Particular aspects of drivers for VCSELs operating at multi-Gb/s

Efstathios D. Kyriakis-Bitzaros, Stavros G. Katsafouros, and George Halkias

Abstract — **It is demonstrated that the conventional current-pulse laser drivers are not adequate in driving VCSELs operating at multi-Gb/s speeds. Simulation results, including the bonding parasitics, show that high-performance VCSELs are more efficiently driven using voltage-pulse mode of operation. The optical output power is almost doubled in the voltage-mode of operation, while the total electrical power consumption of the transmitter decreases by 20%.**

Index Terms — **Optical interconnections, Laser drivers, Vertical-Cavity Surface-Emitting Lasers (VCSELs)**

I. Introduction

Vertical Cavity Surface Emitting Lasers (VCSELs) have attracted great interest in recent years due to their advantages over the Edge-Emitting Lasers (EELs), especially for low-power high-density optoelectronic interconnections. VCSELs having a bandwidth over 10 GHz are expected to play a key role in forthcoming multi-Gb/s optical links for mass-market applications.

In general, the design of a laser diode driver (LDD) is a challenging task since clear eye diagrams at high speeds require abrupt signal edges and low jitter. Traditionally, the LDDs were based on differential pair topologies acting as current-pulse sources for the laser diodes [1]. This choice is straightforward for the EELs exhibiting low series resistance very often combined with considerable series inductance due to packaging parasitics. At first glance, the design task of LDDs for VCSELs seems relaxed due to the lower threshold and modulation currents required by these devices. However, high-speed VCSELs present significantly larger series resistance in combination with relatively high shunt capacitance than EELs leading to distinct requirements and consequently different design approaches for the LDD, especially for multi-Gb/s data rates.

In the present work the current-pulse as well as the voltage-pulse mode of operation of VCSELs are investigated. In addition, realistic circuits for driving VCSELs with either voltage or current pulses were designed utilizing a commercially available 0.8 μm SiGe HBT technology. Using an accurate rate-equation based VCSEL model a consistent comparison between the two configurations at 10 Gb/s operation was performed.

In Section II of this paper we present the results on the simulated performance of VCSELs driven by ideal current and voltage sources. Section III deals with realistic circuits, based on the SiGe HBT technology, used to drive the VCSEL either in current- or in voltage-pulse mode. Finally, the conclusions are presented in Section IV.

II. VCSEL Response to Ideal Current and Voltage Sources

Based on the approach of Mena et al. [2], we have implemented the VCSEL model in Cadence™ Design Framework. The model simulates single mode operation of the VCSEL and includes thermal effects, which are critical for such devices. The implemented VCSEL model was used to simulate a specific oxide-apertured diode consisting of a three InGaAs/GaAs quantum-wells

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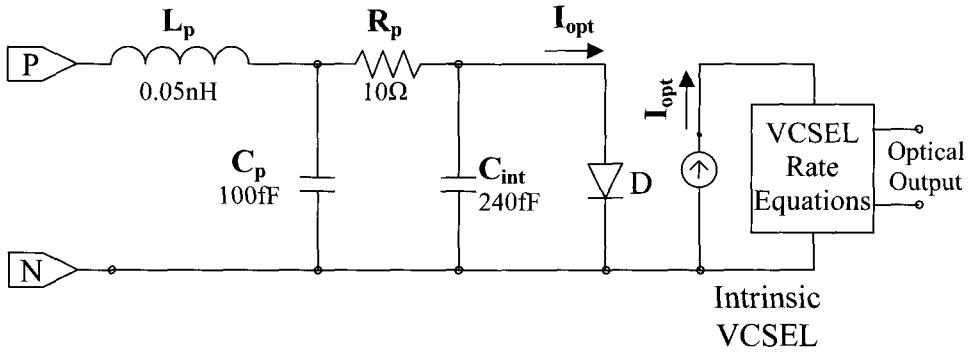

Fig. 1. Equivalent circuit of the VCSEL including parasitics.

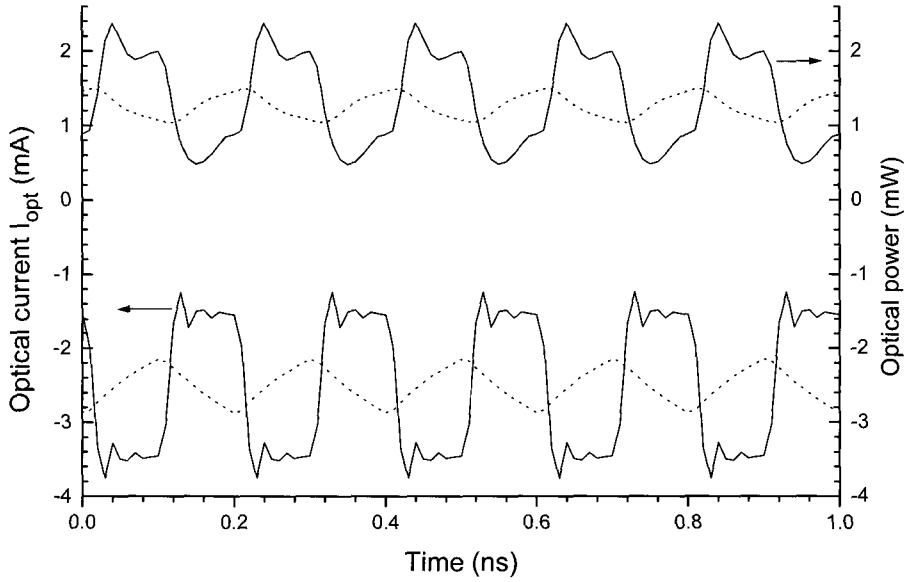

Fig. 2. VCSEL transient response at 10Gb/s when driven by ideal current (dotted lines) and voltage (continuous lines) signal sources. (The negative value of the optical current is drawn to improve the intelligibility of the graph).

active region, an AlGaAs cavity and AlGaAs/GaAs and AlAs/GaAs Bragg reflectors [3]. The diameter of the VCSEL diode is 3.1 μm and an internal parasitic capacitance C_{int} of 0.24 pF is taken into account. The VCSEL emits at λ=0.96 μm and has a threshold current and a slope efficiency of 0.3 mA and 0.57 W/A, respectively. The static current-voltage (I-V) characteristic of the specific VCSEL is produced by a non-linear current-controlled voltage source described by the following diode-like relation [2]:

$$V = 149.8I + 0.9366\ln(1 + \frac{I}{7.918\times10^{-5}})$$

In addition to the intrinsic VCSEL model a number of external parasitics have been included in the simulation model (Fig. 1). Hence, the ohmic contact access resistance, R_p, the anode pad capacitance, C_p, and the metal interconnection series inductance, L_p, were taken to be 10Ω, 0.1pF, and 0.05nH, respectively. The optical current, used as input in the rate equations of the VCSEL to produce its light output is represented by I_{opt} in Fig. 1.

The efficiency of current-pulse as well as of voltage-pulse mode of operation for high-speed VCSELs has initially been tested using ideal pulse sources. In the case of current-pulse mode of operation the VCSEL is driven by a symmetrical current-pulse train at 5 GHz, having 10ps rise and fall time. The DC current level is 1.5 mA

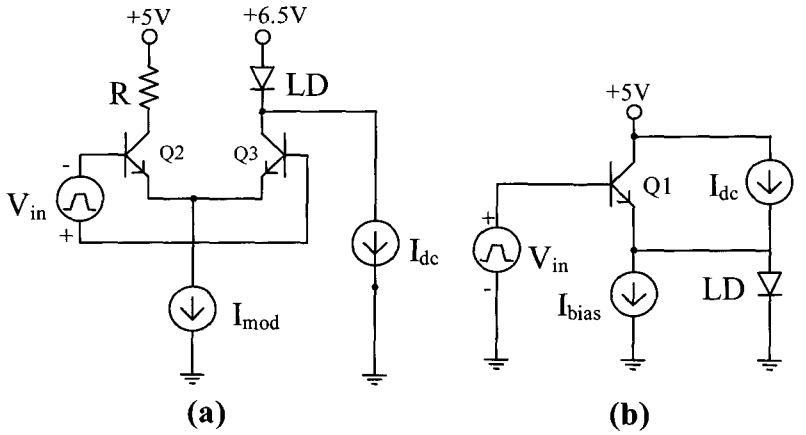

Fig. 3. Current (a) and voltage (b)-pulse laser driver circuits implemented in commercially available SiGe HBT technology.

while the modulation current is 2 mA. The value of the differential resistance of the VCSEL at the selected operating point is approximately equal to 450 Ohms. The –3 dB bandwidth of the intrinsic VCSEL is 12.5 GHz. The optical current I_{opt} and the optical power in current-pulse mode of operation are shown in Fig. 2 with the dotted lines (the negative value of the optical current is drawn to improve the intelligibility of the graph). In the case of the voltage-pulse mode, an equivalent voltage pulse is applied to the VCSEL. Equivalence between the two modes of operation is insured by operating the VCSEL in the same range of its static I-V characteristic. Hence, the DC voltage is 3.028 V while the modulation voltage is 1.066 V corresponding to the operating currents of the current-pulse mode of operation. The optical current I_{opt} and the optical power for the voltage-pulse mode of operation are shown in Fig. 2 by continuous lines.

Fig. 2 shows that, in voltage-pulse mode, the optical signal integrity is improved significantly; the optical power swing, neglecting the over- and under-shoot, is 1.05 mW, very close to the ideal value of 1.1 mW according to the static light-current-voltage (L-I-V) characteristics. In the case of the current-pulse mode the output optical power swing is only 0.48 mW. Also, a sharper optical pulse is obtained in the voltage-pulse mode of operation. It is worthwhile noting that, at a low speed of operation (up to 2 Gb/s) the two driving configurations produce almost identical optical pulses.

These results can be explained by the fact that the shunt capacitances C_{int} and C_p and the high series resistance of D form a current division network. Hence, at high frequencies a large amount of current flows through the shunt capacitances C_{int} and C_p, resulting to optical current degradation and consequently to performance deterioration of the optical signal. The voltage-mode of operation alleviates the current-divider effect and improves significantly the I_{opt}, which generates the light output.

As shown in Fig. 2, a problem, which may arise in the voltage-driving mode of operation, is the ringing oscillation of the optical current, due to the combination of the series inductance L_p with the capacitances C_p and C_{int}. If the frequency of the ringing oscillation of the optical current (corresponding to an overshoot in the transfer function of the equivalent circuit of the input of the VCSEL) is within the operating bandwidth of the intrinsic VCSEL, the transient optical power signal is consequently affected. This effect can be minimized by employing a low-parasitics packaging scheme.

III. Simulation Results using Realistic Vcsel Drivers

The results obtained using ideal current and voltage pulse sources were also confirmed using representative circuits designed with a commercial 0.8μm SiGe HBT technology. A current-pulse LDD based on the open collector differential pair topology (Fig. 3a) and a voltage-pulse LDD based on the emitter follower topology (Fig.3b) have been implemented in Cadence™

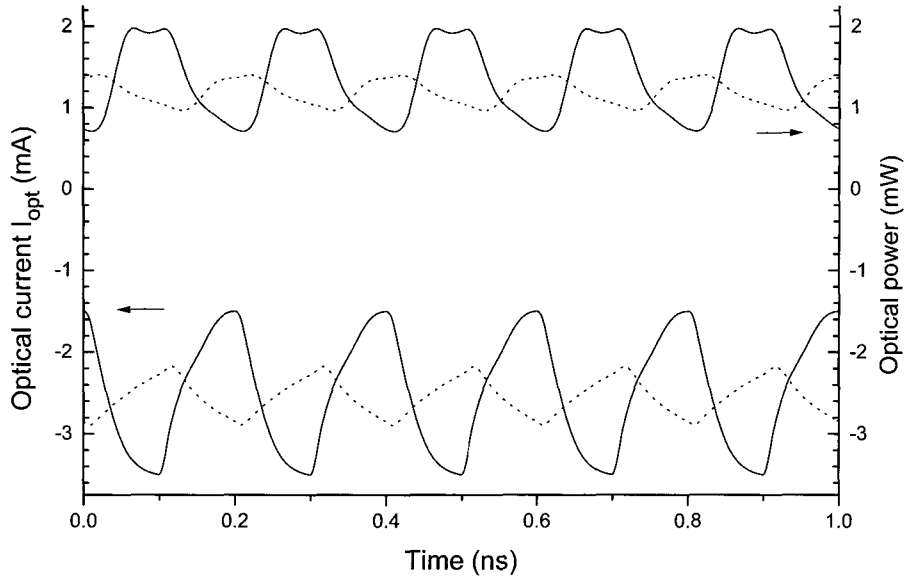

Fig. 4. VCSEL transient response at 10Gb/s when driven by current (dotted lines) and voltage (continuous lines) – pulse laser drivers. (The negative value of the optical current is drawn to improve the intelligibility of the graph).

Design Framework™ along with the VCSEL model. The waveforms at 10Gb/s of the optical current I_{opt} and the optical power are shown in Fig. 4 for both configurations. Continuous lines correspond to the voltage-pulse LDD and dotted lines to the current-pulse LDD. As with the ideal voltage and current sources it is clear that the utilization of voltage-pulse mode of operation produces sharper optical pulses with larger swing (~1mW) as compared to those produced by the current-pulse LDD (~0.4mW optical swing). In summary, Fig. 4 shows that the VCSEL can easily operate at 10Gb/s with the voltage-pulse LDD without any additional impedance matching circuit. This performance is not attainable with the current-pulse LDD.

Moreover, the static and the dynamic power consumption have been estimated for both the LDD configurations. At 10Gb/s the total power consumed by the circuits, including the VCSEL, are 16.9 mW and 20.4 mW for the voltage-pulse and the current-pulse LDD, respectively. The higher power consumption of the current-pulse LDD is due to the following reasons: a) the anode of the VCSEL must be biased at 6.5 V (Fig.3(a)) in order to correctly bias the transistor Q3, resulting in higher voltage drop in the current source I_{dc} used to prebias the VCSEL and b) the modulation current I_{mod} of 2 mA flowing through the differential pair Q2-Q3 is larger than the bias current I_{bias} of 1.2mA (Fig. 3(b)) required by Q1 for optimum operation. In summary the voltage-pulse LDD, besides its superior transient behavior, requires slightly lower power to drive the VCSEL.

IV. Conclusions

Using an accurate VCSEL model and incorporating device and packaging parasitics and ideal driving signal sources or realistic circuits we have demonstrated that the conventional current-pulse mode of operation is inefficient for high-speed VCSELs. In fact, double of the optical output swing is achieved by the use of voltage-pulse mode of operation, while the total power consumed by the transmitter decreases by 20% as compared to the current-pulse LDD.

References

[1] Rein, H.-M., Schmid, R., Weger, P., Smith, T., Herzog T., and Lachner R.: "A versatile Si- bipolar driver circuit with high output voltage swing for external and direct laser modulation in 10 Gb/ s optical- fiber links," IEEE J. Solid-State Circuits, SSC-29, pp. 1014-1021, 1994.

[2] Mena, P.V., Morikuni, J.J., Kang, S.M., Harton, A.V., and Wyatt, K.W.: "A simple rate-equation-based thermal

VCSEL Model", IEEE J. Lightwave Technol., LT-17, pp. 865-872, 1999.

[3] Thibeault, B.J., Bertilsson, K., Hegblom, E.R., Strzelecka, E., Floyd, P.D., Naome R., and Coldren L.A.: "High-speed characteristics of low-optical loss oxide-apertured Vertical-Cavity Lasers," IEEE Photon. Technol. Lett., PTL- 9, pp. 11-13, 1999.

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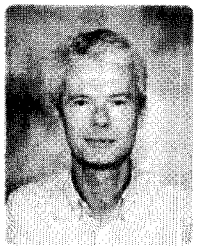

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