Characterization of Gain-Switched Pulses From 1.55-μm VCSEL

Antonio Consoli, I. Esquivias, F. J. López Hernández, J. Mulet, and Salvador Balle

***Abstract*—We report on short optical pulse generation by gain-switching (GS) a low-cost commercial vertical-cavity surface-emitting laser emitting at 1.55 μm. The dependence of pulse characteristics on GS parameters is investigated and analyzed. Pulses with duration of 55 ps and time-bandwidth product between 0.91 and 2.2 are obtained at repetition rates between 1 and 3 GHz.**

***Index Terms*—Gain switching (GS), semiconductor lasers, short pulse generation, time-bandwidth product, vertical-cavity surface-emitting lasers (VCSELs).**

I. INTRODUCTION

SHORT optical pulses with a duration of tens of picoseconds find application in many fields: optical communications, signal processing, time-resolved microscopy, optical radar, 3-D imaging techniques, and material processing among others [1]. Vertical-cavity surface-emitting lasers (VCSELs) emitting at 1.55 μm are cost-effective and high-quality light sources for the above applications, to be used directly or as a seed for an optical amplifier. Low threshold current, high bandwidth, efficient fiber coupling, single-mode operation, and wafer level testability [2] are attractive VCSEL characteristics that make these devices competitive with edge-emitting lasers.

Short pulse generation in semiconductor lasers is normally obtained by means of mode-locking, Q-switching, or gain-switching (GS) techniques [1]. GS is the most simple, cost-effective, and flexible solution due to the facts that only a dc source and an ac source are needed for its implementation and that different pulse duration, amplitude, and repetition rate can be obtained. GS is usually achieved by repetitively turning ON and OFF the laser with either a rectangular current pulse with short rise time or a radio-frequency (RF) sinusoidal current. The best pulses that can be obtained by gain-switching a laser correspond to the excitation of only the first spike of the relaxation oscillations at the lasing turn-ON [3].

GS in VCSELs at 850 nm has been studied by different groups [4]–[8]. Different pulse characteristics have been reported depending on the device and the GS parameters. Pepeljugoski *et al.* [5] obtained highly chirped pulses with durations of 14.6 ps and jitter of 6.6 ps, which were further compressed to 3.4 ps. Zhu *et al.* [6] reported the lowest jitter value of 1.2 ps with pulses 18.5 ps long and with a time bandwidth product (TBP) of 8.7 at 10-GHz repetition rate. Wiesenfield *et al.* [7] obtained pulses with durations of 24 ps, 4.6 ps of jitter, and TBP between 0.6 and 3 with different devices between 1.5 and 8 GHz.

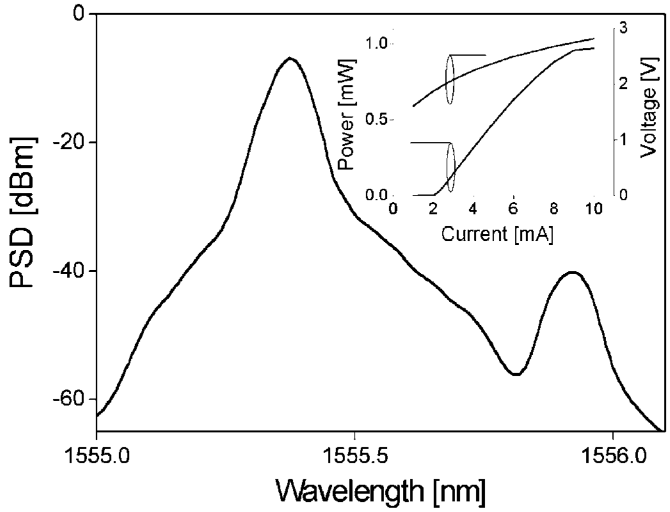

Fig. 1. Spectrum of the VCSEL at $I_{\mathrm{BIAS}} = 4$ mA and P–I–V curve (inset).

In this letter, we report for the first time, as far as we know, on the characterization of pulses obtained from an RF gain-switched 1.55-μm VCSEL. The dependence of pulse durations, amplitudes, jitter, and TBP on the GS parameters is investigated.

II. VCSEL CHARACTERISTICS AND EXPERIMENTAL ARRANGEMENT

The laser is a commercially available (Raycan) fiber pigtailed 2.5-Gb/s VCSEL, based on InAlGaAs active region, buried tunnel junction, air-gap aperture, and InAlGaAs–InAlAs mirrors [9]. The device used in this work has threshold current (I_{TH}) of 2 mA and central wavelength of 1555.38 nm at 4 mA. The VCSEL is fed through a bias-tee with a bias current I_{BIAS} and a sinusoidal RF signal, with amplitude P_{RF} and frequency f_{RF}. The heat-sink temperature is kept constant through a Peltier cell and a temperature controller. Measurements are performed using the optical module of a digital sampling oscilloscope (Tektronix CSA8000) with a bandwidth of 20 GHz and an optical spectrum analyzer (ANDO AQ-6315B) with a resolution of 0.05 nm.

The emission spectrum and the power–current–voltage (P–I–V) characteristics are shown in Fig. 1. The spectrum of

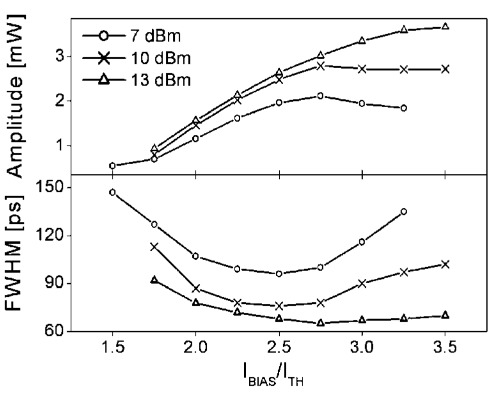

Fig. 2. Pulse amplitude and FWHM as a function of I_{BIAS} at a repetition rate of 2 GHz for $P_{\mathrm{RF}} = 7, 10,$ and 13 dBm.

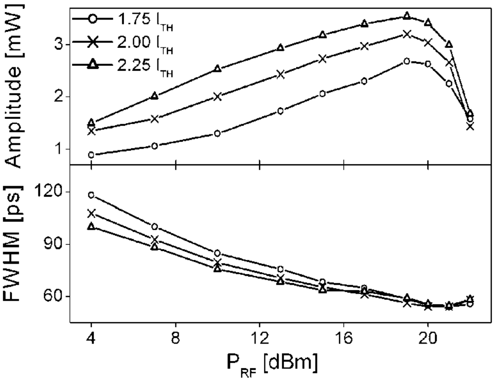

Fig. 3. Pulse amplitude and FWHM as a function of P_{RF}, at repetition rate of 1.5 GHz, for different $I_{\mathrm{BIAS}} = 1.75, 2,$ and 2.25 ITH.

the VCSEL shows two emission peaks separated by 0.5 nm. The two emission peaks are orthogonally polarized to each other, as it has been proven by filtering the emitted light with a linear polarizer. The main peak is dominant for the complete current range above threshold, with a sidemode suppression ratio of around 35 dB. Polarization-switching was not observed along the operation current range.

III. RESULTS AND DISCUSSION

The dependencies of the pulse amplitude and full-width at half-maximum (FWHM) on I_{BIAS} are shown in Fig. 2, for $f_{\mathrm{RF}} = 2$ GHz and different values of P_{RF}. Increasing I_{BIAS} enlarges the portion of the sinusoid above I_{TH} and increases the frequency of the relaxation oscillations. Consequently, at low values of I_{BIAS}, lasing action turns OFF before the maximum of the first spike is reached. As I_{BIAS} increases, the full first spike is generated. At even higher I_{BIAS}, the laser response is fast enough for the second spike of the transient relaxation oscillations to start developing, hereby increasing the FWHM of the light pulse.

Fig. 3 shows the pulse amplitude and FWHM at a repetition rate of 1.5 GHz as a function of P_{RF} with I_{BIAS} as the parameter. When P_{RF} is increased until 19 dBm, the peak amplitude is higher and the duration shorter, but above this value the pulse amplitude rapidly decreases and the FWHM slightly increases. The reason is that initially, the laser responds with faster and more intense pulses that evolve into sharper spikes and shorter due to the increasingly reverse bias applied. However, above some point, the large modulation amplitude induces substantial device heating [7], [8] that degrades the laser response. The thermal impedance (R_{TH}) of our VCSEL, measured by means of the technique described in [10], is around 1680 K/W. This value was used to estimate the temperature of the active region (T_{AR}) for the driving conditions in Fig. 3. For the range of I_{BIAS} considered, when P_{RF} is higher than 19 dBm, T_{AR} exceeds 50 °C, as it was checked by measuring the emission wavelength shift. Pulse degradation is then attributed to the high temperature reached in the active region.

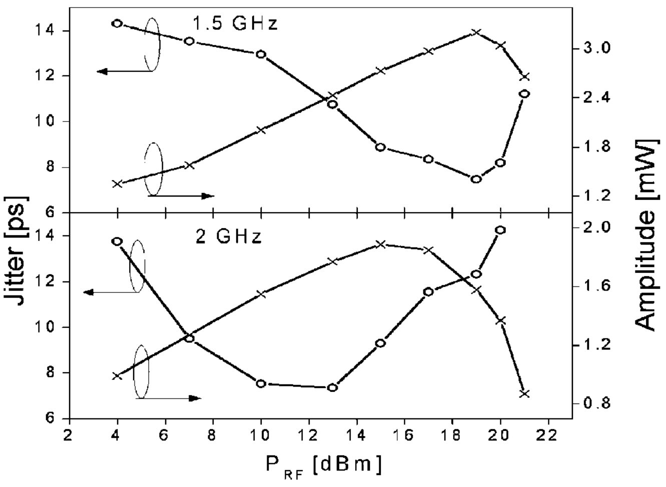

Fig. 4. Timing jitter (left) and amplitude (right) versus P_{RF} for pulses obtained with $I_{\mathrm{BIAS}} = 2I_{\mathrm{TH}}$ at 1.5 and 2 GHz.

In Fig. 4, we compare the timing jitter and pulse amplitude for $f_{\mathrm{RF}} = 1.5$ and 2 GHz. The pulsewidths at both frequencies are similar, as could be expected from the small difference in relaxation oscillation frequency of the laser. However, we observed differences in the timing jitter and pulse amplitude. In both cases, the measured jitter initially decreases with P_{RF} due to the larger current amplitude that speeds up laser response and narrows the distribution of turn-ON delays [11]. At 1.5 GHz, the jitter reduction lasts until $P_{\mathrm{RF}} \sim 19$ dBm, the value where a maximum of the pulse amplitude is observed, while at 2 GHz, the minimum jitter is obtained for $P_{\mathrm{RF}} \sim 12$ dBm, a value lower than the maximum of the pulse amplitude which takes place at $P_{\mathrm{RF}} \sim 16$ dBm. The origin of these differences is not fully understood, as both electrical and thermal effects are closely intermixed at the very high modulation amplitude used in these experiments.

We have also observed substantial impact of the modulation frequency on the chirp characteristics of the optical pulses. For this purpose, the optical spectra of the generated pulses were characterized and the TBP was calculated as the product of the FWHM of the temporal and spectral widths. The measured TBP is shown in Fig. 5 as a function of P_{RF}, for $I_{\mathrm{BIAS}} = 2I_{\mathrm{TH}}$ at 1.5 and 2 GHz. The TBP increases with P_{RF} due to the larger modulation of carrier density, as expected with the GS technique. For $P_{\mathrm{RF}} = 7$ dBm and $f_{\mathrm{RF}} = 1.5$ GHz, the pulses have a very low TBP of 0.83 and duration of 92.7 ps. At 2 GHz, the TBP is larger than at 1.5 GHz; this fact is attributed to the faster increase of carriers at higher frequency, yielding deeper carrier oscillation

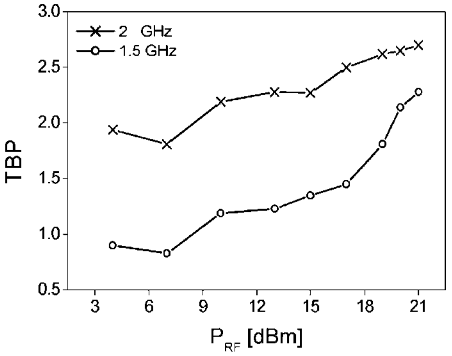

Fig. 5. TBP as a function of P_{RF} at 1.5 and 2 GHz, with $I_{\mathrm{BIAS}} = 2\ I_{\mathrm{TH}}$.

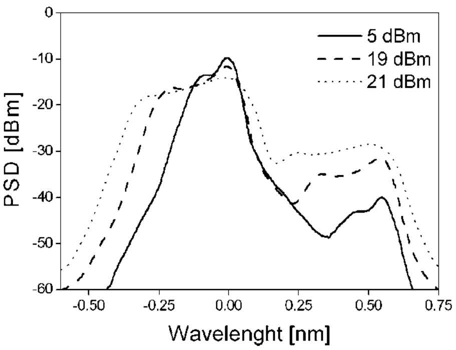

Fig. 6. Spectra obtained at 2 GHz, with $I_{\mathrm{BIAS}} = 2\ I_{\mathrm{TH}}$ and $P_{\mathrm{RF}} = 5$ (continuous line), 19 (dashed line), and 21 dBm (dotted line). The spectra are shifted for clarity.

during the light emission, and in consequence higher chirp and TBP.

The spectra of the pulse trains obtained at 2 GHz with $I_{\mathrm{BIAS}} = 2 \cdot I_{\mathrm{TH}}$ for three values of P_{RF} (5, 19, and 21 dBm) are depicted in Fig. 6. The traces are centered at the peak wavelength for clarity. As P_{RF} is increased, the spectrum red-shifts (2.51 nm at 21 dBm respect to 5 dBm, not shown in the figure) and the peak value decreases, due to the heating effect of injected current. The spectral width broadens because of the deeper modulation of carriers, thus giving rise to more chirped pulses. The secondary peak at about 0.5 nm above the main peak, which emits in the orthogonal polarization with respect to the main peak, is enhanced, probably because the competition of the two polarization modes at the turn-ON of the laser is increased by the greater values of P_{RF}.

The operating conditions I_{BIAS} and P_{RF} were varied in order to obtain the shortest pulsewidths at frequencies between 1 and 3 GHz. Table I reports the pulse durations, the spectral widths, the TBP, and the GS parameters. The increase of f_{RF} shortens the time slice in which current overcomes threshold and efficient pulse generation is obtained if more carriers per period are injected. Consequently, I_{BIAS} and P_{RF} have been increased with f_{RF}.

At 1 GHz, the TBP is as low as 0.91 for pulse duration of 65 ps. When increasing the frequency, shorter pulses are obtained, but with larger spectral widths, thus greater TBP values. The shortest pulses are obtained at repetition rates of 2.5 and 3 GHz. At both frequencies, the FWHM is 55 ps and the TBP varies between 2.06 and 2.2. The minimum pulse duration of 55 ps is longer than the best reported value in 850-nm VCSELS, 14.6 ps [5], probably due to the longer effective cavity design in this particular 1.55-μm device, which is approximately 2.7 μm [9], yielding a photon lifetime of 10.4 ps. The measured pulsewidths are consistent with the estimation of the minimum pulsewidth in gain-switched laser diodes proposed in [3], around five times the photon lifetime.

TABLE I

PULSE DURATIONS AND BANDWIDTH AT DIFFERENT REPETITION RATES AND GS PARAMETERS

f_{RF} [GHz]	Δt [ps]	Δν [GHz]	TBP	I_{BIAS}/I_{TH}	P_{RF}[dBm]
1	65	14	0.91	2	13
1.5	64	25.2	1.61	2.25	18
2	61	26	1.58	2.5	19
2.5	55	37.5	2.06	2.75	19
3	55	40	2.2	3	18

IV. CONCLUSION

Pulse generation from an RF gain-switched VCSEL emitting at 1.55 μm was reported and the pulse parameters were characterized at repetition frequencies ranging between 1 and 3 GHz. The pulsewidth decreased with the RF power and with the bias current until the onset of thermal effects. The best results indicate that, depending on modulation conditions, promising pulse performances can be obtained, i.e., short duration of 55 ps or TBP of 0.91.

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