.59$ GHz, (b) $\Delta\nu = -3.27$ GHz, (c) $\Delta\nu = -4.74$ GHz, (d) $\Delta\nu = -5.88$ GHz. Blue (Black) color represents the orthogonal (parallel) polarization.

However, this situation changes from $\Delta\nu = -3.38$ GHz to $\Delta\nu = -4.88$ GHz where PS happens whilst the parallel polarization is still locked to the optical injection. Fig. 5(c) shows the optical spectra for both polarizations when $\Delta\nu = -4.74$ GHz. Note that the orthogonal polarization is 16.12 dBm higher than the parallel polarization. If we decrease more the frequency of the master laser for $\Delta\nu < -4.88$ GHz, the injection locking regime in the parallel polarization disappears and the orthogonal polarization remains excited as shown in Fig. 5 (d) for a $\Delta\nu = -5.88$ GHz. The orthogonal polarization remains excited from $\Delta\nu = -3.38$ GHz to $\Delta\nu = -6.025$ GHz.

4.2.- Increasing master laser's frequency (ν_{inj})

Now, we analyze the bistability when we increase the frequency of the master laser. In contrast to what happens for high-injected power, we have observed PS when the frequency of the master laser is increased, although the width of the bistability region is always smaller than 0.5 GHz. Fig. 6 shows optical spectra for the same frequency detunings that appear in Fig. 5. When $\Delta\nu = -5.88$ GHz periodic dynamics is observed (see Fig. 6 (a)). The bistability is clearly observed if we compare with Fig. 5(d) for same frequency detuning where the orthogonal polarization is excited. From $\Delta\nu = -5.73$ GHz to $\Delta\nu = -4.45$ GHz, only PS without IL is observed, as it is shown in Fig. 6 (b) for a $\Delta\nu = -4.74$ GHz. As we can see, the orthogonal polarization is clearly excited. However, no IL for the paral-

lel polarization is observed. The two peaks that appear in the optical spectrum at -4.74 GHz and 0.55 GHz for the parallel polarization, correspond to the master laser and the VCSEL, respectively. However, PS and IL appear in Fig. 5(c) for same frequency detuning. The injection locking regime appears from $\Delta\nu = -4.45$ GHz to $\Delta\nu = -0.125$ GHz. Now, IL appears for higher frequencies of the master laser than when we vary the frequency of the master laser in the opposite sense. From $\Delta\nu = -4.45$ GHz to $\Delta\nu = -3.16$ GHz, PS and IL appear simultaneously. Fig. 6 (c) shows for $\Delta\nu = -3.27$ GHz that the parallel polarization of the VCSEL is locked to the master laser, and simultaneously the orthogonal polarization is emitting at 33.21 GHz. Fig. 5 (b) shows for same frequency detuning a IL regime. Fig. 6 (d) shows the optical spectrum at $\Delta\nu = -0.59$ GHz characteristic of a IL regime. Nevertheless, Fig. 5(a) shows periodic dynamics for the same frequency detuning.

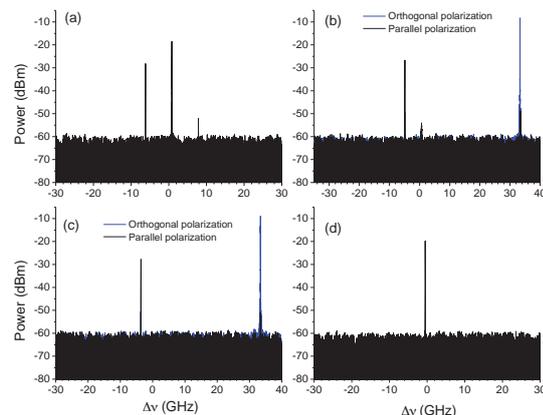


Fig. 6: Optical spectra when the detuning is (a) $\Delta\nu = -5.88$ GHz, (b) $\Delta\nu = -4.74$ GHz, (c) $\Delta\nu = -3.27$ GHz, (d) $\Delta\nu = -0.59$ GHz. Blue (Black) color represents the orthogonal (parallel) polarization.

5.- Conclusion

In conclusion, we have investigated the injection locking regime and the polarization switching in a single mode VCSEL under parallel optical injection when we inject around the parallel polarization of the free-running VCSEL. We have analyzed two cases, for high and low injected power as a function of the frequency detuning. The frequency bistability has also been studied.

We have obtained regimes in which injection locked, polarization switching and periodic dynamics in the parallel polarization are obtained. For high injected power, bistability between the polarization switching and the injection locked solutions is found. For low injected power, bistability between some other solutions is found, for instance between periodic oscillations in the parallel polarization and injection locked or polarization switching solutions.

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