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A Compact VCSEL Model for High-Speed Optical Interconnect Design

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Abstract: A compact model of a commercial high-speed vertical-cavity surface-emitting laser (VCSEL), which captures thermally dependent electrical and optical dynamics is presented. Feed-forward equalization (FFE) is implemented using this model.

1. Introduction

Vertical-cavity surface-emitting laser (VCSEL)-based optical interconnects are well-suited for high-speed data communication systems [1]. The employment of four-level pulse-amplitude modulation (PAM4) and equalization techniques, together with the nonlinearities and thermal dependencies of VCSELs, requires an accurate prediction of VCSEL behavior for link performance estimation and optical front-end circuit design. The VCSEL bandwidth is limited by a combination of electrical parasitics and the electron-photon interaction [2]. Some previous studies are based on a linear electrical input stage, neglecting either bias- or temperature-dependent electrical parasitics [3]. Other works focus mainly on the electrical parameter extraction, without considering the intrinsic laser dynamics [4]. In this paper, a compact VCSEL model that captures thermally dependent electrical and optical dynamics and provides dc and transient simulation capabilities is developed. Using the proposed model, feed-forward equalization (FFE) is implemented to increase the maximum data rate and compensate for the nonlinearities caused by the change in both data rate and temperature.

2. Compact Model for VCSEL

Fig. 1. Proposed VCSEL model. The rate equations are described in [3]. V_a : volume of active region, τ_n : carrier lifetime, g_0 : gain slope coefficient, N_0 : transparency carrier density, τ_p : photon lifetime, ϵ : gain compression factor, Γ : optical confinement factor, β : spontaneous capture efficiency, q : electron charge.

The proposed model is composed of two parts, as shown in Fig.1: the electrical behavior is described with an equivalent circuit, and the intrinsic optical behavior is captured with a rate-equation-based model. The electrical model consists of a parasitic inductor L_{pad} between the probes and VCSEL, the parasitic capacitor C_{pad} and resistor R_{pad} of VCSEL pads, a resistor R_s models the distributed Bragg reflector (DBR), and the active region resistance R_d and capacitance C_d . A current- and temperature-dependent voltage source V_d is included to present the voltage-current (V-I) characteristics extracted from the measured V-I curve. The values of other electrical components are extracted by curve fitting the measured S-parameters at different temperatures and bias currents for a range of frequencies from 1 GHz to 30 GHz. To describe the electrical components dependency on current and temperature, V_d , R_d , C_d , and R_s are modeled as a function of the bias current with first-order coefficients, which change with the temperature:

$$V_d(I, T) = (a_0 + a_1 \cdot \Delta T) \cdot I^{(a_2 + a_3 \cdot \Delta T)} + (a_4 + a_5 \cdot \Delta T) \cdot I \quad (1)$$

$$R_d(T, I) = [(b_0 + b_1 \cdot \Delta T) + (b_2 + b_3 \cdot \Delta T) \cdot I + (b_4 + b_5 \cdot \Delta T) \cdot I^2] / (b_6 + b_7 \cdot \Delta T + I) \quad (2)$$

$$C_d(I, T) \text{ or } R_s(I, T) = (c_0 + c_1 \cdot \Delta T) + (c_2 + c_3 \cdot \Delta T) \cdot I + (c_4 + c_5 \cdot \Delta T) \cdot I^2 + (c_6 + c_7 \cdot \Delta T) \cdot I^3 \quad (3)$$

where $\Delta T = T - T_0$, and Table 1 gives the a_0 – a_5 , b_0 – b_7 , and c_0 – c_7 coefficients for $T_0 = 25^\circ\text{C}$. The optical stage's single-mode rate equations are written in Verilog-A, describing the dynamic carrier and photon interaction, and

therefore the electrical to optical conversion in the laser. The parameters of the equations are estimated or extracted by taking the published values of VCSELs with a similar material and structure [2,5].

Table 1 Curve fitting coefficients of V_d , R_d , C_d , and R_s .

Parameter	a_0	a_1	a_2	a_3	a_4	a_5	/	/
V_d (V)	1.93	-3.51×10^{-3}	5.88×10^{-2}	1.69×10^{-4}	7.70×10^{-2}	2.26×10^{-4}	/	/
Parameter	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7
R_d (Ω)	59.62	1.88	104.34	-0.734	-4.55	5.37×10^{-2}	-4.06	9.35×10^{-3}
Parameter	c_0	c_1	c_2	c_3	c_4	c_5	c_6	c_7
C_d (fF)	50.87	0.106	-6.21	2.00×10^{-2}	8.85×10^{-2}	1.09×10^{-2}	7.08×10^{-2}	-1.33×10^{-3}
R_s (Ω)	103.66	-0.486	-23.88	0.162	2.59	-8.22×10^{-3}	-7.81×10^{-2}	-5.75×10^{-4}

3. Results and Discussion

Fig. 2. (a) Slope efficiency $\eta(T)$ and (b) measured and modeled V-I curve at different temperatures. (c) Measured and modeled electrical input impedance at different bias currents and temperatures.

Fig. 3. (a) 28 GBaud/s PAM4 eye diagram at 25°C. (b) 36 GBaud/s PAM4 eye diagram at 80°C. (c) 36 GBaud/s PAM4 eye diagram at 80°C with 3-tap FFE. The bias current is 5 mA.

As depicted in Fig. 2, the modeled V-I curve matches well with the measurement, and the slope efficiency $\eta(T)$ of the P-I curve is extracted and applied to the rate equations. There is also a good agreement between the modeled and measured electrical input impedance at different temperatures and bias currents. Based on the proposed VCSEL model, the device's nonlinear behavior and advanced signal processing techniques like FFE can be analyzed and discussed. As shown in Fig. 3, at 25°C with a data rate of 28 GBaud/s, a slight level mismatch can be observed in the optical eye due to the VCSEL's bandwidth dependency on the PAM4 level. At 80°C and 36 GBaud/s, the severe nonlinearity caused by the temperature and data rate further degrades the output signal quality, showing a very poor eye opening. The implementation of 3-tap FFE compensates for the level-dependent inter-symbol interference (ISI) and extends the maximum data rate, which is directly shown through the model. In conclusion, the proposed model enables an efficient and accurate approach to predict the link performance and facilitate the high-speed optical front-end design.

4. References

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