

Opto-Electro-Thermal Model of a VCSEL array using VHDL-AMS

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Abstract

In this paper, a new laser diode model is presented including electrical, thermal and optical behaviors. This kind of model is feasible due to the high potential of VHDL-AMS in mixed-technology modeling. When simulating, quantities like current, voltage, dissipated thermal power, junction temperature, optic power and wavelength are calculated simultaneously. Interactions between these parameters are taking into account and equations are near physical laws. Simulation results show static and dynamic characteristics and temperature effects.

Introduction

The work presented in this paper belongs to a national research program called SHAMAN. The aim is to simulate opto-electronic components interfaced with electrical and optical parts under thermal, mechanical and packaging constraints. To reach this purpose, a significant step consists in modeling components taking into account interaction between different domains. VHDL-AMS is appropriate to describe and simulate mixed-technology systems with terminal definition (associated physical quantities have to respect Kirchhoff laws) and with free quantity definition. Therefore, behavioral models are non-linear differential equation sets mixing quantities of different physical natures. Moreover, VHDL-AMS is adequate for multi-abstraction : more or less detailed models can be simulated in the entire system. Modeling levels are descriptive when a simulation of global system behavior is needed or predictive when design improvement is required. Lastly, with VHDL-AMS mixed-technology modeling, powerful electrical simulators like SPICE are available for others disciplines. Multi-domain designers, as opto-electronic module manufacturers, are thus very interested in VHDL-AMS behavioral modeling.

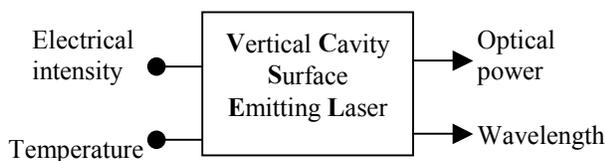


Figure 1. VCSEL block diagram

A key component in opto-electronic module is Vertical Cavity Surface Emitting Laser (VCSEL) which block diagram is shown

in figure 1. Input is electrical intensity, output is HF wave characterized by optical power and wavelength. Digital modulation frequency of input current is a few Gigabits/s. VCSEL behavior is affected by temperature: optical power, wavelength and also threshold voltage are functions of temperature. In parallel optical interconnections, VCSEL diodes are used in array as shown in figure 2. To take into account thermal effects in VCSEL array, the following assumptions are considered:

- Each laser diode is characterized by one temperature
- Each VCSEL temperature is influenced by its neighbors
- Bulk and inner cavity have homogeneous temperatures
- Thermal time constants are greater than others VCSEL time constants

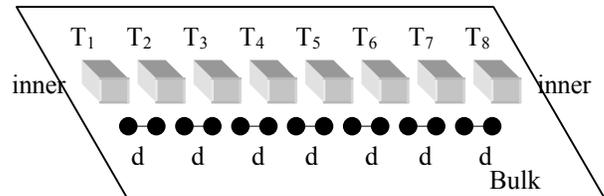


Figure 2. VCSEL array

VCSEL diode modeling

A. Electrical behavioral modeling

Electrical behavior description is based on Lauritzen model (1). This template is a simple, basic diode model with reverse recovery and parasitic series resistance. The standard SPICE model is used for capacitance. High level injection effects such as forward recovery and conductivity modulation are omitted.

The charge at junction edge Q_e is given by :

$$Q_e = \tau_n \cdot I_{SS} \cdot (\exp(V_{12}/nvt) - 1) \quad (1)$$

τ_n is the recombination carrier lifetime, I_{SS} the diode saturation current, V_{12} the internal voltage across p-n junction and nvt the thermodynamic potential. When considering temperature effect on electrical behavior, nvt and I_{SS} are no longer constant, but become variable quantities. Thus, the first step to complete Lauritzen model with thermal effects, is to add connections providing the component temperature.

B. Thermal behavioral modeling

Then, a thermal terminal is defined with two associated quantities : the diode temperature $Temp$ and the power dissipated by the junction P_{th} . Thermal fluxes between diode and its environment are presented on figure 3. With the bulk, the inner cavity and the neighboring diodes, exchanges are modeled in two dimensions with thermal resistances. And the thermal time constant is modeled by the thermal capacitance C_{th} .

This schematic is easy to traduce in VHDL-AMS code and several equations are added. Firstly, thermodynamic potential is a function of temperature :

$$nvt = ne \cdot k \cdot (Temp + 273) / q \quad (2)$$

Secondly, diode saturation current is a function of temperature :

$$I_{SS} = I_{SS0} \cdot ((Temp + 273) / 298)^\eta \quad (3)$$

I_{SS0} is the saturation current value at 25°C and η is the variation coefficient of I_{SS} with temperature.

Thirdly, dissipated power is equal to consumed electrical power minus emitted optical power :

$$P_{th} = i_d \cdot v_d - P_{opt} \quad (4)$$

Evaluation of emitted optical power P_{opt} is proposed in the following part with opto-electronic modeling of the VCSEL.

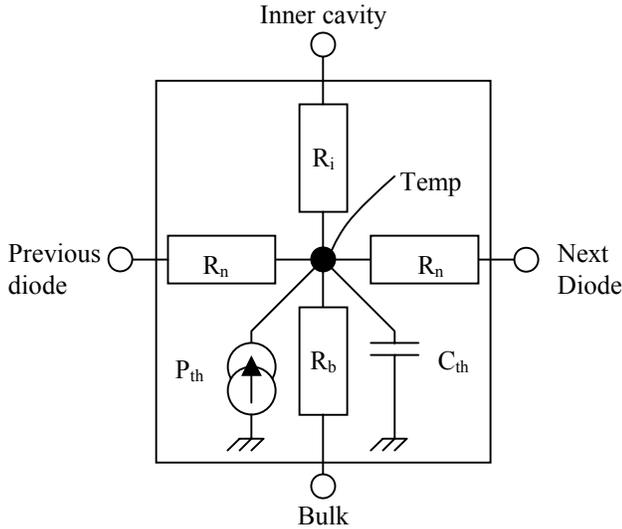


Figure 3. VCSEL diode thermal behavior

C. Opto-electronic behavioral modeling

In response to injected electrical current $I(t)$, laser diode emits optical power $P_{opt}(t)$ with wavelength $\lambda(t)$ and these output quantities vary with temperature. Laser effect modeling is based on rate equations (2) which main variables are carrier number N and photon number S .

$$\begin{aligned} \frac{dN}{dt} &= \frac{I}{q} - \frac{N}{\tau_n} - G_0 \cdot (N - N_0) \frac{S}{1 + \epsilon \cdot S} \\ \frac{dS}{dt} &= -\frac{S}{\tau_p} + \beta \frac{N}{\tau_n} + G_0 \cdot (N - N_0) \frac{S}{1 + \epsilon \cdot S} \end{aligned} \quad (5)$$

τ_p is the photon lifetime, G_0 the differential gain rate, N_0 the transparency carrier number, ϵ the gain compression factor and β the spontaneous emission fraction. These equations include photon stimulated emission, recombination and spontaneous emission but noise contribution is omitted. The efficient injected current I and the optical power P_{opt} are expressed by (3) :

$$I = \eta_i (i_d - i_{off}(T)) \quad (6)$$

η_i is the current injection efficiency.

$$P_{opt} = \frac{h \cdot \nu \cdot \alpha_m \cdot v_g}{2} \cdot S \quad (7)$$

$$\nu = \frac{c}{\lambda_0(T)} - \frac{\alpha_h}{2} \cdot \left(\frac{G_0}{1 + \epsilon \cdot S} \cdot (N - N_0) - \frac{1}{\tau_p} \right) \quad (8)$$

ν is the wave frequency, α_m the mirror leakage factor, v_g the group velocity and α_h the Henry factor.

Temperature effect modeling is supported by the two functions $i_{off}(T)$ and $\lambda_0(T)$ which parameters are deduced from experimental curves for each specific diode.

$$\begin{cases} i_{off}(T) = m_0 + m_1 \cdot T + m_2 \cdot T^2 + m_3 \cdot T^3 + m_4 \cdot T^4 \\ i_{off}(T_0) = 0 \end{cases} \quad (9)$$

$$\lambda_0(T) = \lambda_{FP}(T_0) + \Delta\lambda_{FP}(T - T_0) \quad (10)$$

T_0 is the outer cavity temperature and $\lambda_{FP}(T_0)$ is the Fabry Perot wavelength.

Simulation results

The three behavioral models have been implemented in a VHDL-AMS program. A few validation tests are presented in this part. The employed simulator is part of hAMSter simulation system by Ansoft Corporation.

A. Static characteristic

Firstly, a low frequency sinusoid is input to test static behavior. According to figure 4, with a positive input current the diode voltage v_d varies above the threshold voltage which is near 0.5V and between 0.5 and 1.5V. If a 50 mA input current is used, the consumed electrical power P_{elec} is near 50 mW. When the current level is under the emission threshold I_T , approximately 23 mA, no optical power is emitted and the carrier number is proportional to i_d . On the other hand, when i_d is over I_T , laser effect is efficient and the carrier number stabilizes whereas the photon number and the optical power increase. If the laser diode is supplied by 50 mA, optical emitted power is near 7 mW. Temperature elevation is due to the difference between electrical power and optical power. To simulate junction temperature, figure 3 model is employed with four connections to constant temperature sources at 25 °C. The temperature rise observed have consequences on opto-electronic behavior because of $i_{off}(T)$ and $\lambda_0(T)$.

Sinusoidal current input i_d between 0 and 100 mA at 1 MHz

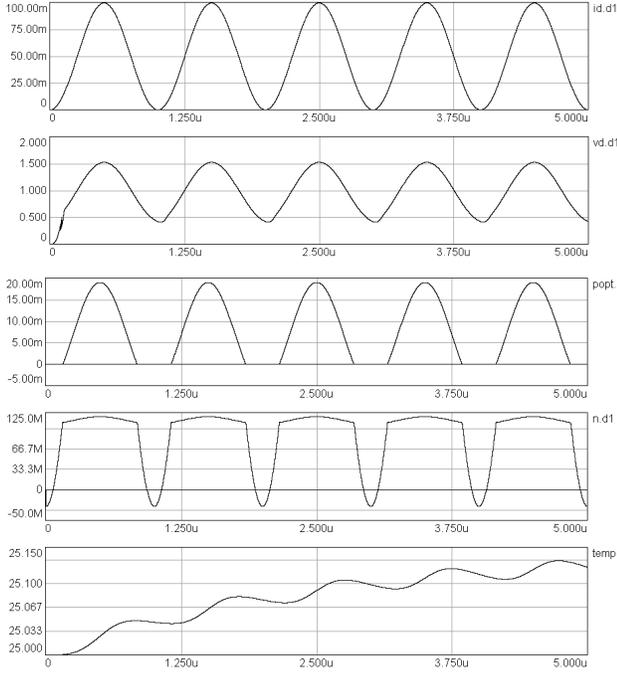


Figure 4. Diode current and voltage, optical power, carrier number and junction temperature versus time

B. Dynamic characteristic

Current input between 20 and 50 mA at 100 MHz

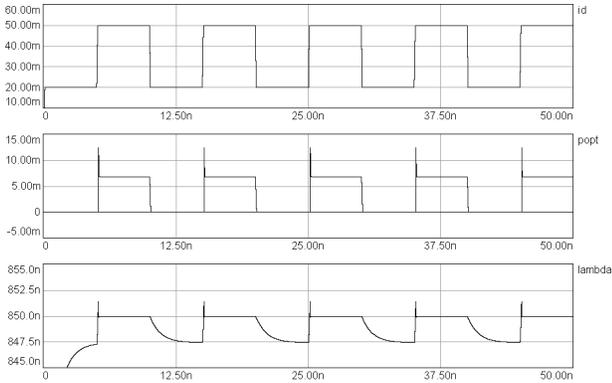


Figure 5. Emitted optical power and wavelength in response to digital input

Dynamic behavior of optical parameters is presented on figure 5 when the diode is used for digital transmission at 100 MHz. The '0' corresponds to input current under the threshold I_{Tmin} whereas the '1' corresponds to input current above the threshold I_{Tmax} . I_{Tmin} and I_{Tmax} are the limits of I_T when the total temperature range is considered.

After overshooting their nominal values, the optical power and the wavelength stabilize speedily in 250 ps at their nominal values, 7 mW and 850 nm. This shows that this component operates up to 1 or 2 GHz.

C. Temperature effects

In this part, model parameters are adjusted to a diode operating between 0 and 10mA with a emission threshold I_T , approximately equal to 4 mA.

$$I_T = \frac{N_0 \cdot q}{\tau_n} \quad (11)$$

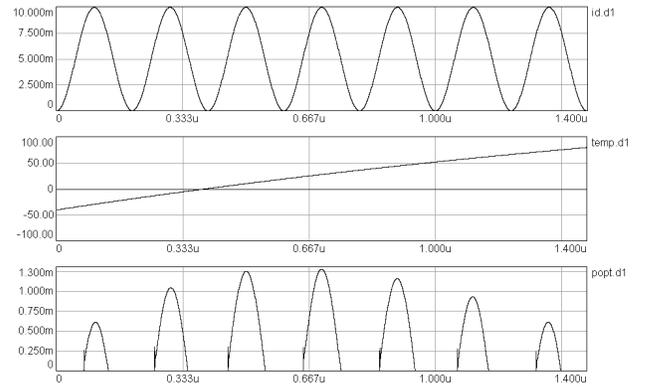


Figure 6. Optical power static response versus temperature

The junction temperature is a ramp between -40°C and 85°C . Simulation reported in figure 6 shows then that emitted optical power is greater around 25°C . If a good transmission required a minimum value of 1mW for P_{opt} , input current of 10 mA is not sufficient on the complete temperature range.

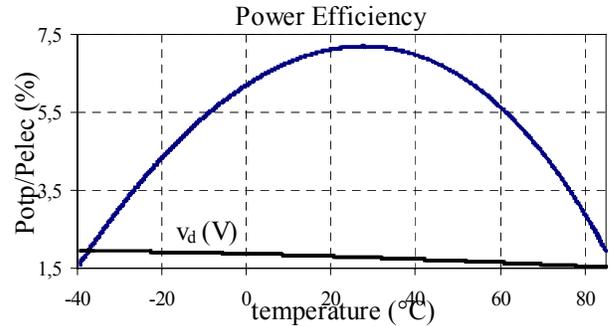


Figure 7. Optical power over dissipated electrical power and diode voltage versus temperature for $i_d=10$ mA ($I_T=4$ mA)

The model is now simulated with a 10 mA input current and DC points are calculated over the whole temperature range. Figure 7 shows that P_{opt} over P_{elec} ratio is maximum at ambient temperature and minimum at low temperature because of the increase of diode voltage at low temperature. Figure 8 shows a linear increasing of resonance wavelength with temperature.

$$\frac{\partial \lambda}{\partial T} = 0,06 \text{ nm.K}^{-1} \quad (12)$$

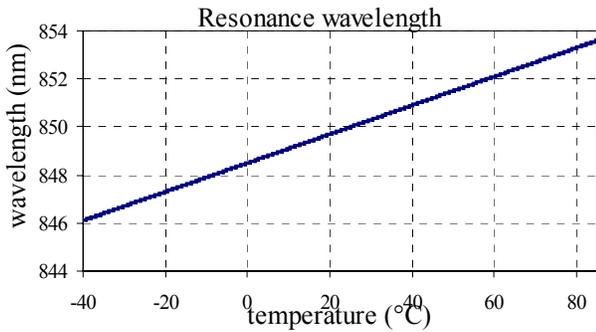


Figure 8. Resonance wavelength versus temperature

Results presented in the previous three sections match VCSEL operation description found in literature (4). For each type of diode, parameter measures and calculus are needed before a right exploitation of the model.

Thermal coupling in VCSEL array can be simulated connecting N diodes with N electrical terminals and N thermal terminals. Simulation results show that when a diode is intensively excited, its temperature grows, leading to temperature increasing for neighboring diodes. Finally, power efficiency is significantly reduced for three diodes.

Conclusions

The main advantages of this new VCSEL model in VHDL-AMS is to combine electrical, thermal and opto-electronic effects and to propose a thermal modeling for VCSEL array. This model will be included in higher hierarchical modeling level as parallel opto-electronic module. In this module, mechanical and thermo-mechanical effects and output fiber coupling will be take into account. Because equations are near physical laws, this model could also serve design of efficient VCSEL diodes.

References

- (1) P.O. Lauritzen and C.L. Ma, "A simple diode model with reverse recovery", *IEEE Trans. Power Electronics*, vol. 6, pp 188-191, April 1991.
- (2) D.E. Dodds, "Fabry-Perrot Laser Diode Modeling", *IEEE Photonics Tech. letters*, vol. 7, n° 3, Mars. 1995.
- (3) P.V. Mena, "Circuit-level Modeling and Simulation of Semiconductor Lasers", *Doctoral Thesis*, Department of Electrical and Computer Engineering, University of Illinois, Urbana-Champaign, 1998.
- (4) R. Stevens, "Modulation Properties of Vertical Cavity Light Emitters", *Doctoral Thesis*, Department of Microelectronics and Information Technology, Royal Institute of Technology, Stockholm, 2001.

Annex : VCSEL.vhd

```

ENTITY VCSEL IS
  GENERIC (
    Iss0 : REAL ;
    Cj0 : REAL ;
    Rs : REAL ;
    mj : REAL ;
    Vj : REAL ;
    ne : REAL ;
    TT : REAL ;
    eta : REAL ;
    Temp0 : REAL ;
  )
  PORT (
    TERMINAL p, m : ELECTRICAL ;
    TERMINAL Tvi, Tvo, Ti, Ts : THERMAL;
    QUANTITY Popt, lambda : out real);
END ENTITY VCSEL ;

ARCHITECTURE thermo_opto_elec OF VCSEL IS

-- Internal quantities for optical modeling
  QUANTITY N : real ;
  QUANTITY S : real ;
  QUANTITY I : real ;
  QUANTITY ioff : real ;
  QUANTITY nu : real ;
  QUANTITY T : real ;
  QUANTITY nu0 : real;

-- Internal terminals and quantities for thermal modeling
  TERMINAL Td : THERMAL ;
  QUANTITY Temp ACROSS Pth, power_int THROUGH Td ;
  QUANTITY Tdi ACROSS Pdi THROUGH Td to Ti ;
  QUANTITY Tdvi ACROSS Pdvi THROUGH Td to Tvi ;
  QUANTITY Tdvo ACROSS Pdvo THROUGH Td to Tvo ;
  QUANTITY Tds ACROSS Pds THROUGH Td to Ts ;
  QUANTITY nvt : real ;
  QUANTITY Iss : real ;

-- Internal quantities for electrical modeling
  QUANTITY vd ACROSS id THROUGH p TO m;
  QUANTITY Im : REAL;
  QUANTITY Qj : REAL;
  QUANTITY Qe : REAL;
  QUANTITY V12 : REAL;
  QUANTITY Qm : REAL;
  QUANTITY QmNew: REAL;

-- Parameters common with SPICE diode model
  CONSTANT k : REAL := 1.381e-23;
  CONSTANT q : REAL := 1.602e-19;
  CONSTANT fc : REAL := 0.5;
  CONSTANT a0 : REAL := fc*Vj;
  CONSTANT b0 : REAL := mj/Vj/2.0;
  CONSTANT c0 : REAL := Cj0*Vj/(1.0-mj);
  CONSTANT d0 : REAL := 1.0-mj;
  CONSTANT f1 : REAL := Vj*(1.0-(1.0-fc)**d0)/d0;
  CONSTANT f2 : REAL := (1.0-fc)**(1.0+mj);
  CONSTANT f3 : REAL := 1.0-fc*(1.0+mj);

```

BEGIN

-- Optical behavior

```
N'dot == I/q - N/tn - G0*(N-N0)*S/(1.0+eps*S);
S'dot == -S/tp + beta*N/tn + G0*(N-N0)*S/(1.0+eps*S);
T == Temp + 273.0;
ioff == m0 + m1 * T + m2 * T*T;
I == etai*(id - ioff);
Popt == (h*nu*alphan*vg/2.0)*S;
nu0 == c/(al*Temp + (lambda0-al*25.0));
nu == nu0 - alphah/2.0 * (G0*(N-N0)/(1.0+eps*S)-1.0/tp);
lambda == c/nu;
```

-- Thermal behavior

```
Pth == -id*vd + Popt;
Power_int == Cth*Temp'dot;
Tdi == Ri*Pdi;
Tdvi == Rv*Pdvi;
Tdvo == Rv*Pdvo;
Tds == Rsub*Pds;
break Temp => Temp0;
break nvt => ne*k*(Temp0+273.0)/q;
nvt == ne*k*(Temp+273.0)/q;
Iss == Iss0 * ((Temp+273.0)/298.0)**eta;
```

-- Electrical behavior

-- Junction capacitance: SPICE junction capacitance model

```
IF V12 < a0 USE
    qj == Cj0*(1.0-(1.0-V12/Vj)**d0);
ELSE
    qj == Cj0*(f1+1.0/f2*(f3*(V12-a0)+b0*(V12*V12-a0*a0)));
END USE;
```

--Calculation OF charge at junction edge.

```
Qe == tn * Iss *(exp(V12/(nvt+1.0E-8)) -1.0);
```

-- Diffusion current

```
Im == (Qe - Qm)/TT;
vd == V12 + Rs*Im;
QmNew == tn*Qm;
Qm == tn*Im - QmNew'dot;
id == Im + Qj'dot;
```

END ARCHITECTURE thermo_opto_elec;
