Optical Injection-Induced Timing Jitter Reduction in Gain-Switched Single-Mode Vertical-Cavity Surface-Emitting Lasers

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ABSTRACT

We report an experimental and theoretical investigation of the effect of optical injection on the characteristics of optical pulses generated by gain-switching a 1550 nm single transverse mode vertical-cavity surface-emitting laser (VCSEL). Under continuous wave operation the VCSEL emits in a linear polarization along the whole current range. The experimental analysis of the effect of external optical injection on the timing jitter, maximum power, and pulse width of optical pulses generated by gain-switching the single mode VCSEL is performed for several repetition rates and for different values of the detuning between the frequency of the optical injection and the VCSEL. Experimental results show that for 1 GHz repetition frequency, jitter reductions greater than 70 % can be obtained over a 47 GHz frequency detuning range with a slight increase of 22% in pulse width with respect to the solitary case. A clear anticorrelation between the maximum power and pulse width is also obtained. A theoretical study is also performed by using a model that incorporates both spatial dependence of carrier density and optical field profiles. The two polarization modes are also taken into account in the model. The theoretical results are in good agreement with the experimental results.

Keywords: Optical injection, gain-switching, timing jitter, vertical-cavity surface-emitting laser (VCSEL)

1. INTRODUCTION

Injection locking is a technique commonly employed to improve the semiconductor laser performance. Laser spectral narrowing, suppression of laser noise, reduction of frequency chirp under modulation and improvement of the laser intrinsic frequency response have been obtained by using that technique. Such studies were extended to vertical-cavity surface-emitting lasers (VCSELs) [1]-[2] which present significant advantages over their edge-emitting counterparts, including a low threshold current, single-longitudinal-mode operation and wafer-scale integrability [3]. VCSELs are attractive for use in injection locking because of their compactness, low power consumption, and circular output beam [3]. Injection in VCSELs has been also used for performing several all-optical signal processing functions like all-optical inversion and all-optical regeneration [3]. 1550 nm VCSELs have been recognized as potential low-cost high-quality signal light sources compared to the conventional distributed feedback lasers (DFB) for optical communication systems [4]. A low-cost 1550 nm semiconductor laser is important for fiber-to-the-home applications, especially with the wavelength-division-multiplexing (WDM) or optical code division multiplexing (OCDMA) access systems utilizing 1550 nm wavelength regions [5,6]. Short optical pulse generation at 1550 nm from a low-cost commercial gain-switched VCSEL was recently reported [7]. As the pulse width becomes shorter and shorter timing jitter becomes a serious factor in determining the performance of the VCSEL. Short optical pulses with small timing jitter are desirable as data signals in high-frequency optical communication systems. Timing jitter reduction has been achieved by using optical injection in gain-switched DFB lasers [8]-[9]. A similar study has been recently considered in VCSELs in a theoretical way [10]. Numerical simulations indicate that jitter reductions greater than 50 % can be obtained with a slight increase in pulse width (smaller than 25 %) [10].

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In this paper we investigate experimentally the effect of external optical injection on the timing jitter, maximum power, and pulse width of optical pulses generated by gain-switching a single mode VCSEL at several repetition rates. A theoretical study is also performed by extending previous analysis [10] to the repetition rate of 1 GHz considered in the experiments. The two polarizations of the fundamental transverse mode of the VCSEL are also taken into account in the model. The paper is organized as follows. In Section 2 we describe the experimental set-up and the solitary VCSEL characteristics. Experimental results are described in Section 3. Section 4 is devoted to the theoretical results. Finally, Section 4 contains the conclusions.

2. EXPERIMENTAL SET-UP

Optical injection in a gain-switched VCSEL is experimentally achieved by using the setup shown in Fig. 1. An all fiber system has been developed in order to inject the light from a tunable external-cavity laser diode (TL, Tunics Plus-CL) into a quantum-well commercial VCSEL (Raycan) that emits around 1555 nm. The output of the tunable laser is injected into the VCSEL via a three-port polarization maintaining optical circulator (PMOC). The control of the polarization injected into the VCSEL is achieved by using a polarization controller (PC). Gain-switching of the VCSEL is obtained by using a bias-T that is driven by the bias current generator (I_{BIAS}, Keithley 236) and by the pulse generator (PG, Anritsu MP1800A). The light is analyzed by using a 20 GHz communication signal analyzer (CSA, Tektronics CSA8000) and an optical spectrum analyzer with a resolution of 0.07 nm (OSA, Anritsu MS9710B).

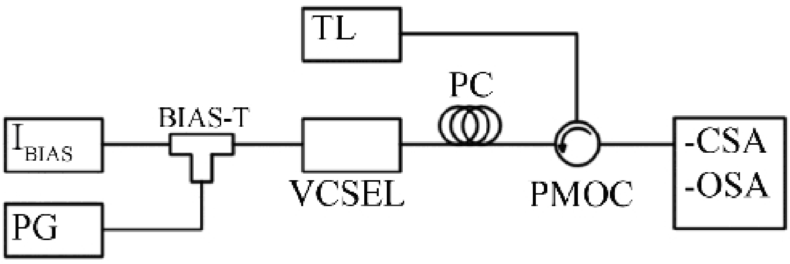

Figure 1. Experimental set-up. TL: tunable external-cavity laser diode; I_{BIAS}: bias current generator; PG: Pattern Generator; PC: Polarization Controller; PMOC: Polarization Maintaining Optical Circulator; OSA: Optical Spectrum Analyzer; CSA: communication signal analyzer.

The VCSEL threshold current, I_{th}, is 2.3 mA. Under continuous wave operation the VCSEL emits in a linearly polarized fundamental transverse mode along the whole current range. The subsidiary orthogonal polarization is suppressed more than 30 dB and it is shifted 0.48 nm to the long wavelength side with respect to the dominant one. The solid line of Fig. 2 corresponds to the optical spectrum when the applied bias current is 3 mA. The two peaks that appear at longer wavelengths correspond to the two orthogonal linear polarizations of the fundamental transverse mode. The peak that appears at longer wavelengths corresponds to the depressed polarization (referred as orthogonal polarization) of the fundamental transverse mode. The dominant linear polarization (referred as parallel polarization) appears at a shorter wavelength. Peaks appearing at shorter wavelengths correspond to non lasing higher-order transverse modes. When using the setup of Fig. 1, the PC is adjusted in such a way that the light is injected parallel to the dominant linear polarization. In this situation, the subsidiary orthogonal polarization suffers a maximum attenuation because it orthogonally couples to the preferential direction of the polarization maintaining OC. This is illustrated in Fig. 2, where the dashed line corresponds to the spectrum with the orthogonal polarization suppressed.

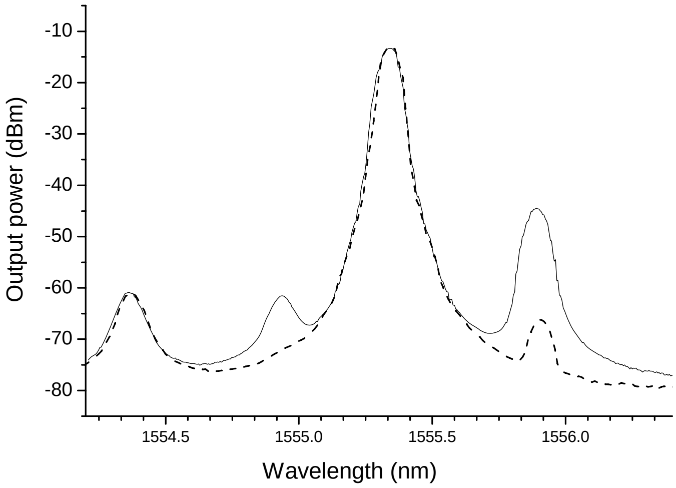

Figure 2. Optical spectrum of the VCSEL for a bias current of 3 mA without polarization selection (solid line) and with the orthogonal polarization suppressed (dashed line).

Under continuous wave operation the orthogonal polarization is suppressed more than 30 dB with respect to the parallel polarization of the fundamental transverse mode (see the two peaks at longer wavelengths of the solid line of Fig. 2). However, when the VCSEL is modulated the subsidiary orthogonal polarization is enhanced. We show in Fig. 3 the spectrum obtained when the VCSEL is gain-switched with a repetition rate of 100 MHz under the following conditions: I_{BIAS} = 3 mA, modulating amplitude of 2.5 V, pulse width 250 ps and duty cycle of 2.5%. The peak that appears at longer wavelengths corresponds to the orthogonal polarization, that is suppressed only 7 dB with respect to the parallel polarization (solid line of Fig. 3). Then the side mode suppression ratio is reduced more than 20 dB due to the gain-switching operation of the VCSEL. The dashed line of Fig. 3 corresponds to the spectrum when the PC is adjusted in such a way that the orthogonal polarization is suppressed.

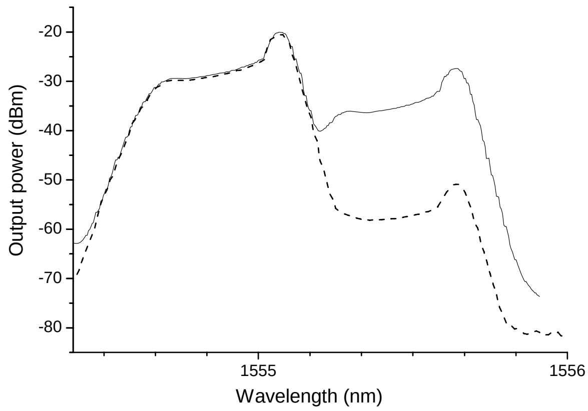

Figure 3. Optical spectrum of the gain-switched VCSEL for a repetition rate of 100 MHz without polarization selection (solid line) and with the orthogonal polarization suppressed (dashed line).

3. EXPERIMENTAL RESULTS

We have measured the characteristics of optical pulses generated by gain-switching the VCSEL at several repetition rates. We first consider the case of 1 GHz repetition frequency. A square-wave modulation is applied to the VCSEL with a repetition rate of 1 GHz and duty cycle of 50% and I_{BIAS}= 1.3 I_{th}= 3mA. The voltage in the PG is 2.5 V during 500 ps and 0 V during the rest of the pulse. Bias current is set greater than I_{th} because the bias-tee suppress the mean value of the pulse signal, and therefore the laser is switched from below threshold to above threshold condition. The optical spectrum of the free-running VCSEL is shown in Fig. 4 (solid line). Note that the PC is adjusted in such a way that the orthogonal polarization is suppressed. Spectral broadening due to chirping effects is obtained [11]. The main peak is the one corresponding to the parallel polarization. The secondary peak appearing at longer wavelengths corresponds to the orthogonal polarization. The optical spectrum of the VCSEL subject to optical injection is also shown in Fig. 4 (dashed line). The optical injection is such that the power of the tunable laser, $P_{ML,}$ is 1mW and its wavelength, λ_{ML}, is 1558.26 nm, near to the wavelength of the parallel polarization, $\lambda_{||}$=1558.3 nm. The corresponding frequency detuning, $\Delta\nu=\nu_{ML}-\nu_{||}$, of the injected signal with respect to the parallel polarization is 5 GHz. Fig. 4 shows that, as previously reported in DFB lasers [9], optical injection produces a narrowing of the optical spectrum and an improvement of the side mode suppression ratio of 23 dB.

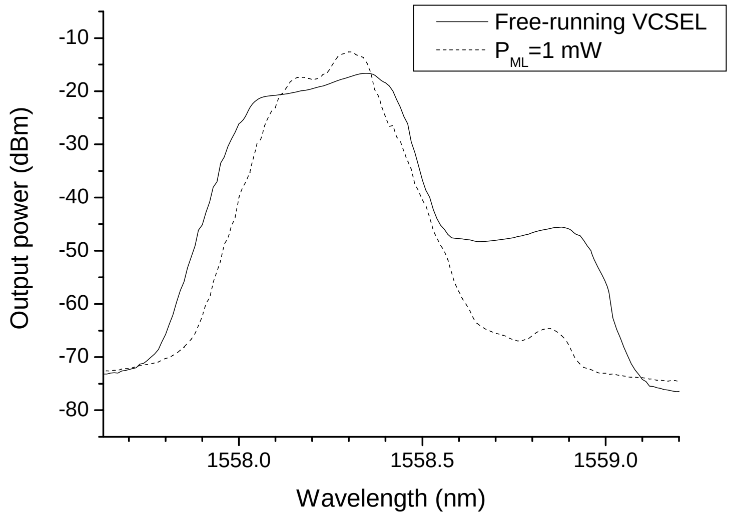

Figure 4. Optical spectrum of a gain-switched VCSEL for a repetition rate of 1 GHz without (solid) and with (dashed) optical injection (P_{ML}=1 mW, λ_{ML}=1558.26 nm and frequency detuning $\Delta\nu$= 5 GHz).

The optical spectrum becomes narrower because of the chirping reduction obtained by the injection locking of the VCSEL [1]. The mean spectrum width [12] is 14.8 GHz for the free-running VCSEL and 9.3 GHz for the VCSEL subject to optical injection with a frequency detuning $\Delta\nu$= 5 GHz. Therefore a reduction of 37% in the spectrum width is obtained by optical injection.

We now characterize the optical pulses obtained for different injection wavelengths and P_{ML}=1 mW. We show in Fig. 5 (a)-(c) the averaged shapes of pulses when λ_{ML}=1558.58, 1558.48 and 1558.26 nm, that correspond to a frequency detuning of $\Delta\nu$= -35, -22.5 and 5 GHz, respectively. Pulses obtained when λ_{ML}=1558.58 nm are very similar to the ones obtained without optical injection (full width at half maximum, FWHM=59.7 ps and maximum power, P_{max}=0.79 mW) because the frequency detuning, $\Delta\nu$= -35 GHz, is very large.

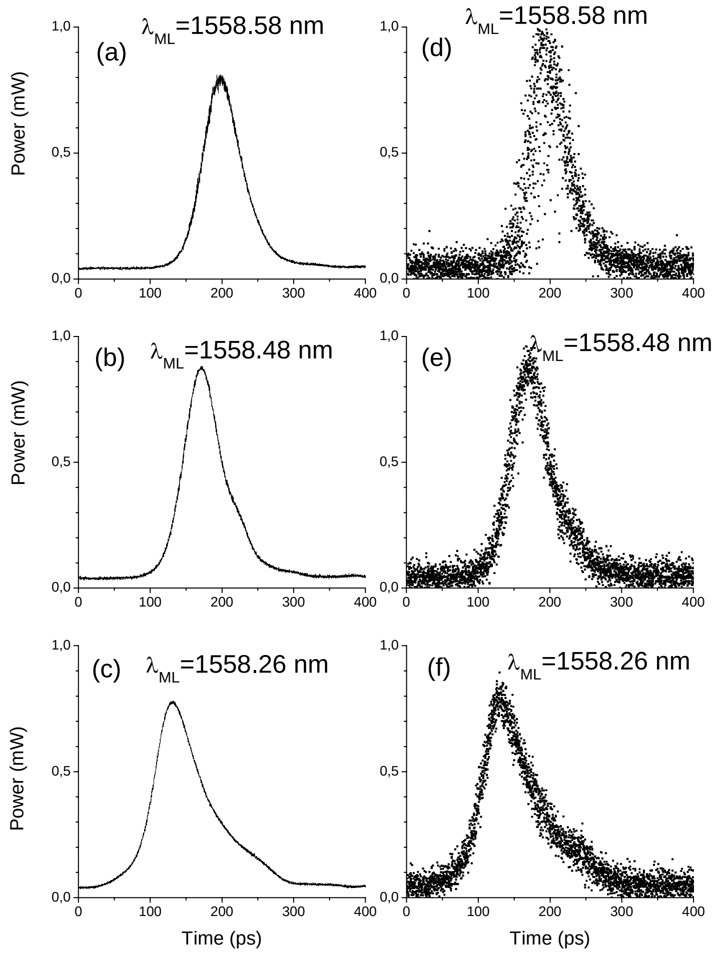

Figure 5. Averaged shapes of pulses generated by the VCSEL with optical injection for three values of λ_{ML} and P_{ML}=1 mW are shown in parts (a), (b) and (c) that correspond to a frequency detuning of $\Delta\nu$= -35, -22.5 and 5 GHz, respectively. The corresponding oscilloscope traces are shown in parts (d)-(f).

In Fig. 6 we show the FWHM and P_{max} as a function of λ_{ML} (upper horizontal axes) and of the corresponding frequency detuning, $\Delta\nu=\nu_{ML}-\nu_{||}$ (lower horizontal axis). Figs. 5 and 6 show that pulses become wider and more asymmetric as λ_{ML} approaches $\lambda_{||}$. That detrimental fact is however compensated by the much smaller values of the timing jitter when λ_{ML} approaches $\lambda_{||}$, as it is shown in Fig. 6 (a). That jitter is calculated as the standard deviation of the time at which the laser power crosses a level situated at one third of the maximum power. The decrease of the timing jitter is also illustrated in Figs. 5 (d)-(f) in which the oscilloscope traces of the pulses corresponding to Figs. 5 (a)-(c) are shown. Fig. 6 (a) shows that for a range from –20 to 27 GHz optical injection reduces the 11.6 ps jitter of the solitary VCSEL to a value below 4 ps. The averaged value of the jitter over that 47 GHz detuning range is 3.45 ps that results in a jitter reduction larger than 70%. Over that $\Delta\nu$ range the averaged FWHM is 73 ps that produces just a slight increase in pulse width (22 %) with respect to the solitary case. It can also be seen that low values of the jitter also result in pulse broadening. A clear anticorrelation between P_{max} and pulse width is seen in Fig. 6 in the detuning range –24 GHz < $\Delta\nu$ < 30 GHz with a value of the correlation coefficient of -0.93.

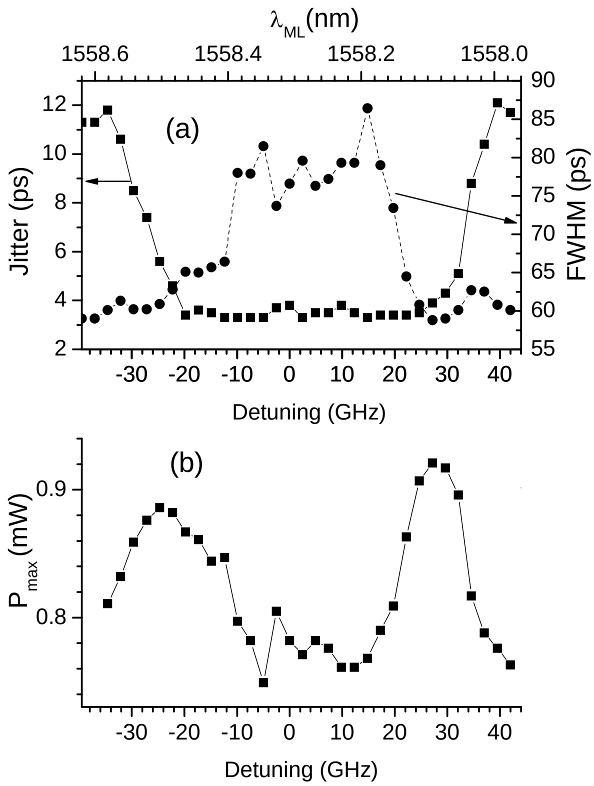

Figure 6. a) Jitter, FWHM and b) P_{max} as a function of frequency detuning $\Delta\nu$ and λ_{ML} when the repetition frequency is 1 GHz and P_{ML}=1mW.

We have also considered the case of a lower repetition frequency. This case has a special interest in a simple OCDMA encoder based on optical delay lines [7,13], in which the length of the optical code, given by the ratio between the modulation period and the pulse width, is large. The number of possible users depends on that code length. Fig. 7 shows the results obtained for a 100 MHz repetition frequency with P_{ML}=1 mW and I_{BIAS}= 0.87 I_{th}. The voltage in the PG is 2.5 V during 250 ps and 0 V during the rest of the pulse. Again the optical injection decreases the timing jitter below its solitary value, 11 ps, over a wide $\Delta\nu$ range: when –20 GHz < $\Delta\nu$ < 22 GHz the jitter is below 3 ps. The qualitative behavior of jitter, FWHM and P_{max} is similar to the 1 GHz repetition frequency case. Then optical injection can induce a low jitter optical pulse train that can be used in OCDMA systems with a code length of around 150 chips for a 100 MHz repetition frequency.

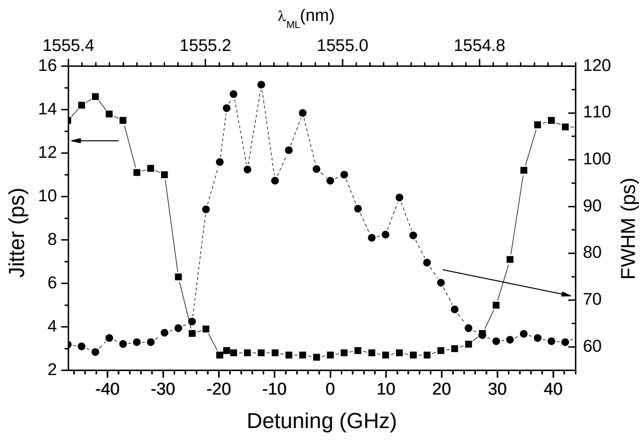

Figure 7. Jitter and pulse width as a function of $\Delta\nu$ when the repetition frequency is 100 MHz and PML=1mW.

4. THEORETICAL RESULTS

We perform a theoretical study by extending previous analysis [10] to take into account the two polarization modes. The pulse characteristics are obtained for the repetition rate of 1 GHz considered in the experiments. The model utilized incorporates both spatial dependence of carrier density and optical field profiles [14]. A cylindrical weakly-index guided VCSEL with transverse modes LP_{mn} is considered. The dynamical evolution of the complex field amplitude of each mode is given by

$$\frac{dE_i(t)}{dt} = \frac{(1-i\alpha)}{2}\left[v_g \Gamma g_i(t) - \frac{1}{\tau_{p,i}}\right]E_i(t) + \sqrt{\frac{\beta \pi d \int_0^a N(r,t) r dr}{\tau_n}}\,\xi_i(t) + \kappa_i \sqrt{P_{inj}}\,\exp(-i2\pi\Delta\nu_i t) \tag{1}$$

where $g_i(t)$ and $\tau_{p,i}$ are the modal gain and losses, respectively, of that mode, v_g is the group velocity, Γ is the longitudinal confinement factor, a is the radius of the waveguide, d is the active region thickness, τ_n is the carrier lifetime, Γ is the longitudinal confinement factor, α is the line-width enhancement factor, β is the spontaneous emission factor, ξ is a complex white Gaussian noise term of zero mean, and $N(r,t)$ is the carrier density. The last term of Eq. (1) accounts for optical injection. P_{inj} is the injected power, κ_i is the injection parameter into the i-mode and $\Delta\nu_i = \nu_{inj} - \nu_i$ is the frequency detuning of the injected signal from the frequency of the i-mode. Results in this work are given in terms of the detuning $\Delta\nu = \nu_{inj} - \nu$ with respect to the frequency of the lowest threshold mode ν.

The modal gain of the i-mode is given by $g_i(t) = \int_0^\infty \psi_i^2(r) A(N(r,t) - N_t) r dr / <\psi_i^2>$, where the symbol < > is used for denoting the following integral, $<f> = \int_0^\infty f(r) r dr$, r is the modulus of the spatial vector in the active layer, $\psi_i(r)$ is the electrical field profile of the i-mode, N_t is the carrier density at transparency, and A is the gain coefficient. The modal gain represents the degree of spatial overlap between the mode intensity profile and the carrier distribution. The evolution of the carrier density profile, $N(r,t)$, is given by the carrier continuity equation applied to the active region:

$$\frac{\partial N(r,t)}{\partial t} = \frac{D}{r}\frac{\partial}{\partial r}\left(r \frac{\partial N(r,t)}{\partial r}\right) - \frac{N(r,t)}{\tau_n} + \frac{j(r,t)}{ed} - \sum_i a_i \psi_i^2(r) g_i(t) P_i(t) \tag{2}$$

where D is the diffusion coefficient, $j(r,t)$ is the current density injected in the active region, e is the electron charge, and $a_i = v_g \Gamma / (2\pi d <\psi_i^2>)$. We consider a uniform injection of current over a disk of radius s and then, $j(r)=j$ if $r<a$, and $j(r)=0$ elsewhere. The evolution of the electrical field is found by integrating Eqs. (1) and (2). A complete description of the model together with the values of the parameters can be found elsewhere [10,14].

We consider that the VCSEL emits only in the two linear polarizations of the fundamental mode LP_{01} at a wavelength 1558.3 nm for the dominant parallel polarization and 1558.79 nm for the orthogonal polarization. We take into account this in the modeling by considering that the modal losses of these two polarizations are much smaller than those of the rest of the modes. The modal losses of the parallel and orthogonal polarizations are taken as $\tau_{p,1}$ =1.5 ps and $\tau_{p,2}$ =1.48 ps, respectively. We also consider the same field profile for the two polarizations, $\psi_1(r)=\psi_2(r)$, corresponding to the fundamental transverse mode. Under continuous wave operation the orthogonal polarization is suppressed more than 30 dB with respect to the parallel polarization in agreement with the experimental results.

A square-wave modulation is applied to the VCSEL with a repetition rate of 1 GHz and duty cycle of 50%. The laser is switched from below threshold to above threshold condition. We consider a bias current $j_b=0.5\, j_{th}$ and an on-state current $j_{on}=2j_{th}$ in order to have short pulses with a good extinction ratio. The power of the injected signal P_{inj} is given in *dBs* with respect to the power of the solitary laser P_{on} that corresponds to the on-state current j_{on}. The light is injected parallel to the dominant linear polarization. The optical spectrum of the free-running VCSEL calculated with a resolution of 1 GHz is shown in Fig. 8. Spectral broadening due to chirping effects is obtained. The main peak corresponds to the parallel polarization. The peak that appears at longer wavelengths corresponds to the orthogonal polarization that is suppressed only 7.5 dB with respect to the parallel polarization (solid line of Fig. 8). Then the side mode suppression ratio is reduced more than 20 dB due to the gain-switching operation of the VCSEL in agreement with the experimental results shown in Fig. 3. The optical spectrum of the VCSEL subject to optical injection is also shown in Fig. 8 (dashed line). The optical injection is such that the power of the tunable laser is P_{inj} = -34 dB and the frequency detuning of the injected signal with respect to the parallel polarization is $\Delta\nu$= 5 GHz. Fig. 8 shows that optical injection produces a narrowing of the optical spectrum and an improvement of the side mode suppression ratio of 13 dB. The optical spectrum becomes narrower because of the chirping reduction obtained by the injection locking of the VCSEL. A reduction of 29% in the mean spectrum width of the parallel polarization is obtained by optical injection with a frequency detuning $\Delta\nu$= 5 GHz. All these results are in qualitative agreement with the experimental results shown in Fig. 4.

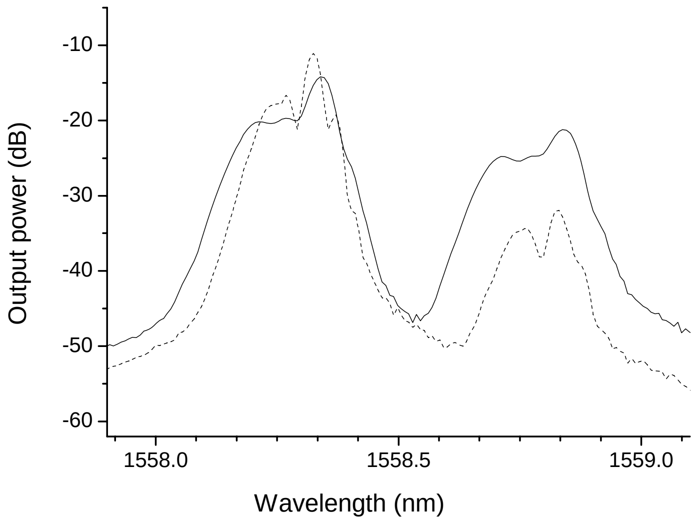

Figure 8. Theoretical results for the optical spectrum of a gain-switched VCSEL at a repetition rate of 1 GHz without (solid) and with (dashed) optical injection (P_{inj} = -34 dB and frequency detuning $\Delta\nu$= 5 GHz).

We now analyze the effect of optical injection on timing jitter, pulse width (full width at half maximum, FWHM), and peak power, P_{max}. We only consider the parallel polarization component of the pulses in order to compare with the experimental results. The jitter is obtained by using a reference value situated at $P_{max}/3$. In Fig. 9 we show the jitter and FWHM as a function of the frequency detuning $\Delta\nu$ for an injection power of –34 dB. A good qualitative agreement is obtained between the theoretical and the experimental results shown in Fig. 6a. It is found that for a detuning range from –10 to 10 GHz optical injection reduces the 13.6 ps jitter of the solitary VCSEL to a value below 7 ps. The averaged value of the jitter over that 20 GHz detuning range is 5.2 ps that results in a jitter reduction larger than 60%. When the injected power P_{inj} is increased, jitter reduction can be achieved for a greater detuning range. However, the oscillations of the jitter (see Fig. 9 for small negative values of $\Delta\nu$) also increase. Over the detuning range from –10 to 10 GHz the averaged FWHM is 76 ps that produces a slight increase of 15% in pulse width with respect to the solitary case. It can also be seen that low values of the jitter result in pulse broadening.

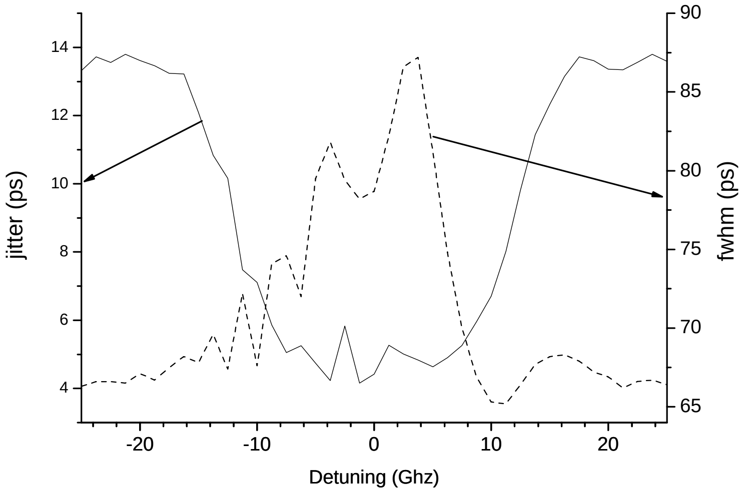

Figure 9. Theoretical results for jitter and pulse width as a function of frequency detuning Δν when the repetition frequency is 1 GHz and P_{inj}= -34dB.

We show in Fig. 10 the peak power as a function of the frequency detuning Δν for an injection power of –34 dB. The theoretical result is in good agreement with the experimental result shown in Fig. 6b. A clear anticorrelation between P_{max} and pulse width is seen in Figs. 9 and 10 in the detuning range –15 GHz < Δν < 15 GHz with a value of the correlation coefficient of -0.93. This value is very close to the one obtained from the experimental results.

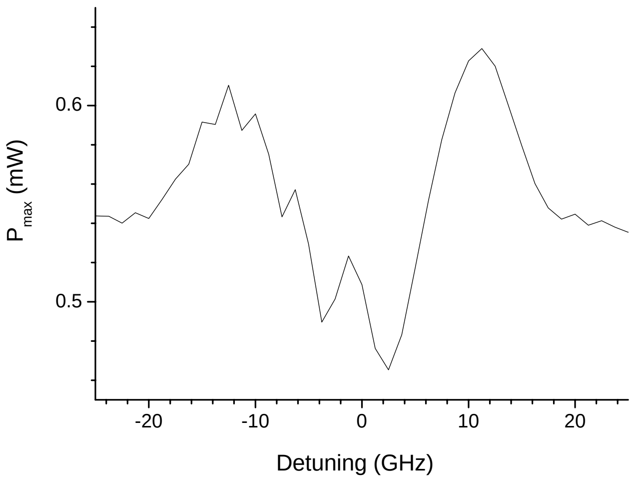

Figure 10. Theoretical results for peak power P_{max} as a function of frequency detuning Δν when the repetition frequency is 1 GHz and P_{inj}= -34dB.

5. CONCLUSIONS

We have investigated the effect of optical injection on the characteristics of optical pulses generated by gain-switching a 1550 nm single transverse mode VCSEL. Under continuous wave operation the VCSEL emits in a linear polarization along the whole current range. We have performed an experimental analysis of the effect of external optical injection on the timing jitter, maximum power, and pulse width of optical pulses for two repetition rates, 100 MHz and 1 GHz, and for different values of the detuning between the frequency of the optical injection and the VCSEL. The qualitative behavior is similar for both repetition rates. In the 1 GHz case we have obtained jitter reductions larger than 70% over a

47 GHz detuning range centered around the VCSEL lasing frequency. That jitter reduction is accompanied by a slight increase in pulse width with respect to the free-running case. A clear anticorrelation between peak power and pulse width is obtained. We have also performed a theoretical study by using a model that incorporates both spatial dependence of carrier density and optical field profiles. The two polarization modes of the fundamental transverse mode are taken into account in the model. We have obtained timing jitter, maximum power, and pulse width of optical pulses for a repetition rate of 1 GHz, and for different values of the detuning between the frequency of the optical injection and the VCSEL. The results obtained from numerical simulations for pulse characteristics are in good qualitative agreement with the experimental results.

ACKNOWLEDGEMENTS

The authors acknowledge support from the Ministerio de Ciencia e Innovación under projects TEC2009-14581-C02-01 and TEC2009-14581-C02-02.

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