Multilevel Behavioral Simulation of VCSEL based Optoelectronic Modules

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Abstract— The assembly within a single optoelectronic interconnect module of different components, including VCSEL and photodiode arrays, optical fibers and electronics implying electrical, optical, mechanical and thermal interactions, introduces new constraints in the conception phase and necessitates a new and different approach for modeling and simulation. A promising solution, when conceiving optoelectronic MEMS is obtained by simulation with the multilevel language VHDL-AMS based on system component parameters and standards.

Index Terms—Behavioral modeling, Optical interconnections, Optoelectronic devices, VCSEL arrays, VHDL-AMS.

I. INTRODUCTION

Optoelectronic complex modules integrate electronics, and optical components within a single system. This points out the need for suitable computer aided design (CAD) tools, able to simulate in different domains such as electronics, optics, temperature effects, mechanics, and their interactions.

During the last 10 years, the development of new low-cost optoelectronic components, such as Vertical Cavity Semiconductor Lasers, VCSELs, has demonstrated that optics can be considered a solution for high capacity applications in short distance communications defined also as optical interconnects [1]. Components are available, but the question is at what time will optical interconnects be sufficiently performing and their production cost fall low enough, to replace copper cabling. For short distance applications, up to 300m, parallel optical links using VCSEL and photodiode arrays coupled to multimode fiber ribbons are the best solution resulting in aggregate data rates exceeding 10 Gbps.

Optical interconnects are successfully used in Local Area Networks, LANs, and in electronic backplane connections, this is also encouraged by new datacom standards such as GigaEthernet IEEE802.3ae, Very Short Range, VSR, from the Optical Internetworking Forum, OIF, Fiber Channel and Infiniband [2]. The goals of these standards are co-operation among telecom industry participants including equipment manufacturers, telecom service providers and end users in order to promote global development of optical internetworking products and promote nationwide and worldwide compatibility and interoperability. Actual proposed technical solutions present stringent constraints such as extended temperature range, a problem for integration and dynamic performances, low volume and low consumption. This is necessary for general telecommunications applications but also in other fields such as space, defense, aeronautics and automotive fields. General optoelectronic interconnect module standard specifications are presented on Table I.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Channels</td>
<td>(N_h)</td>
<td>-</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>(V_r)</td>
<td>V</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>(T)</td>
<td>°C</td>
<td>-40/+85</td>
<td>Range</td>
</tr>
<tr>
<td>Data Rate</td>
<td>(B)</td>
<td>Gbps</td>
<td>1 – 10</td>
<td>Range</td>
</tr>
<tr>
<td>Bit Error Rate</td>
<td>(BER)</td>
<td></td>
<td>(&lt; 10^{-12})</td>
<td>Full speed</td>
</tr>
</tbody>
</table>

II. SIMULATION OF OPTOELECTRONIC MODULES

A. Simulation goals in the SHAMAN project

Simulation of complex optoelectronic modules, in these applications, containing complete transmission chains is of great interest. However the complexity of such advanced optoelectronic datacom systems is greatly increased compared to conventional electrical interconnects. Effects such as thermal, electrical and mechanical interactions have to be taken into account from the beginning of the development, this requires reliable modeling.

Spice thermal models have been developed for single...
VCSELs [3], but when considering components in the form of arrays, global models have to be taken into account using a multi-level approach [4].

The high integration level of optoelectronic modules using components such as VCSEL and photodiode arrays, optical fibers, connectors and associated electronic circuits leads to strong electrical, optical, thermal and mechanical interactions. It is thus mandatory to use a multi-domain simulation tool taking into account these cross-interactions.

Physical models necessary for a reliable and not time consuming simulation of the optoelectronic modules must be based on available component parameters. We define them as system parameters, these are found in component manufacturer data sheet or are based on measurements made with standard equipment such as for example power meters, wavelength-meters, optical reflectometers, modern oscilloscopes including eye diagram analysis, error detectors, optical and electrical spectral analyzers…

Commonly in the relatively new optoelectronic field, simulation models use extensively internal physical component parameters which are very difficult to obtain or to measure especially for non-manufacturing and non-research developers and users. This fact leads to low versatility simulation tools and at the end to a limited diffusion of new optoelectronic technologies when compared to microelectronics technologies which dispose of powerful CAD tools based on standard and realistic parameters.

Models developed from the SHAMAN (Simulation Hybride analogique Mixte pour Applications Numériques) project parallel optoelectronic demonstrator modules are dedicated to end-users such as the telecom and datacom equipment manufacturers and communications and signal processing designers.

Very accurate physical or mathematical modelling with large amount of internal material parameters and specific optoelectronic, thermal or mechanical know-how is not suitable for a large diffusion of these models among communities which operate principally at the system level. Therefore one of the main objectives of the SHAMAN project is to develop and evaluate reliable physical models and define as exhaustive as possible system parameter lists. Not too consuming simulation times are mandatory for such complex optoelectronic modules, this because there is no necessity to completely focus on accurate physical component models in optical, mechanical thermal or electrical domains, but a more challenging issue is to develop reliable behavioural models with correct simulation time.

The figures extracted from our physical models, such as power and wavelength variations or eye diagrams are also intended to match the standard specifications for optical interconnects recommended by IEEE802.3ae and VSR.

A large diffusion of these behavioural models implies the use of largely spread simulation software, SPICE, devoted to analog simulation has not been created for such complex systems and therefore is not optimised for such applications. The approbation of the analog extension of the IEEE-1076 VHDL world largely used language for digital & logical description and simulations; the so called VHDL-AMS high level open language specified by the extension IEEE1076.1-1999 [2],[6] has been specifically designed for multidimensional component and system description and simulations. SHAMAN models are based on this language.

To validate our models we first implement them first in an optical link simulation software, COMSIS [5], and compare them with tests on our demonstrator optoelectronic modules.

In a second time validated models are implemented using VHDL-AMS. This leads to an integrated tool using the capabilities of this multidisciplinary language in order to develop a library of models which will allow to simulate Micro-Opto-Electro-Mechanical Systems, MOEMS, within a multi-constraint environment. Since the library of models will be standard based, it will be possible to implement it in any VHDL-AMS simulator. VHDL-AMS is appropriate to describe and simulate mixed-technology systems with terminal definition.

B. Prototype Optoelectronic modules

Demonstrator optoelectronic prototype modules developed for this project [7] use passive optical alignment in order to reduce fabrication costs and to free assembly constraints, a module example is shown on Fig. 1.

Combination of classical pick-and-place machine and flip-chip processes with silicon micro-machining allows the integration of multi-channel optical interconnect modules in a very thin and small package (15x15x4nm). Small packages are required for severe environment applications such as space, defense, automotive or avionics applications, where the ratio of performances over volume must be as high as possible because overall equipment size and weight is directly proportional to the maximum payload. EMI & EMC are also of great importance for high-speed operation in such environments necessitating therefore careful design.

Optoelectronic modules include principally three functions:
A) Optical sub-assembly in charge of the passive coupling

Fig. 1. Optoelectronic module including optical subassembly, electronics and packaging, and connectorized 12 fiber ribbon.
of optical fibers with non-thermally controlled optoelectronic components, VCSEL and PIN photodiodes. Careful design flip-chip processes and realization lead to accurate positioning.

B) Electronic transmitter drivers, detector amplifiers and limiters.

C) Final packaging elements, which are chosen to be the same for the emitting and receiving modules, flip-chip process with silicon micro-machining allows the integration of multi-channel optical interconnect modules in a very thin and small package.

Such integration implies to take into account at the design level cross correlation between the previous functions and components very early in the design flow in order to increase performances and decrease the design steps and final cost.

The essential characteristics of the optical interconnect modules considered here are given on Table I. Actual realized prototype modules have an aggregated data rate of 12×1.25 Gbps. The design and simulation is undertaken on new prototypes in order to achieve aggregated data rates of 12×10 Gbps.

Components used in an optoelectronic module are:

1) Optoelectronic components: VCSELs and photodiodes.
2) Optical components: multimode optical fibers and optical connections.
3) Electronic components: drivers for VCSELs and amplifiers/limiters for photodiodes.
4) Positioning, assembly and report systems: such as flip-chip, bonding and different substrates.

On Fig. 2 we show the general assembled diagram of a general optoelectronic module including different component models. This diagram shows the multilevel input and output signals, which belong to the four domains, optical, electrical, thermal and mechanical. We use system parameters for the specific component models and consider technological and geometrical constraints.

This diagram architecture will be used at the VHDL-AMS programming level. Models are described on a generic component basis in order to make them independent from specific manufacturer technology.

### III. VCSEL SOURCES

VCSELs are commonly accepted optical sources for parallel short distance optical communication systems, because of their high integration possibilities and relative low-cost. The specified optoelectronic modules described here are composed of non thermally stabilized GaAs quantum-well VCSEL arrays, emitting in the 850 nm wavelength window. Other wavelength windows such as 1300 nm and 1550 nm can be easily adapted in the framework of our models.

The most relevant system parameters used for an optical interconnect VCSEL array transmitter, are shown on Table II, they will be used either as inputs or as parameters for our simulation models.

The VCSEL sub-model, part of the general model, is shown in Fig. 2, with its inputs and outputs. It includes also assembly techniques that play an important role in heat transfer between components and the rest of the module. VCSEL arrays have thermal coupling among different laser chips, due to self and cross heating. Temperature variations and optical coupling are considered as global effects.

### TABLE II

<table>
<thead>
<tr>
<th>VCSEL TRANSMITTER SYSTEM PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>Supply Current</td>
</tr>
<tr>
<td>Output Optical Power</td>
</tr>
<tr>
<td>Beam Divergence</td>
</tr>
<tr>
<td>Slope Efficiency</td>
</tr>
<tr>
<td>Peak wavelength</td>
</tr>
<tr>
<td>Total Spectral Width</td>
</tr>
<tr>
<td>\lambda, Temp. Coefficient</td>
</tr>
<tr>
<td>FM modul. or chirp</td>
</tr>
<tr>
<td>Operating Voltage</td>
</tr>
<tr>
<td>Bias Current</td>
</tr>
<tr>
<td>Dynamic Resist (dV/dI)</td>
</tr>
<tr>
<td>Threshold Current</td>
</tr>
<tr>
<td>Modulation Bandwidth</td>
</tr>
<tr>
<td>Damping factor</td>
</tr>
<tr>
<td>Rel. Intensity Noise</td>
</tr>
<tr>
<td>Rise/Fall (20%-80%)</td>
</tr>
<tr>
<td>Random Jitter</td>
</tr>
</tbody>
</table>

#### A. VCSEL model

For system purpose the most relevant VCSEL output characteristics are the static optical power versus injection current, the \( I, T \) curve, and the pulse response. The total VCSEL output power has almost linear behavior above the threshold current \( I_{th} \) as shown on Fig. 5.

VCSEL mode structure affects static figures such as optical output beam profile and polarization and optical spectrum structure as we will discuss in IIIIF. It also affects the frequency response of the Relative Intensity Noise, \( RIN \), mostly at low frequency [10],[11]. At our simulation level we will not consider detailed \( RIN \) structure, transmitted \( RIN \) will...
be added to the other noise sources at the receiver level as we will describe in V. Also, as quoted by several authors [11], the value of the relaxation frequency $f_R$ is proportional to the square root of the total photon number in the active layer irrespective of the number of excited transverse modes and thus of Spatial Hole Burning (SHB).

In order to get the optical output power response to an input current pulse we solve the semiconductor laser single-mode rate equations [3],[8], as function of total photon and carrier numbers $S$ and $N$ given in (1) and (2). Rate equation parameters are defined on Table III.

$$\frac{dS}{dt} = G_N (N - N_j)(1 - \varepsilon_n S)S - \frac{S}{\tau_p} + \frac{N}{\tau_n}$$ (1)

$$\frac{dN}{dt} = \frac{I}{e} - G_N (N - N_j)(1 - \varepsilon_n S)S - \frac{N}{\tau_n}$$ (2)

Rate equations are expressed in function of the number of carriers $N$ and photons $S$, and not of concentrations, as was introduced by G.P. Agrawal, [3], [8], this leads to symmetrical gain expressions needing less parameters such as the confinement factor, the cavity volume and group index.

Our original approach here is to use exclusively system parameters and some internal default parameters. These parameters are obtained essentially from the LI curve giving the slope $\eta_{LI}$ and the threshold current $I_{th}$ and from the AM modulation response giving the resonance frequency $f_R$ and bandpass $f_{3dB}$ and the oscillation damping factor $\xi$. The rate equations are used as behavioral semiconductor laser equations the aim is not to extract internal laser parameters but to fit as best as possible to laser data sheet and standard measurements.

The bi-linear dependence on carriers $N$ minus transparency carrier number $N_t$ and photons $S$ is used for the gain term $G_N(N - N_t)S$, this corresponds to a first order expansion of the usual logarithmic carrier dependence in quantum wells. This approximation is valid when considering operation above threshold where carrier variations are small [8], because of carrier clamping. The gain term is also proportional to the total photon number $S$ because at our approximation SHB effects are integrated as discussed above.

The resolution of these equations give the temporal behavior of the optical power $P(t)$. Thus a digital current input will result in the corresponding digital optical power output. This is shown on Fig. 3.

For wavelength dynamic variations, chirp, a third equation on phase is necessary. The relevant parameter is the optical phase-amplitude Henry’s factor $\alpha_{HI}$, which is rarely available from manufacturers. $\alpha_{HI}$ can be derived from chirp measurements $\delta v/\delta I$ function of modulation frequency $f_m$. Chirp is not very relevant in datacom short distance applications and we will not consider it in our further discussion even though it could be very easily implemented in the models.

**B. VCSEL equivalent circuit**

A combination of the linear laser rate equations and the Kirchoff’s equations give an equivalent small-signal circuit of the VCSEL active zone shown on Fig. 4 which will be useful for the description of the input interface from drive electronics to VCSEL. This circuit model gives a conversion between electrical parameters and its physical counterparts, the corresponding relations are given in (3). Electrical variables are the injection current $I$ and the junction voltage $V_j$.

$$C_j = \frac{N}{k_BT}$$

$$R_jC_j = \frac{1}{G_N S + \frac{1}{\tau_n}}$$

$$r_0 = \frac{\varepsilon_n}{G_N C_j}$$ (3)

$$L_0 = \frac{\omega_0^2}{\omega_i^2}$$

$$L_0 = \frac{G_N S}{\tau_p}$$

$$\omega_i = \frac{1}{\omega_0 C_j}$$

Fig. 4. VCSEL active zone equivalent electrical circuit, inputs are laser injection current $I$ and junction voltage $V_j$. 
C. VCSEL system to physical parameter conversion

Parameters defined in the rate equations are physical internal parameters. Usually general default values are used when specific laser values are not available, and this leads to non-reliable and non-dedicated simulations. In order to get the maximum information from an available component, in our case a VCSEL, we want to convert system parameters available from data sheet or from standard measurement equipment into physical parameters.

We use the static behavior derived from the approximated steady state solutions of the rate equations. We consider general semiconductor laser behavior: that is linear power behavior \( P_0 = \eta_A I_0 - I_{th} \) and carrier clamping above laser threshold current \( I_{th} \). Threshold current \( I_{th} \) and slope efficiency \( \eta_{LI} \) are available system parameters. In combination with the diode voltage \( V \) we get the differential quantum efficiency \( \eta_d = \eta_{LI} / V \). In a VCSEL emission is made from the top facet so that the output power coupling coefficient \( \eta_c \) is approximately equal to the differential quantum efficiency \( \eta_c = \eta_d \) [3]. At threshold we consider that optical power is negligible, these considerations lead to the following relations given in (4).

\[
\frac{N_{th}}{\tau_n} = \frac{I_{th}}{e} \quad \text{for} \quad I_0 = I_{th} \quad \text{and for} \quad I_0 \geq I_{th}
\]
\[
N_0 = N_{th} \quad \text{and} \quad G_N (N_{th} - N_l) S_0 = \frac{S_0}{\tau_p} = \frac{I_0 - I_{th}}{e}
\]
\[
P_0 = \eta_{LI} (I_0 - I_{th}) = \eta_c \frac{h c S_0}{\lambda_0} \tau_p \quad \text{with} \quad \eta_c = \eta_d = \frac{\eta_{LI}}{V}
\]

From the VCSEL dynamic AM optical power response, which is also commonly available, we can extract the resonance frequency \( f_R \) and the resonance damping factor \( \xi \) these parameters are bias dependent function of the injection current \( I_l \). Generally on a system level one specifics modulation bandwidth \( f_{3db} \). In semiconductor lasers because of resonance it is easier to extract peak resonance frequency \( f_R \), for system use we can consider that the bandwidth limit should fall below the resonance frequency in order to avoid ringing. Another useful system parameter is the well-known K factor which is the slope of the damping coefficient \( \gamma = 2 \xi \omega_k \) versus \( f_R^2 \). For \( \omega_k = 2 \pi f_k \) and \( \gamma \) we get the following conversion relations in (5) derived from the rate equations [21].

\[
\omega_R^2 = G_N \left( \frac{I_0 - I_{th}}{e} \right) \quad K = 4 \cdot \pi^2 \left( t_p + \frac{e_n}{G_N} \right)
\]
\[
\gamma = \gamma_0 + \left( \frac{\tau_p}{G_N} \right) \omega_R^2 \quad \gamma_0 = \frac{1}{\tau_n}
\]

System parameters related to the laser noise characteristics are threshold current \( I_{th} \), \( RIN \) spectra and un-modulated mode linewidth \( \Delta \nu_0 \), also known as the Schawlow-Townes linewidth. \( RIN \) and \( \Delta \nu_0 \) are bias dependent. \( RIN \) is sometimes available from manufacturers at one value for a specific bias current and modulation frequency. \( RIN \) spectra are rarely available and are difficult to measure due to very low noise levels. Mode linewidth \( \Delta \nu_0 \) is difficult to measure because it necessitates mode separation and a very high-resolution optical spectrum analyzer, most of the time only total spectral width \( \Delta \lambda \), including all spatial modes and laser under modulation is available.

From known \( RIN \) and \( \Delta \nu_0 \) it is possible to estimate the spontaneous-emission-rate \( R_{sp} \) and the inversion factor \( n_{sp} \) above threshold and relate them to rate equation parameters in (6).

\[
\Delta \nu_0 = \frac{R_{sp} \left( 1 + \alpha^2 \right)}{4 \pi S_0} \quad RIN(\omega = \omega_R) = 2 \frac{R_{sp} \left. 1 \right)}{S_0} \gamma^2
\]
\[
R_{sp} = \beta_{sp} \frac{N_{th}}{n_t} = \frac{n_{sp}}{n_p} \quad n_{sp} = \frac{N_{th}}{N_{th} - N_t}
\]

By using equation (4) to (6) we can extract the rate equation parameters defined in Table III. Equations used for the physical parameter conversion shown in the fourth column of Table III are not unique, so parameter redundancy can be obtained using more than one relation. An internal parameter useful for the determination of the photon lifetime \( \tau_p \), is the Bragg facet mirror losses coefficient \( \alpha_m = -(2 \alpha_{eff})^{-1} \ln(R_b R_s) \), where \( R_b \) and \( R_s \) are the top and bottom mirror reflectivity and \( L_{eff} \) the effective cavity length. Typically \( \alpha_m = 30. \text{cm}^{-1} \) [4], [22]. The inversion factor \( n_p \) is also very useful it can be obtained from \( RIN \) or \( \Delta \nu_0 \) if not available the default value generally admitted is \( n_{sp} = 2 \) [11].

### TABLE III

VCSEL SYSTEM-PHYSICAL PARAMETERS CONVERSION

<table>
<thead>
<tr>
<th>Ra.</th>
<th>Eq.</th>
<th>Name</th>
<th>Typ. value</th>
<th>Conversion towards syst. parameters</th>
<th>Needed system parameter</th>
<th>Needed Phys. param.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_N )</td>
<td>Differen-tial gain</td>
<td>5.10^4 \text{s}^{-1}</td>
<td>( G_N ) = [(e n_{LI})(P_b) ] ( (2 \pi f_k)^2 )</td>
<td>Slope ( \eta_{LI} )</td>
<td>Power ( P_b )</td>
<td>Res. freg. ( f_k )</td>
</tr>
<tr>
<td>( \tau_p )</td>
<td>Photon lifetime</td>
<td>2.10^{-12} \text{s}</td>
<td>( \tau_p = \frac{(\eta_{LI} \alpha_c G_N)}{(hc \alpha_m)} )</td>
<td>Slope ( \eta_{LI} )</td>
<td>Wavelength ( \lambda )</td>
<td>Cavity loss ( \alpha_m )</td>
</tr>
<tr>
<td>( \tau_c )</td>
<td>Carrier lifetime</td>
<td>1.10^{-9} \text{s}</td>
<td>( \tau_c = \frac{(e n_{LI})(P_b)}{[n_{sp}^2(\tau_p, \gamma p)]} )</td>
<td>Thresh curr. ( I_{th} )</td>
<td>Those of ( G_N ) and ( \tau_p )</td>
<td>Inver. factor ( n_{sp} )</td>
</tr>
<tr>
<td>( \beta_{sp} )</td>
<td>Spont. emission fraction</td>
<td>5.10^{-5}</td>
<td>( \beta_{sp} = \frac{(e I_{th})(n_{sp}/\gamma p)}{(\tau_p, \gamma p)} )</td>
<td>Thresh curr. ( I_{th} )</td>
<td>Those of ( \tau_p ) and ( \gamma )</td>
<td>Inver. factor ( n_{sp} )</td>
</tr>
<tr>
<td>( \epsilon_n )</td>
<td>Gain compress factor</td>
<td>10^{-6}</td>
<td>( \epsilon_n = G_N \gamma (2 \pi f_k)^{2} )</td>
<td>Res. freg. ( f_k )</td>
<td>Damping ( \gamma )</td>
<td>Those of ( G_N )</td>
</tr>
</tbody>
</table>


\[ P(T) = \eta_{\lambda,T}(T) \cdot [I - I_{th}(T)] \]  

(7)

Wavelength \( \lambda(T) \) and voltage \( V(T) \) dependence with temperature \( T \) are included in the model for higher precision in order to express effects on differential laser gain \( G_N(T) \) and carrier number \( N(T) \).

VCSEL diode voltage can be expressed as \( V = V_j + R_s I \), where \( V_j \) is the junction voltage and \( R_s \) the series resistance given by the slope of \( V(I) \). \( R_s \) is considered as temperature independent in our approximation [4]. Thus the temperature dependence of \( V \) is mainly determined by dependence of \( V_j \) and of current \( I \). Relative variations of \( V_j \) depend on carrier number \( N \) and on gap energy \( E_g \) [12]. Considering that for a VCSEL \( (V - E_g) \) is much greater than the thermal excitation energy \( (k_B T \epsilon) \), we express the relative variations of carrier number \( N \) with temperature in (8).

\[
\frac{1}{N} \frac{\delta N}{\delta T} = \frac{1}{V_j - E_g} \left( \frac{\delta V_j}{\delta T} - \frac{\delta E_g}{\delta T} \right)
\]

with \( dV_j(T) = dV_j(T) - R_s dI(T) \)

\[
\delta I(T) = -\delta I_{th}(T)
\]

\[
E_g(T) = E_{g0} - \frac{\alpha \cdot T^2}{T + \beta}
\]

We consider 850 nm GaAs VCSELs, with \( E_{g0} = 1.519 \text{ eV} \), \( \alpha = 5.405 \times 10^{-4} \text{ eV.K}^{-1} \) and \( \beta = 204 \text{ K} \) [12].

Gain is temperature dependent through \( N(T) \), given in (8), and also through the wavelength \( \lambda(T) \). We express the relative differential gain variations \( \delta G_N \) with temperature in (9). \( \delta G_N \) depends also on spectral width \( \Delta \lambda \) considered as temperature independent at this approximation level [4].

\[
\frac{1}{G_N} \frac{\delta G_N}{\delta T} = -4\lambda \frac{\delta \lambda}{\Delta \lambda^2} \frac{\delta \lambda}{\delta T}
\]

(9)

Measurements of optical power \( P \), voltage \( V \) and wavelength \( \lambda \) function of injection current \( I \) and temperature \( T \) are available data from VCSEL manufacturers and can thus be used for parameter determination. Typical variations for optical power \( P \) and diode voltage \( V \) measured on a VCSEL array are given in Fig. 5.

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**D. VCSEL temperature behavior**

Temperature dependence of rate equation parameters can be evaluated, this necessitates supplementary system parameters such as wavelength \( \lambda \) and voltage \( V \) and their temperature variations. Temperature variation affects VCSELs, by changing threshold current \( I_{th}(T) \) and in a minor way the slope of \( \eta_{\lambda,T}(T) \) leading to optical power temperature dependence in (7).

\[ P(T) = \eta_{\lambda,T}(T) \cdot [I - I_{th}(T)] \]

\[ \text{Typical variations for} \quad P(T) \text{ are available data from VCSEL manufacturers and can thus be used for parameter determination. Typical variations for optical power} \quad P \text{ and diode voltage} \quad V \text{ measured on a VCSEL array are given in Fig. 5.} \]

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**E. VCSEL Array Temperature Modeling**

In VCSEL arrays mutual and self-heating can induce optical output power and wavelength variations. The principle of thermal coupling in a VCSEL array is shown on Fig. 6.

In order to obtain the temperature distribution on the array diodes we have used analytical Joyce-Dixon solutions for the heat equation [13]-[16], adapted to the geometry of our VCSEL with GaAs substrate material thermal conductivity \( k_s = 40 \text{ W.K.m}^{-1} \). The result is illustrated on Fig. 7, showing the temperature rise \( \Delta T(x,y,z) \) due to VCSEL heating. Adjacent lasers contribute, in our configuration, up to some degrees to temperature. Active zone temperature can be high in a VCSEL, up to 100°C or more, due principally to self-heating. The detail of temperature increase in the active zone is not shown on Fig. 7.

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**Fig. 5.** VCSEL Power \( P \) and voltage \( V \) variation as function of injection current \( I \) for different temperatures \( T \) measured for a VCSEL of an array in an optoelectronic module.

**Fig. 6.** Thermal coupling in a VCSEL array showing its influence on optical power variations and on wavelength shift.

**Fig. 7.** Temperature increase distribution in the bulk near the top of a VCSEL array calculated from analytical solutions. The central VCSEL emits at the double of the power as the adjacent ones. Isothermal curves correspond to an increase of \( \Delta T = 2 \text{ C} \).
To simulate thermal effects in the VCSEL array model, a thermal terminal must be defined with two associated parameters: the diode temperature $T$ and the power dissipated by the junction $P_{th}$. Thermal exchanges between the diode and its environment and between bulk, the inner cavity and the neighboring diodes, through thermal resistance $R_{th}$, are represented on Fig. 8. Thermal time constants are introduced in the model through thermal capacitance $C_{th}$ [17].

Temperature exchanges are located inside the module: due to high thermal resistance. Resins and FR-4 limit the temperature propagation to the outside of the module. Due to the mode structure a VCSEL will have different optical power $P$ and wavelength $\lambda$ function of injection current $I$ (Fig. 9). A bell-shape profile corresponds to the fundamental mode and an annular, or donut, profile corresponds to higher order modes. Annular profiles couple principally high order modes in multimode fibers, this can diminish modal dispersion and thus increase bandwidth on short fiber lengths as is the case in our application. In general a superposition of bell-shape and annular beams must be considered.

We seek a model that can be adapted to different coupling distances $z$. Spatial multimode profiles can be approximated by using different gaussian profiles [19].

$$I_i(r, z) = I_{0i} \exp \left( -\frac{2r^2}{w_i(z)^2} \right)$$

$$w_i(z) = w_{0i} \sqrt{1 + \left( \frac{\lambda z}{\pi w_{0i}^2} \right)^2} \quad w_{0i} = \frac{\lambda}{\pi \theta_{th}} \quad I_{0i} = P_{tot} \frac{2}{\pi w_{0i}^2}$$

A simple, but satisfying, approximation consists in the superposition of two different gaussian profiles $I_{\text{mod}}(r,z) = |I_1(r,z) + e^{i\phi} I_2(r,z)|$ where the single profiles are expressed according to (10). $I_{0i}$ is the maximum intensity at the optical axis related to the emitted mode power $P_{lux}$, $r$ is the radial coordinate and $w_i$ the beam waist which is a function of wavelength $\lambda$ and of beam divergence $\theta_{th}$. This approximation can fit bell-shape, annular and intermediate profiles [19]. Experimental measured profiles compared to the superposition of gaussian profiles are shown on Fig. 10.

Due to the mode structure a VCSEL will have different beam profiles [11], [18] function of injection current. A bell-shape profile corresponds to the fundamental mode an annular,
shown on Table V.

The detector sensitive area. Photodiode model parameters are surrounding temperature heating, their performances are mainly influenced by manufacturer data, and can be integrated in the model as a function of fiber propagation distance giving the fiber output power $P_f$.

$$P_f = A.L.P_c$$

(12)

Dispersion effects are considered as a limitation on the transmission bandwidth $\Delta f_c$. For a gaussian fiber transmission transfer function which is justified with multimode fibers we can express $\Delta f_c = 0.2/\sigma_T$ , where $\sigma_T$ is the total temporal pulse spreading in the fiber of length $L$. Its expression as function of modal $\sigma_m$ and intramodal $\sigma_d$ pulse time dispersion is given in (13), with $\Delta \lambda$ the total source linewidth.

$$\sigma_T = \sqrt{\sigma_m^2 + \sigma_d^2}$$

$$\sigma_m = \frac{L.(NA)^3}{8.n^3.c} \quad \sigma_d = L.\Delta \lambda .D$$

(13)

### TABLE IV  
MULTIMODE FIBER AND COUPLING MODEL PARAMETERS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Attenuation</td>
<td>$A$</td>
<td>dB/km</td>
<td>3-7</td>
<td>Range</td>
</tr>
<tr>
<td>Fiber Length</td>
<td>$L$</td>
<td>m</td>
<td>300</td>
<td>Max</td>
</tr>
<tr>
<td>Fiber core index</td>
<td>$n_c$</td>
<td>-</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Fiber core radius</td>
<td>$r_c$</td>
<td>µm</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Numerical Aperture</td>
<td>$NA$</td>
<td>-</td>
<td>0.2</td>
<td>Typ</td>
</tr>
<tr>
<td>Intramodal Dispersion</td>
<td>$D$</td>
<td>ps/(nm.km)</td>
<td>-46</td>
<td>Typ</td>
</tr>
<tr>
<td>Source linewidth</td>
<td>$\Delta \lambda$</td>
<td>nm</td>
<td>0.5</td>
<td>Max</td>
</tr>
<tr>
<td>Source Power</td>
<td>$P_s$</td>
<td>mW</td>
<td>0.5</td>
<td>Typ</td>
</tr>
<tr>
<td>Source beam diverg.</td>
<td>$\theta_d$</td>
<td>°</td>
<td>14</td>
<td>Max</td>
</tr>
<tr>
<td>VCSEL fiber distance</td>
<td>$z$</td>
<td>µm</td>
<td>50</td>
<td>Typ</td>
</tr>
</tbody>
</table>

### V. DETECTORS

PIN Photodiode arrays do not present significant self-heating, their performances are mainly influenced by surrounding temperature $T$ and optical coupling efficiency on the detector sensitive area. Photodiode model parameters are shown on Table V.

A shown on Fig. 2, detector sub-model inputs are the optical receiver input power $P_r$, the temperature $T$ and assembly constraints. Parameters are affected by manufacturer technology. The electrical output corresponds to the detected receiver current $I_r$ which is proportional to $P_r$ through the responsivity $R_d$ as expressed in (14).

$$I_r = R_d.P_r$$

(14)

Three phenomena limit photodiode dynamic behavior: carrier diffusion, carrier drift, and junction capacity $C_j$, $C_d$ can be calculated from charge value in depleted zone, for example using a SPICE model. An optical characteristic time constant $\tau_{opt}$ is derived from the receiver bandwidth $\Delta f_r$, provided by manufacturers, from $C_j$ and $R_eq$ and is given in (15).

$$\tau_d = R_eq.C_d = 0.35.\Delta f_r^{-1}$$

$$t_{RC} = R_eq.C_j \quad \tau_{opt} = \tau_d - \tau_{RC}$$

(15)

Then, an additional equation (16) is introduced in order to model photodiode dynamic behavior :

$$I_r + \frac{\tau_{opt}}{2.2} \frac{dI_r}{dt} = R_d.P_r$$

(16)

In a PIN photodiode temperature effects are principally observed in responsivity $R_d$ through wavelength $\lambda(T)$ and in dark current $I_d(T)$ through the gap energy $E_g(T)$ (see (8)). Relative responsivity and dark current variations are given in (17). Gap energy as function of temperature $E_g(T)$ in (8).

$$\frac{dR_d}{R_d} = \frac{\Delta \lambda(T)}{\lambda}$$

$$\frac{\Delta I_d}{I_d} = \frac{E_g(T) \cdot \delta T}{k_b T}$$

(17)

### TABLE V  
PHOTodiode MODEL PARAMETERS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>$\lambda$</td>
<td>nm</td>
<td>850</td>
<td>Typ</td>
</tr>
<tr>
<td>Responsivity</td>
<td>$R_d$</td>
<td>A/W</td>
<td>0.5</td>
<td>Typ</td>
</tr>
<tr>
<td>Reverse Voltage</td>
<td>$V_b$</td>
<td>V</td>
<td>-5</td>
<td>Max</td>
</tr>
<tr>
<td>Dark Current</td>
<td>$I_0$</td>
<td>µA</td>
<td>5</td>
<td>Max</td>
</tr>
<tr>
<td>Photodiode Capacitance</td>
<td>$C_d$</td>
<td>pF</td>
<td>0.5</td>
<td>Max</td>
</tr>
<tr>
<td>Rise/Fall Time</td>
<td>$t_{ff}$</td>
<td>ps</td>
<td>100</td>
<td>Max</td>
</tr>
<tr>
<td>Receiver bandwidth</td>
<td>$\Delta f_r$</td>
<td>GHz</td>
<td>4</td>
<td>Min</td>
</tr>
</tbody>
</table>

Noise at the detector level consists of quantum noise, which is a function of the received optical power level $P_r$, and dark noise function of the dark current $I_d$. Detector electronics leads to thermal noise through an equivalent input circuit resistance.
\( R_{eq} \) and defines in conjunction with the photodiode capacity \( C_d \) also the bandwidth \( \Delta f_r = (2\pi R_{eq} C_d)^{-1} \). Noise contributions to the detected current, including filtered source \( RIN \) noise, are given in (18) and depend on temperature \( T \) through expressions given above in (17).

\[
\begin{align*}
    i_q^2 &= 2eR_d P_i \Delta f_r, \\
    i_D^2 &= 2eI_D \Delta f_r, \\
    i_T^2 &= \frac{4kT}{R_{eq}} \Delta f_r, \\
    i_{RIN}^2 &= R_{eq}^2 P_i^2 RIN. \Delta f_r, \\
    i_n^2 &= i_q^2 + i_D^2 + i_T^2 + i_{RIN}^2
\end{align*}
\] (18)

VI. ELECTRONICS AND ASSEMBLY TECHNIQUES

A. Electronics

Electronic elements, based on MOS integrated technology, are simulated on a system basis. A more detailed simulation can be considered for certain specific functions such as the digital input and output circuits and the optoelectronic analog drivers. The different electronic elements and the optical sub-modules are assembled on an integrated circuit board and packaged to form the complete module. The same basic structure is used for both the emitter and the receiver.

The source driver circuit for each VCSEL in the array is composed of two stages: an input buffer designed for electrical communication standards and an analog stage for the conversion to injection laser current. The optoelectronic driver circuit is assembled with the optical input coupling stage.

The electronic receiver circuit includes the function of amplification, through a transimpedance amplifier, and signal reshaping, through a limiter stage, of the detected current issued from the array photodiodes. The optoelectronic receiver circuit is assembled with the optical output coupling stage.

B. Assembly Techniques

Report and assembly techniques have to be taken into account globally for the entire optoelectronic module and not for individual components. Fabrication tolerances are taken into account and their influence on optical coupling is considered. Thermal dilatation parameters are considered as they are linked to the coupling efficiency of the optical components.

The main assembly and report techniques that have been explored are: classical hybridization process, brasure or gluing, using face up wire bonding and flip-chip hybridization process using tin-lead solder bumps. Hybridization process is the less stressing one when regarding thermal effects. The silicon layer acts as a good heatsink due to its low thermal resistivity towards the GaAs VCSEL.

Flip-chip technology allows passive alignment techniques, but has higher thermal resistivity, with a non homogeneous heat extraction due to the geometrical aspect and the localization of the bond pads. Optical power measurements over the −40°C to +85°C temperature range show differential results lower than 2dB at extreme temperatures −40°C and 85°C. Results are shown on Fig. 11.

First thermal simulations and validation measurements have shown that internal module temperature range is reduced from the outside one and remains quite stable. More precise and in-condition tests are still ongoing.

VII. TESTS AND VHDL-AMS IMPLEMENTATION

A. General considerations

Simulation of different physical effects interacting at the same time is a difficult task. The classical method is to express the different models in a common language using analogies. This is done currently in SPICE, where all effects are expressed in SPICE-like electrical models. This is not a straightforward procedure leading to accumulated errors, scale factors must be adapted and modified for each new model.

VHDL was designed to support many tasks in the design process of digital integrated circuit and systems [6]. Its extension, VHDL-AMS, allows to design analog parts of the systems.

Behavioral models of our optoelectronic module components are implemented in the VHDL-AMS language. The result is a single complete model that can be used for every kind of simulation. Parameters are generic, inputs and connections to the model are defined in a special VHDL-AMS file called testbench. The real interest is that the same complete model is used whatever the simulation.

B. Static VCSEL VHDL-AMS opto-thermal simulation

Because thermal time constants are much greater than VCSEL and photodiode time constants, if complete dynamic optoelectronic and thermal behavior are tested in the same simulation, simulation time can be prohibitive. It is more time efficient to test first static optoelectronic behavior in conjunction with dynamic thermal behavior. Electro-optothermal model of the VCSEL is implemented in the VHDL-AMS language and static simulation is done for several
junction temperatures. Resulting output optical powers and diode voltages as a function of injection current are reported in Fig. 12. Emitted optical power is maximal for $T = 20°C$ whereas diode voltage always decreases with temperature. These results match measurements shown in the figure 5.

![Fig. 12. VCSEL Power $P$ and voltage $V$ variation as function of injection current $I$ for different temperatures $T$ calculated by the VHDL-AMS model.](image)

VHDL-AMS simulation results for a five VCSEL array are shown on Fig. 13. The complete VCSEL model including all the equations and the thermal schematics presented in figure 8 is instanced five times for this simulation. At $I = 0$, five current steps are applied to the array, input currents are 1 mA in diode 1 and 5.5 mA in diode 2 and 4 and 10 mA in diode 3. Inner cavity and bulk are maintained at 25°C and junction temperatures are initialized at 25°C. The curves represent, on the left, optical and thermal powers created by the input currents. The central VCSEL (number 3) emits at the double of power as the adjacent ones. On the right temperatures are reported. They stabilize after 2ms because input currents are constant, the increases are limited because array environment is maintained at 25°C. However, final values result from both mutual and self heating.

![Fig. 13. VHDL-AMS simulation results for a five VCSEL array showing temperature, optical and thermal power on typical thermal time constants.](image)

C. Component test procedures

Electrical measurement results and manufacturer data sheet will be sufficient for physical tests. Depending on different component modeling levels there can be specific component tests.

Static tests are undertaken on VCSEL arrays, for optical power $P$ as function of injection current $I$, temperature $T$ and diode voltage swing $V$. Static tests will permit to define and extract characteristic component parameters over a large operating temperature range. Mode structure can be obtained with optical spectrum analysis and by the measurement of optical radiation pattern.

Dynamic tests on VCSELs are undertaken on modulation bandwidth, resonance characteristics, extinction ratio, temporal behavior of the optical signal and jitter. Coupling between VCSEL arrays and fiber ribbon and fiber ribbon and photodiode array are also tested.

D. Module global performance: Eye Diagram.

A global behavioral test will be obtained by the eye diagram, simulated and measured as shown on Fig.14-15. Eye diagram measurements at the transmitter and the receiver level permit a system validation of a great number of communication performance criteria. These are principally:

1) Noise and noise margin.
2) Sample time and its margin.
3) Jitter and Skew.
4) Bit Error estimation (BER)
5) Extinction ratio.

The communication standards from where tests are issued are IEEE802.3ae (10Gbps), STM8/OC24 (1.25Gbps), 10G Fiber channel (10Gbps) and VSR.

According to standards the required transmitter pulse shape characteristics are specified in the form of a mask of the transmitter eye diagram as shown in Figure 14. The typical mask consists of an hexagonal window and two forbidden bands, which define a standard $BER$. Normalized times of 0 and 1 on the unit interval scale are to be determined by the eye crossing means measured at the average value of the optical eye pattern.

The normative requirement for receivers is stressed receiver sensitivity. Stressed sensitivity is measured with a conditioned input signal where both vertical eye closure and jitter have been added. Receivers must operate with $BER$ less than $10^{-12}$ when tested with a conditioned input signal that combines vertical eye closure and jitter.

It is beyond the scope of this paper to discuss standard specifications, but we want to emphasize that these standards aim to give a general test procedure for these complex systems. The eye diagram characteristics lead to the $Q$ factor, obtained from the vertical eye closure, and to Jitter enabling to determine in the end the $BER$ of the entire system.

Modern dedicated measurement equipment deliver adapted stressed input signals and analyze eye diagrams by the means of a digitizing oscilloscope with special software enabling the detailed analysis of noise statistics. Power noise can be separated from Jitter, and different jitter components can be...
evaluated. The advantage of this method is to get almost real-time results well adapted to low-cost high speed datacom optoelectronic module performance analysis.

Fig. 14. Eye diagram at 1.25 Gbps of an optoelectronic module, with hexagonal mask according to datatcom standards.

E. Module global performance: VHDL-AMS simulation.

The validation process in the simulation of the entire optoelectronic module model is done by the means of a testbench. The input is a random digital signal under stressed standard specification. At the output we obtain the eye diagram of the receiver signal as shown on Fig. 15.

This eye diagram corresponds to the worst case design of an actual parallel optical module. The input signal bit type is directly processed including skew and jitter. Then after this preprocessing, it is associated to calculated parameters. These parameters are modified by rise and fall times, noise and bandwidth. Noise is generated by a random local quantity and multiplied by its amplitude calculated at the receiver level. In order to drive correctly the simulator we must manage the noise by a clock driven process [20].

If a generic parameter is used directly to drive the value of an output, the model is considered as a formal and executable specification. In this work, each parameter of the specification is used as a generic parameter. The simulation results are directly driven by these values.

VIII. CONCLUSION

In the framework of the SHAMAN project we propose models of different components of optoelectronic emitter and receiver modules for short range optical parallel communications. Models use system parameters available from manufacturers or measurements thus allowing a more reliable simulation and transposition to components from different manufacturers. Tests are made on an original optoelectronic module prototype according to recent optical communication high bit rate short range communication standards.

Developed models are used as the building blocks for the multilevel VHDL-AMS programming. The main advantages of these VHDL-AMS optoelectronic based models is to combine electrical, thermal and opto-electronic effects, with the possibility to switch from behavioral to physical model implementation depending on the simulation requirements (time, accuracy, etc.). Mechanical and thermo-mechanical effects and output fiber coupling are also taken into account. All these effects are taken into account in the same model, thus introducing a new virtual prototyping methodology with the goal to enhance productivity of MOEMS.

Multi-domain designers, as optoelectronic module manufacturers, should be interested in VHDL-AMS behavioral modeling. These kind of models allow to manage worst case design in virtual prototyping. The development of complex component libraries, such as components integrated in a MOEMS, will considerably facilitate the task of design and circuit engineers, and will allow to increase the efficiency of their work by reducing the number of iterative loops in the design and increasing the overall system performances, reducing therefore the time-to-market which is a manufacturer’s key issue.

Fig. 15. Eye-diagram of the VCSEL module (VSR1 1.25 Gbps) using the VHDL-AMS model.

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