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VERILOG-A IMPLEMENTATION OF A 2D SPATIOTEMPORAL VCSEL MODEL FOR SYSTEM-ORIENTED SIMULATIONS OF OPTICAL LINKS

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ABSTRACT: An implementation of a highly efficient spatiotemporal vertical-cavity surface-emitting laser (VCSEL) model in the circuit simulation environment of Cadence is presented. The VCSEL model, based on a set of modified rate equations, is written in Verilog-A. It enables the association of the VCSEL model with transistor-level models of the driver and detector circuits. Furthermore, the spatiotemporal nature of the model allows the generation of multimode responses and corresponding far-field intensity profiles, which can be used to investigate fibre coupling and propagation mechanisms. An optimization of the VCSEL drive signal performed using the built-in optimizer of Cadence is presented. © 2003 Wiley Periodicals, Inc. Microwave Opt Technol Lett 38: 304–308, 2003; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.11044

Key words: diode lasers; laser driver; optical link; system simulations; VCSEL

1. INTRODUCTION

Conventional board-to-board and chip-to-chip electrical interconnections are approaching their fundamental limits and represent a major performance bottleneck [1] for modern computer architec-

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1. INTRODUCTION

Conventional board-to-board and chip-to-chip electrical interconnections are approaching their fundamental limits and represent a major performance bottleneck [1] for modern computer architencers, such as multiprocessor systems. Optics may solve or mitigate this issue, but may also create radical opportunities for new architectures that have no analogy in the electrical world, such as free-space interconnects.

The application of well-known concepts and devices from the telecommunication industry to short-distance optical interconnects is appealing. Moreover, individual devices such as vertical-cavity surface-emitting lasers (VCSELs) [2], drive circuits [3], waveguides [4], and detectors [5] are already available. However, significant modifications of the typical design approaches are required before efficient and inexpensive solutions appear on the market. The major challenge lies in the integration and optimization of hybrid systems combining these different technologies (electronics and optics), based on the properties of the individual components and their interactions.

Special attention needs to be paid to the modeling of VCSELs, since they are the central part of the system where the actual optoelectronic conversion is performed. Phenomenological models, often based on rate equations, are numerically efficient and can easily be implemented in circuit simulation environments [6], but generally they provide no information about the spatial distribution of the optical field and multimode behavior. On the other hand, first-principle tools give very detailed information based on the device’s geometry and material system, but are numerically so demanding that they can generally not simulate dynamic responses, and are therefore badly suited for system-simulation purposes.

The VCSEL integrated spatio-temporal advanced simulator (VISTAS) is a system-oriented VCSEL model that was recently proposed by Jungo [7]. It is available for free download in the form of Matlab m-files [8]. VISTAS shows a very good trade-off between accuracy and numerical effort. It is based on 2D rate equations, and can therefore compute the detailed spatial interactions between the modal fields and carrier profile in the active region (see Fig. 1). The rate equations are transformed from a set of partial differential equations (pde) to ordinary differential equations (ode), based on physical and geometrical properties of cylindrical oxide-confined VCSELs. This new formulation reduces the required simulation time by several orders of magnitude compared to the original spatiotemporal rate equations, and enables the implementation of the model in circuit simulation tools.

In this paper, we propose a Verilog-A [9] implementation of VISTAS in the simulation environment of Cadence. It is expected to enable system-oriented simulations and optimizations of entire optical links combining driver, VCSEL, waveguide, and detector.

The model is briefly introduced in section 2, and its implementation is described in section 3. Optimization results showing the benefit of driving the VCSELs with peaked signals are proposed in section 4, and a brief conclusion is given in section 5.

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TABLE 1 Rate Equations Parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_p$</td>
<td>photon lifetime</td>
<td>2–2.2 ps</td>
</tr>
<tr>
<td>$\tau_N$</td>
<td>carrier lifetime</td>
<td>2.5 ns</td>
</tr>
<tr>
<td>$\beta_m$</td>
<td>spontaneous recombination coefficient</td>
<td>$3 \cdot 10^{-5} - 10^{-4}$</td>
</tr>
<tr>
<td>$\eta_s$</td>
<td>current injection efficiency</td>
<td>1</td>
</tr>
<tr>
<td>$D_N$</td>
<td>ambipolar diffusion coefficient</td>
<td>15 cm$^2$/s</td>
</tr>
<tr>
<td>$N_{tr}$</td>
<td>transparency carrier density</td>
<td>1.85 $\cdot 10^{10}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$\alpha_o$</td>
<td>linear gain coefficient</td>
<td>4.5 $\cdot 10^{-16}$ cm$^2$/s</td>
</tr>
<tr>
<td>$v_s$</td>
<td>group velocity</td>
<td>7.14 $\cdot 10^5$ cm/s</td>
</tr>
<tr>
<td>$\varepsilon_m$</td>
<td>gain compression factor</td>
<td>5 $\cdot 10^{-17}$ cm$^3$</td>
</tr>
<tr>
<td>$V_m$</td>
<td>optical confinement factor</td>
<td>3–4%</td>
</tr>
<tr>
<td>$d_w$</td>
<td>single quantum well thickness</td>
<td>8 nm</td>
</tr>
<tr>
<td>$n_w$</td>
<td>number of quantum wells</td>
<td>3</td>
</tr>
<tr>
<td>$R$</td>
<td>cavity radius</td>
<td>8 $\mu$m</td>
</tr>
<tr>
<td>$R_{ovs}$</td>
<td>oxide aperture radius</td>
<td>2.25 $\mu$m</td>
</tr>
</tbody>
</table>

2. MODEL

The well-known rate equations are ideally suited for computing the time response of laser diodes. They consist of two coupled nonlinear differential equations, one for the carrier density $N$ and one for the photon density $S$. In order to describe the interactions between the inhomogeneous transverse distributions of carriers and optical field in the cavity (see Fig. 1), often referred to as spatial hole burning (SHB), the carrier and photon densities must be rewritten in the form of spatiotemporal functions in the active area:

\[
S_m(r, t) = S_{m0}(t)|\psi_{m0}(\rho)|^2 \cos^2(\varphi) + S_{m1}(t)|\psi_{m1}(\rho)|^2 \sin^2(\varphi).
\]

In this case, the VCSEL can be approximated by a step-index weakly guiding cylindrical waveguide, and the field distribution can be calculated as in [17]. However, any normalized mode profile $|\psi_m(\rho)|^2$, either calculated or measured, can be used as well.

No such natural separation exists for the carrier distribution in the active layer. The variables are therefore separated by expansion of the carrier density multiplied by the ambipolar diffusion coefficient $D_N \nabla^2 N(r, t)$, which yields the general formulation of the spatially-dependent rate equations:

\[
\begin{align*}
\frac{dN(r, t)}{dt} &= \frac{\eta_s(r, t)}{eV} - \frac{N(r, t)}{\tau_N} + D_N \nabla^2 N(r, t) - v_s \sum_m G_m(r, t)S_m(t) \\
\frac{dS_m(t)}{dt} &= \frac{\Gamma_m}{\pi R^2} \int_0^R \int_{\varphi_0}^{\varphi_1} G_m(r, t) dr d\varphi - \frac{S_m(t)}{\tau_m} + \frac{\sum_{j=0}^{\infty} N_{trj}(t) \cos(q\varphi) + N_{trj}(t) \sin(q\varphi)}{\gamma^2}\Gamma_m \beta_m \frac{\int N(r, t) dr}{\pi R^2} \frac{\int G_m(r, t) dr}{\pi R^2} \frac{\sum_{j=0}^{\infty} N_{trj}(t) \cos(q\varphi) + N_{trj}(t) \sin(q\varphi)}{\gamma^2}.
\end{align*}
\]

where the index $m$ indicates the optical mode. The other parameters are listed in Table 1. The local material gain $G_m$ “seen” by the $m^{th}$ mode can be approximated as a linear function of the carrier density:

\[
G_m(r, t) = \frac{N(r, t) - N_{tr}}{1 + \varepsilon_m S_m(t)} |\psi_m(\rho)|^2.
\]

Such extended rate equations have already been extensively used for simulation of various dynamic effects in VCSEL cavities, such as transverse mode competition [10], mode partition noise [11], modulation response [12], harmonic distortions [13], external reflections [14], or polarization dynamics [15]. However, solving these equations is numerically inefficient, due to the need for spatial discretization in the plane of the active layer. Nevertheless, applying a series of mathematical transformations based on the physical and geometrical properties of circular oxide-confined VCSELs allows reformulation of the rate equations of Eq. (1) into a system better suited for fast numerical computations.

The main idea behind the model’s transformation consists in separating the time and space variables. The large refractive index difference between the oxide and surrounding layers provides the dominant field confinement mechanism of oxide VCSELs [16]. This allows the photon rate equations to be written as the product of the modal photon densities (proportional to the mode intensity) and a normalized time-independent field profile (in polar coordinates $r = (\rho, \varphi)$ for generic cylindrical VCSEL structures):

\[
S_m(r, \varphi, t) = S_{m0}(t)|\psi_{m0}(\rho)|^2 \cos^2(\varphi) + S_{m1}(t)|\psi_{m1}(\rho)|^2 \sin^2(\varphi).
\]

In this case, the VCSEL can be approximated by a step-index weakly guiding cylindrical waveguide, and the field distribution can be calculated as in [17]. However, any normalized mode profile $|\psi_m(\rho)|^2$, either calculated or measured, can be used as well.

No such natural separation exists for the carrier distribution in the active layer. The variables are therefore separated by expansion of the carrier density $N(\rho, \varphi, t)$ in a Bessel series along the radial direction [18], and then in a Fourier series along the azimuthal direction [17]:

\[
N(\rho, \varphi, t) = \sum_{j=0}^{\infty} N_{j0}(t) \cos(j\varphi) + N_{j1}(t) \sin(j\varphi).
\]

Making use of the orthogonality properties of both series, Eq. (1) can be transformed into a modified system, which only consists of ordinary differential equations (odes) and basic algebraic operations, instead of partial differential equations, as illustrated in Eq. (5):

\[
\begin{align*}
\frac{dN_{j0}(t)}{dt} &= \cdots + \sum_i d_i N_{ji} \\
\frac{dN_{j1}(t)}{dt} &= \cdots \\
\frac{dS_{j0}(t)}{dt} &= \cdots + \frac{\sum_i N_{ji}(t) \cos(q\varphi) + N_{ji}(t) \sin(q\varphi)}{\gamma^2} \\
\frac{dS_{j1}(t)}{dt} &= \cdots + \frac{1}{2} \frac{N_{ji}(t) \cos(q\varphi) + N_{ji}(t) \sin(q\varphi)}{1 + \varepsilon_m S_m(t)} S_m.
\end{align*}
\]
It is evident in Eq. (5) that any explicit spatial dependency has disappeared from the modified system. There is therefore no need to discretize the plane of the active layers, and the odes that form the modified model can be solved using efficient numerical algorithms, such as Runge–Kutta with adaptive time steps [19]. Furthermore, radically new methods for computing static VCSEL responses could be derived based on the model’s reformulation in the form of ordinary differential equations [20]. Finally, this specific formulation allows the implementation of the modified model in standard electronic circuit simulation tools. The price to pay for such simplification is an increased number of equations, but the modified model still shows a massive reduction (of several orders of magnitude) of the computation time required to solve a given problem, without any noticeable diminution of the accuracy.

Figure 2 shows that the fundamental capability of the model consists in generating complex multimode time-domain responses and corresponding intensity profiles. Although the total optical response (dotted line) to a square current pulse shows the expected behavior with damped oscillations, the individual modal responses exhibit complex transient behaviors, which are governed by SHB and carrier diffusion. The model is capable of generating eye diagrams, as well as small signal and steady-state responses. The exact equations and their detailed derivation can be found in [21].

The model can readily be extended with a variety of additional effects that affect the performance of optical links, such as electrical parasitics, noise, feedback, or thermal effects [7]. This modified model builds the core of the simulation package VISTAS used in this paper. It is available free of charge in the form of Matlab m-files [8].

3. IMPLEMENTATION

An equivalent circuit model of Eq. (5) would be rather cumbersome and inflexible. For that reason, the hardware description language Verilog-A [9], which allows a description of the analog behavior of devices in standard circuit simulators, has been preferred for the implementation of the model in Cadence. Although Verilog-A does not yet provide matrix operations and other features of common high level languages (for example, self-defined types), an implementation of the model has been possible.

The modified model consists of ordinary receivers of the injected current as the input and provides the photon density in each mode as the output, as shown in Figure 3. The time-dependent carrier density reaches values in a range from 0 to \(10^{20} \text{cm}^{-3}\) and the photon density varies typically from 0 to \(10^{18} \text{cm}^{-3}\). To implement the modified rate equations, they must be adapted, because typical circuit simulators can only work with currents and voltages. Carrier and photon densities are therefore modelled as voltages. Another restriction of circuit simulators relies upon the fact that circuit simulators have limited signal range and accuracy. The input and output signals should have comparable values (as do conventional signals in circuits). For those reasons, the carrier and photon density have been normalized after \(N^s = \eta_N \cdot N\) and \(P^s = \eta_P \cdot P = \eta_P \cdot k \cdot S \cdot N^s\) and \(P^o\) are the normalized carrier density and output optical power, respectively. They are given in volts. The coefficients \(\eta_N = 10^{-21} \text{cm}^3 \text{V}\) and \(\eta_P = 10^{-3} \text{V/W}\) are the normalization factors, and \(k\) is the power conversion coefficient that relates the photon density in the cavity to the output power (in mW).

The implementation is divided into two parts, as shown in the flowchart of Figure 4. The initial step contains all time-independent calculations. The cavity modes are computed after the weakly-guiding, step-index approximation for the VCSEL. The resulting eigenvalue equation [22] is solved using a secant method [19]. The \(n^{th}\)-order Bessel functions of the first kind \(J_n\) are approximated by polynomials. The higher-order functions \(J_n\) are calculated recursively from the lower-order Bessel functions [19]. The Bessel functions of the second kind \(K_n\) needed for the mode distribution, can be expressed in terms of the Bessel functions of the first kind. Integrals describing the overlap between the various Bessel functions and mode profiles need be calculated in the initial step as well [7]. A trapezoidal rule has been implemented for that purpose.

![Figure 2](image2.png)  
**Figure 2**: Simulated optical response to a rectangular current pulse applied between \(t = 0\) and \(t = 2.5\) ns. The near-field intensity pattern consists of 12 modes.

![Figure 3](image3.png)  
**Figure 3**: Interface of spatially-independent VCSEL model. \(INp\) is input signal (input current), \(INn\) and \(OUT_p\), are output current and optical output power signals, respectively. \(OUT_{opt}\) is given in volts to simplify further processing.

![Figure 4](image4.png)  
**Figure 4**: Flow chart illustrating the program sequence. Implementation is divided into two steps: first, all time-independent coefficients are calculated; then the odes are solved by discrete time integration.
In the simulation step the odes are solved in the time domain. With the Verilog-A built-in integration method [9], severe problems arise in transient simulations because the simulator decreases the time step in such a way that a short transient simulation will require several days. The use of discrete time integration with fixed timestep combined with Verilog-A timer events ensures the convergence of the simulator, without the need for changing its settings. Thus, other models (typically transistor models) employed in the same simulation are not affected. All algorithms are optimized for Verilog-A and therefore achieve relatively short simulation times with respect to the complexity of the spatiotemporal model. Simulating a 10-ns response requires approximately 1 s of CPU time for a single-mode laser, 1 min for a multimode 1D (doughnut-shaped modes) cavity, and 1 h for a very complex 2D case with 12 modes.

The Verilog-A source files are available free of charge on the Internet [8].

4. DRIVE SIGNAL OPTIMIZATION

As an illustration, we present a simulation of the implemented VCSEL model together with parasitics and the macro-model of a driver circuit built with ideal components. The high-frequency behavior of VCSELs is significantly affected by electrical parasitic, such as the oxide or depletion-layer capacitances, or the series resistance built by the Bragg reflectors. The package introduces additional parasitics that must be taken into account for system level simulations. Figure 5 schematically shows the parasitics of the intrinsic VCSEL, their physical origin, and the equivalent circuit used for the simulations. Since high-speed digital modulation requires the above threshold bias, the carrier-density-dependent voltage drop over the laser diode can be considered as constant (approximately clamped carrier density above threshold).

Current peaking is an appealing solution for improving the large signal response of laser diodes [3]. The concept and the parameters to be optimized are described in Figure 6. The role of the first peak applied during both turn-on and turn-off is to charge or discharge the parasitic capacitances faster, whereas the second peak is supposed to help dampen the relaxation oscillations. A maximization of the eye opening has been introduced, based on the built-in optimizer of Cadence. Figure 7 shows the eye-patterns at 10 Gb/s obtained with the rectangular (left) and peaked (right) drive signal. The eyes consist in the superposition of 1000 bit periods (100 ns), which improves the already high numerical efficiency of the model. The eye pattern obtained with the optimized current-peak scheme clearly shows a much wider eye opening than the one obtained with the standard rectangular drive signal. Current peaking clearly allows modulating VCSELs at much higher frequencies without the need for smaller parasitics.

Although the above simulation only took a simple driver model into account, it can be replaced with a transistor circuit in a next step of the system design. Furthermore, the spatiotemporal nature of the employed model allows for the simulation of effects related to improper waveguide coupling after far-field transformation of the optical intensity profile [23]. VISTAS is therefore an ideal candidate for building the core of a future system-oriented simulation and optimization tool for complete optical links.

5. CONCLUSION

The implementation in Verilog-A of a VCSEL model that provides information about the multimode spatiotemporal evolution of the laser output has been presented. The model takes into account effects related to SHB and carrier diffusion. It can be used in a circuit simulator together with other models, such as transistor circuits of the laser driver. The interactions between the different elements of complex hybrid systems can therefore be taken into account in simulations. Preliminary results indicating the positive influence of a peaked current drive scheme on the opening of eye diagrams were shown. The parameters have been optimized using the built-in optimizer of Cadence. This implementation represents the first step towards a system-oriented tool for simulation and optimization of entire optical links, including driver, detector, waveguide, and VCSEL.

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REFERENCES

USE OF B-SPLINE CURVES AND GENETIC ALGORITHMS TO REDUCE THE SIDELOBE LEVEL IN ARRAY-PATTERNS

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ABSTRACT: A method of minimizing the sidelobe level for linear array patterns by amplitude-only adjustment in element excitations, which involves combining B-spline techniques and genetic algorithms, is considered. We demonstrate this technique using a 30-element linear array. It is also capable of limiting the coupling effects between adjacent elements. © 2003 Wiley Periodicals, Inc.

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Key words: B-spline curve; genetic algorithms; sidelobe level

INTRODUCTION

It is well known that in synthesizing an array pattern, the main concern is to find an appropriate set of amplitude and phase weights that will yield the desired far-field pattern. Usually, to reduce interference effects and avoid power waste, low sidelobe levels for the array power pattern are required, and this can be achieved through amplitude-only adjustment, generally by amplitude tapering. Design procedures for minimizing the sidelobe level by adjusting a small number of elements based on genetic algorithms have been discussed in the literature [1, 2]. However, with this partial adjustment, other feasible or even better solutions may be overlooked. In this paper, we tackle the task by searching for a few element excitations, but in doing so, we actually adjust all the excitations by combining genetic algorithms and B-spline techniques. A quasi-optimal B-spline curve is created by genetic algorithms, is considered. We demonstrate this technique using a 30-element linear array. It is also capable of limiting the coupling effects between adjacent elements. © 2003 Wiley Periodicals, Inc.

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