A circuit-level simulation approach to analyse system level behaviour of VCSEL-based optical interconnects

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ABSTRACT

In order to satisfy the increasing demand for interchip interconnect bandwidth, a number of current research projects are concentrating on the use of waveguided optical interconnect arrays to span PCB-range distances. To accelerate system design and technology development, CAD tools for the design and the simulation of the interconnects are indispensable. We are developing a design methodology for optical inter-chip interconnects, to produce a tool for assisting system designers on deciding on product and parameter options for the different interconnect building blocks. A mandatory first step in this methodology development concerns the investigation of the combined impact of individual product and parameter variations on system-level interconnect system properties. Accurately predicting some interconnect properties requires analog simulation of the full electrical-optical-electrical links. Detailed models for the link building blocks involving geometrical calculations are much too slow for this purpose. Circuit-level simulation tools, with appropriate model descriptions, are much more suitable. In this paper, we describe our framework for the joint simulation of the entire optical interconnect with a mixed analog/digital system. We discuss in detail a number of issues that are involved with the implementation of circuit-level simulation models in the analog modelling language Verilog-AMS, and show a link simulation example.

Keywords: optical interconnects, design methodology, circuit-level simulation, VCSEL, Verilog-AMS

1. INTRODUCTION

1.1. Optical Interconnections

Technological development is pushing chip performances higher every day. Feature sizes are decreasing, while chip size and data rates continue to rise. However, optimal exploitation of this increasing number of faster devices per chip is often hampered by too slow a communication rate between interconnected integrated circuits.[1] The problem has already become a critical bottleneck in some applications with very intensive data traffic, and is expected to proliferate into more mainstream designs as well in the coming years.[2] Examples of such applications include IP-routers,[3] parallel computing systems, image processing applications and very large databases.[4]

In order to satisfy this increasing demand for interconnect bandwidth at the PCB level, optical solutions are being widely investigated.[2] Although electrical workaround solutions like thicker wires,[5] wire inductance,[6] low voltage swing[7] and differential signaling[8] may stretch the applicability of electrical interconnects, optics offer the true physical means to avoid the fundamental problems of electrical interconnects.[1,9]

Indeed, photonic links fundamentally provide low-power high-bandwidth interconnect and do not suffer from electromagnetical interference, alleviating the crosstalk problem. Furthermore, they have potential to scale with future generations of silicon IC's. Other benefits include an end-to-end electrical isolation and less weight and size compared to dense electrical interconnects.[1,9] This simplifies system integration and overall design and can lead to benefits on an architectural level.[10]

The technology of the building blocks of optical interconnects has made immense progress over the past decade, especially in the area of Vertical Cavity Surface-Emitting Laser (VCSEL) fabrication; photodetectors, optical waveguides and interface circuitry have become much more mature as well.

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During the past few years, much focus has been put on the use of parallel optical interconnects, i.e. transceivers consisting of 2D arrays of VCSELs, optical waveguides and photodetectors.[3,4,11] Besides waveguided optical links, free-space optical interconnects (FSOI) are getting much attention as well. In case of parallel interconnects, the main problem associated with FSOI is that the maximal allowable misalignment between the source and detector arrays is only feasible if the distance between sources and detectors is rather small compared to the source and detector pitch. When this distance becomes relatively large—as with the aforementioned applications—this leads to a complex mechanical system design. In this paper, we will therefore only discuss waveguided links.

Despite the fast technological progress on waveguided optical interconnects, other issues remain to be (and are being) investigated. Amongst these is the development of a systematic design methodology for designing parallel optical interconnects, which we will concentrate on in this paper.

1.2. Design Space Exploration

When an optical interconnect system is being conceived for a particular application, the designer gets confronted with a large number of options. The main categories in which decisions have to be taken include:

- VCSEL and photodetector device technology family
- CMOS integration technique of the electro-optical devices
- interface circuits for the electro-optical devices
- digital encoding and clock recovery systems
- waveguide technology (ribbons, flexes, glass sheets...)
- chip packaging technology for the optical interface

Between different categories, decisions can most certainly not be taken independently. First of all, opting to use one technology for a certain part of the interconnect system reduces the number of feasible options for another part of the design. A very obvious example is when the designer decides on a VCSEL technology that yields devices operating at a certain wavelength. This introduces restrictions as the photodetector and waveguide system choice have to be tuned to this wavelength.

Secondly, there are certain trade-offs to be made in choosing some parameters. For instance, increasing the numerical aperture (NA) of an optical fiber will improve the VCSEL-fiber coupling efficiency, but at the same time the fiber-detector efficiency will decrease. Whether this will increase or decrease cross-talk between different channels is not easy to predict!

We can say that exploring the design space and making the right choices is not a simple task. As with normal electrical designs, CAD simulation and design tools can greatly simplify this exploration by avoiding costly and time-consuming fabrication and testing cycles and by correctly predicting system-level link properties when changing component parameters or component technologies.

1.3. Design Methodology Development

Our eventual target is the development of a design metholodogy for optical links, the result of which should be formalized into a design tool. When the designer states his interconnect requirements, this design environment should assist him in making decisions on product and parameter choices. To achieve this goal, we have set up a methodology development program comprising three stages (figure 1):

1. To begin with, the combined impact of individual link building block variations on the properties of the complete interconnect system is investigated. This comprises the development of tools to predict how system-level link properties will change when certain parameters are adapted.

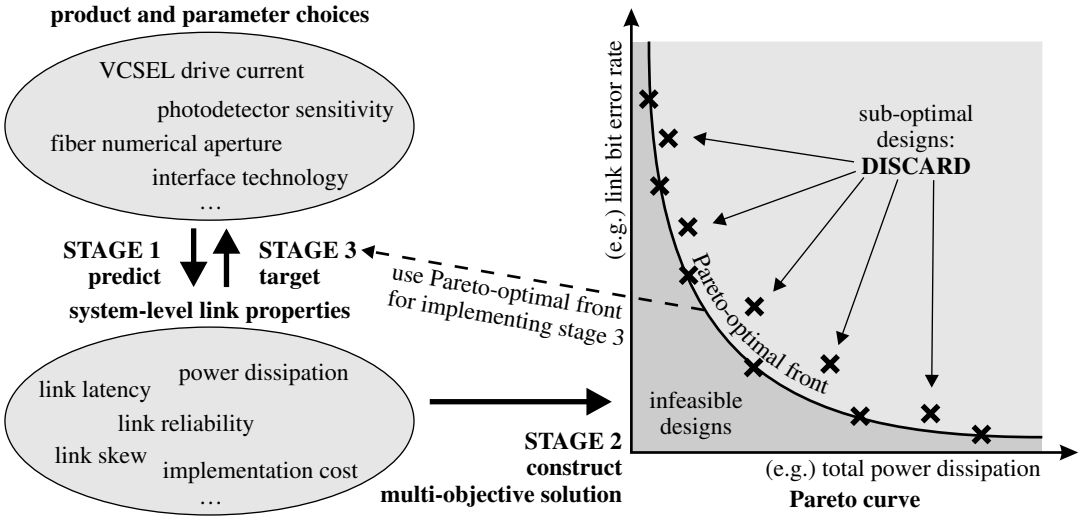

Figure 1: Design methodology development in three stages.

2. In a second stage, the design space of optical links is searched for the combinations that optimize a set of important objectives (power consumption, skew,…), and the Pareto-optimal front is constructed, i.e., we discard combinations that are uniformly worse than others.[12] Essentially, this front will contain a multi-objective solution for optical links, where no objective can be improved without making some other objective worse. The Pareto plot on figure 1 illustrates this with a tradeoff between power consumption and link bit error rate.

3. In a third stage, using this front data, a design tool is developed that helps the system designer choose a feasible tradeoff between link properties, i.e., given certain total performance requirements, it predicts optimal choices for link building blocks and values for their design parameters.

Currently, we are implementing stage 1: predicting link properties given a combination of link building blocks, the design parameters of which (e.g. VCSEL technology, driver bias current or fiber numerical aperture) are fixed.

In this paper, we report about our progress implementing stage 1. To this end, in section 2 we describe a simulation framework that can be used to extract link properties: it enables the joint simulation of an entire optical interconnect system with a mixed analog/digital design. We first describe how the simulation framework has been conceived and integrated into Cadence. Thereafter, a number of issues that are involved with the implementation of circuit-level simulation models in the analog modelling language Verilog-AMS are discussed in detail. In section 3, we demonstrate the operation of our models with the simulation of a digital-optical-digital interconnection. Finally, in the next section we discuss future work, and we summarize our findings in section 5.

2. SIMULATION FRAMEWORK

2.1. Simulator Choice

The ability to assist people in making the right design choices requires a prediction capability on the effect of different design alternatives on important system-level characteristics such as reliability, technological interoperability, overall delay, power consumption, etc. A number of issues arise with this task:

Firstly, individual component parameters will not only determine this component's performance, but can also influence the performance of other components. This can result in a complex relation between individual component parameters and total link performance. For example, signal attenuation in the optical path and cross-talk at interface points will have a significant impact on the receiver latency, and is subject to statistical variations due to waveguide misalignment.

Secondly, activities in the electrical and optical domains are dynamically interdependent. For example, internal VCSEL behaviour is associated with complex rate equations, yielding dynamic electrical, optical (and thermal) behaviour which is not separable into isolated different domains.

definition of pin signals

model parameter definition

behaviour description

```
module capacitor(p,n);
    inout p,n;
    electrical p,n;

    parameter real c=0;

    analog begin
        I(p,n) <+ C*ddt(V(p,n));
    end
endmodule
```

```
module pin_photodiode(in,anode,cathode);
    input in;
    inout anode, cathode;
    power in;
    electrical anode, cathode;

    parameter real Cdep=0, Cbo=0, Rbas=0, Resp=0, Id=0;

    parameter real pole=-1/(Cdep*Rbas);
    parameter real laplace_coeff_0=Cdep+Cbo;
    parameter real laplace_coeff_1=Cdep*Cbo*Rbas;
    charge rc;

    analog begin
        I(cathode,anode) <+ laplace_zp(Resp*Pwr(in)+Id,
            {},{pole,0});
        Q(rc) <+ laplace_np(V(cathode,anode),
            {laplace_coeff_0,laplace_coeff_1},{pole,0});
        $pwr(V(anode,cathode)*I(anode,cathode)+Pwr(in));
    end
endmodule
```

Figure 2. Example Verilog-AMS models of a capacitor and a PIN photodetector. The parameters that are equated to zero are overridden on another level, by the netlist files from which the model is instantiated.

The first issue implies that total link performance cannot be extracted from detailed individual component-by-component simulations, as they do not account for mutual component interactions and dynamic noise effects. Often, simulations of a complete optical link or even the entire design are needed. The second issue implies the need for concurrent simulation of electrical and optical signals to take electro-optical interactions into account.

Because of these issues, we have been working towards a solution that can jointly simulate an electrical design with an optical interconnect system. It is not only our purpose to use it as an optical link system characterization utility, but also, in a later design stage, to simulate a completed design with optical interconnects to verify correct behaviour.

Given the plethora of existing circuit-level simulators, we chose to extend an existing simulator instead of developing our own from scratch. Detailed physical models exist for the optical, optoelectronic and electronic components—often making extensive use of geometrical calculations—yielding very accurate results. However, they are much too slow for time-domain simulations. Circuit-level simulation tools, supplied with appropriate model descriptions, provide adequate precision with much less computing power.[13]

The most common package for circuit-level simulation is undoubtedly Berkeley SPICE.[14] However, we chose to use a more recent environment that allows for the direct expression of differential equations, and which natively supports the notion of signal disciplines, i.e. it supports signals in the optical and thermal domains.

We chose to describe link elements using behavioural models implemented in the industry-standard Verilog-AMS language, and to simulate them with the Cadence Spectre simulator. VHDL-AMS would also have been feasible, and we plan to port our framework to that language as well in the near future.

The integration with Cadence has several advantages: Spectre can be used in a mixed-signal configuration to co-simulate the optical interconnect within a digital system. This allows for the direct verification of interconnected complex digital designs without having to fall back to slow analog simulation of *all* digital cells. Furthermore, our setup enables easy switching between process corner simulations and statistical simulations, in much the same way as is done with some standard-cell design kits (more on this in subsection 2.4).

2.2. Behavioural Modelling

In order to be able to simulate optical interconnects, we need behavioural models describing the different link building blocks. These should be Verilog-AMS files that describe their input signals, their output signals and the relation between

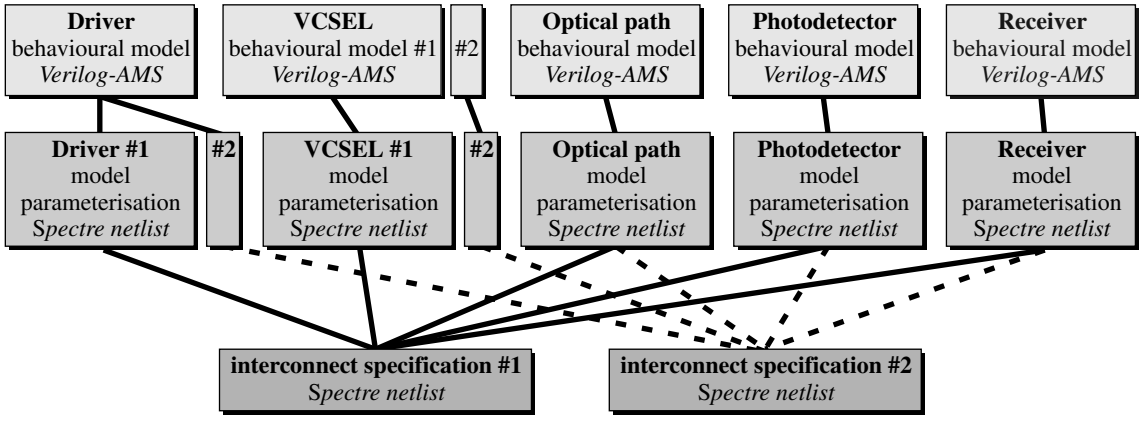

Figure 3: Organisation of simulation models, model parameters and simulator configurations in three levels of hierarchy.

both (the behaviour). The relations can be directly represented as a set of differential equations, or by an equivalent description like Laplace transforms. Verilog-AMS models describing a capacitor and relatively simple photodetector behaviour can be found in figure 2.

We made an effort to make the model files as independent as possible of variations within a category of link building blocks. This is done by incorporating symbolic parameters in the model descriptions. When simulating, we include a Spectre file with the generated netlist, which specifies a suitable instantiation of these parameters. For example, one can say that all VCSELs can be described by the same set of equations: the VCSEL rate equation.[15] Differences between VCSEL products are caused by different technology or production parameters (material technology, cavity properties, gain, etc.). This yields different constants for the rate equations, which we collect into a product-specific set of parameters.

To put model and parameter separation into effect, we have organised our data in three levels of hierarchy (figure 3). On the top level, behavioural models for the different link building blocks can be found. Note that we implement a model for each different kind of behaviour, not only for different kinds of link functions. For instance, VCSELs or LEDS are both light sources, but display very different behaviour. Therefore, if we would want to simulate a LED-based link, we will need a Verilog-AMS model dedicated to LEDs.

On the middle level, Spectre netlist files exist, each of which contains parameter instantiations for a higer-level behavioural model, in order to completely describe a specific product. It is still possible that such a netlist file introduces a symbolic parameter, for instance if some device part is tunable (e.g. fiber length).

The bottom level consists of netlist files that are used for instantiating a collection of netlist descriptions from the middle level, in order to fix the entire interconnect behaviour. Also, device parameters from the middle level are fixed here. When configuring Spectre, only one bottom-level file needs to be included to describe the optical interconnect behaviour to the simulator.

The development of models consists of two stages. Firstly, models for the different link building blocks are searched in literature or developed, and implemented in Verilog-AMS. Thereafter, the model parameters are fitted to measured data.

2.3. Model Implementations

In this subsection, we discuss the development of behavioural models of each link building block and their implementation in Verilog-AMS.

Driver and receiver circuitry VCSEL driver circuits and photodetector receiver circuits are ‘normal’ analog designs, whose inner workings can be natively simulated. However, their analog schematics are normally not available, as circuit design corporations want to protect their intellectual property.

The best alternative is to get a description at one level coarser: the circuits are then not described on the gate level, but by a parameterised flowchart (figure 4). In this flowchart, the different blocks represent circuit subparts that can be described

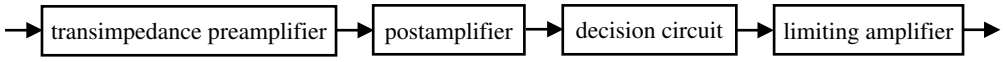

Figure 4: Flowchart of the main building blocks of a receiver circuit.

by equations, the complexity of which is just as coarse as necessary to not reveal the exact circuit design, but at the same time detailed enough for a reliable link simulation. For instance, we are unable to figure out the exact constitution of a receiver preamplifier from its description, but important effects like the impact of supply voltage noise remain incorporated.

Vertical Cavity Surface-Emitting Laser The optical operation of a VCSEL can be described by *rate equations* that describe the time evolution of the carrier (N) and photon (S_k) densities in the cavity.[13,15] Formula 1 shows the spatially-dependent rate equations; for an explanation of the different parameters we choose to refer to Moriki, et. al.,[15] as explaining them here would lead us too far.

$$\begin{cases} \frac{\partial N(r,t)}{\partial t} = -\frac{N(r,t)}{\tau_N} - \nu_g g_0 \sum_k \frac{N(r,t)-N_{tr}}{1+\varepsilon S_k(r,t)} S_k(r,t) + D\nabla^2 N(r,t) + \frac{\eta_{inj} I(r,t)}{qV} \\ \frac{\partial S_k(r,t)}{\partial t} = -\frac{S_k(r,t)}{\tau_S} + \Gamma \nu_g g_0 \frac{N(r,t)-N_{tr}}{1+\varepsilon S_k(r,t)} S_k(r,t) + \beta \frac{N(r,t)}{\tau_N} \end{cases} \tag{1}$$

Solving these spatially-dependent equations requires finite-element methods, which are much too slow for a circuit-level simulation. Luckily, the spatial dependence can be removed by making use of assumed mode profiles for the photon densities.[16,17] This yields more equations, but with the removal of the spatial dependencies, simulations can be performed several magnitudes faster.

We opted to use the comprehensive circuit-level VCSEL model by Mena et al.,[13] a multimode VCSEL model that takes important effects into account, such as thermal behaviour, spatial hole burning and carrier diffusion. Although the implementation in Verilog-AMS seemed rather straightforward given the differential equations, we encountered multiple problems:

First of all, directly solving the rate equations for steady state behaviour yields multiple solutions (figure 5). This presents a problem, since it makes the transient simulator fail at finding an initial operating point. Luckily, the suggestion[13] to replace every positive-valued quantity by the squared sum of a new quantity with a constant, helped to alleviate this problem. However, the Newton-Rhapson method used by Spectre to compute the initial operating point still failed for driving currents well above threshold. This could be solved by providing an initial guess for all quantities, consisting of the steady-state values that they assume when the VCSEL is operated around the threshold current.

Secondly, some quantities that appear in the rate equations give rise to very large values, causing Spectre to panic during simulation, even if we configured it to accept high values for the datatypes holding N and S. This was resolved by rescaling all quantities to magnitudes that are common to voltages and currents.

Thirdly, Verilog-AMS—as well as VHDL-AMS—does not allow to directly equate the time derivative of a quantity to some formula, as is done in the (transformed) rate equations; one can only put untransformed quantities into the left-hand side of the differential equation. Integration of the right-hand side did also not help here, as this attacked the convergence properties of the simulator. To resolve this problem, we implemented a workaround solution also applied by Morikuni et al.[18]: the basic idea is that no current can flow through a branch with only one node. Solving rate-equations in Verilog-AMS is then achieved by equating the difference of the right-hand side and the left-hand side of the rate-equation to this zero current.

In contrast with optical VCSEL behaviour, an electrical model is much easier to set up: a custom $U(I)$ formula with additional input capacitance is often accurate enough.

Once the Verilog-AMS implementation was done, we have been trying to fit the VCSEL model parameters to some measured VCSEL data, which was not an easy task. We discuss this in more detail in section 4.

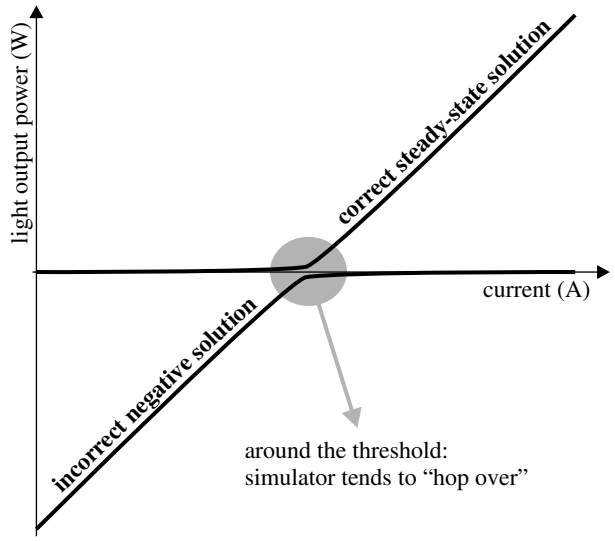

Figure 5. Two solutions to the steady-state VCSEL rate equations. The wrong solution can confuse the initial operating point estimation if appropriate measures are not taken.

PIN photodiode The electrical part of the photodiode is modelled by a simple circuit model. It jointly includes the extrinsic and the intrinsic delays by adding a serial output resistance and parallel output capacitance to a variable current source carrying the output current I_{out}. The relation between I_{out} and the incident optical power $P_{optical,in}$ is defined by

$$I_{out} = I_{dark} + \Re \cdot P_{optical,in} \tag{2}$$

where $\Re$ is the responsitivity and I_{dark} the dark current of the photodiode.

Optical path For the optical path, we currently focus on plastic optical fibers (POFs), which offer an optical path technology well suited for interconnects at the PCB level, because of their small bending radius. In this technology, for the purpose of creating a behavioural model, the optical path can be divided into subparts that belong to one of two categories:

- uninterrupted fiber runs
- POF-to-something interfaces: VCSEL-to-POF, POF-to-POF *(connectors)*, and POF-to-photodetector

Simply put, the behaviour of the optical path can be characterised by two effects: losses and crosstalk. Losses occur at each interface point and over each fiber run, and can be modelled by multiplying the input light power by a constant between zero and one. Crosstalk foremostly originates at the interfaces, and can be implemented by contributing fractions of the incoming light at the interface point to adjacent fibers.

Sadly, some non-straightforward issues are involved here. For instance, the VCSEL-fiber coupling efficiency can dynamically change depending on the different mode excitations. Furthermore, coupling efficiencies are very much subject to statistical variations caused by misalignment and imperfections at the POF extremities. We are currently looking for options to tackle this issue.

2.4. Simulation Features

In a real-world manufacturing process, process parameters are subject to variations, i.e. they fluctuate, within feasible tolerances, around their ideal values. Important fluctuations include the photodiode dark current and responsitivity, the VCSEL threshold current and the misalignment of waveguides.

For optical links, the combined variation within the different link building blocks introduces some behavioural uncertainty for the whole interconnect. This is handled in two ways:

Process corner simulations A process corner simulation is a quick way to retrieve upper and lower boundaries for the effect of process parameter fluctuations on a given objective (delay, power, ...). In the different behavioural models, it is relatively easy to predict whether making some parameter larger than its designated value will make the overall result of an objective better or worse. For example, increasing a simulation parameter directly related to some real-life electrical capacitance will always yield a longer link delay, while decreasing a parameter directly corresponding to fiber absorption will shorten it. Note that we are really referring to *simulation parameters* here, not to *design parameters*, like a fiber numerical aperture. After all, a change to such a design parameter could affect multiple simulation model parameters, yielding an unpredictable cumulative effect.

To retrieve the *worst case* boundary for some objective, each model parameter receives the value for which 95% of the expected process fluctuations yield a better value with respect to that objective. (The *best case* boundary is attained in much the same way.) In order to provide an easy choice between best case, worst case and typical values for different objectives, our Spectre netlist files are constructed as netlist libraries consisting of multiple sections, each of which instantiates the behavioural model at hand with the desired parameter values. Given this setup, configuring the simulator for using the desired process corner becomes a trivial task.

Statistical simulations While process-corner simulations are relatively easy to implement and interpret, the resulting worst and best case boundaries are generally unduly loose, as the probability that all model parameters simultaneously take extreme values is very small. A statistically more founded approach is certainly desirable for the purpose of accurate characterisation of optical link properties.

To this end, we apply the approach taken in some standard-cell libraries, in which Monte-Carlo design simulations are possible that take process fluctuations into account. This is put into effect by specifying statistical distributions for the model parameters. Generally, a normal distribution is imposed with a mean parameter value and a standard deviation that takes fluctuations between different process runs into account. Furthermore, correlations between distributions of the same parameter for different model instances can be specified, in order to account for reduced fluctuations within one process run.

3. SIMULATIONS

Current framework status As mentioned above, in order to perform meaningful simulations of optical links, items need to be in place in two categories: behavioural models in Verilog-AMS format, and netlist files that instantiate the models with a set of parameters. The realisation of both categories requires different actions: for the model implementations, we need to translate the model description to Verilog-AMS code that the Spectre circuit simulator is willing to simulate. In the netlist files, we can instantiate the model with varying parameter values—to see the impact on the result—but if the model should correspond to a real-world component, we need to fit the parameters to measured data. This characterisation process not only needs to result in one value for each parameter, but statistical parameter variations are to be quantified as well.

So far, we have been able to realize the first category: implementing behavioural models in Verilog-AMS for regular variants of all link building blocks that constitute a VCSEL-based waveguided optical link. We plan to support models for some building block alternatives as well in the near future.

Work on the characterisation is currently in progress (see section 4). Therefore, we limit ourselves here to a demonstration of the operation of our framework by instantiating the model parameters with inferred mean values where available, and with values found in different papers otherwise. Specifically, the VCSEL model was instantiated with parameters based on the default data for two-mode VCSEL simulations that came with the model description,[13] and the optical path was configured for an aggregate optical path loss that is probable for a 90cm POF waveguide.

Transient simulation To illustrate the functioning of our simulation framework, we have set up a single digital-optical-digital link simulation. Figure 6 shows the electrical or optical signal at different locations alongside the links building blocks. We should remark that the applied default VCSEL model values and drive control yield a behaviour that oscillates much more than acceptable, but which is allright for demonstration purposes. Furthermore, note that the instantiated receiver model inverts the digital signal.

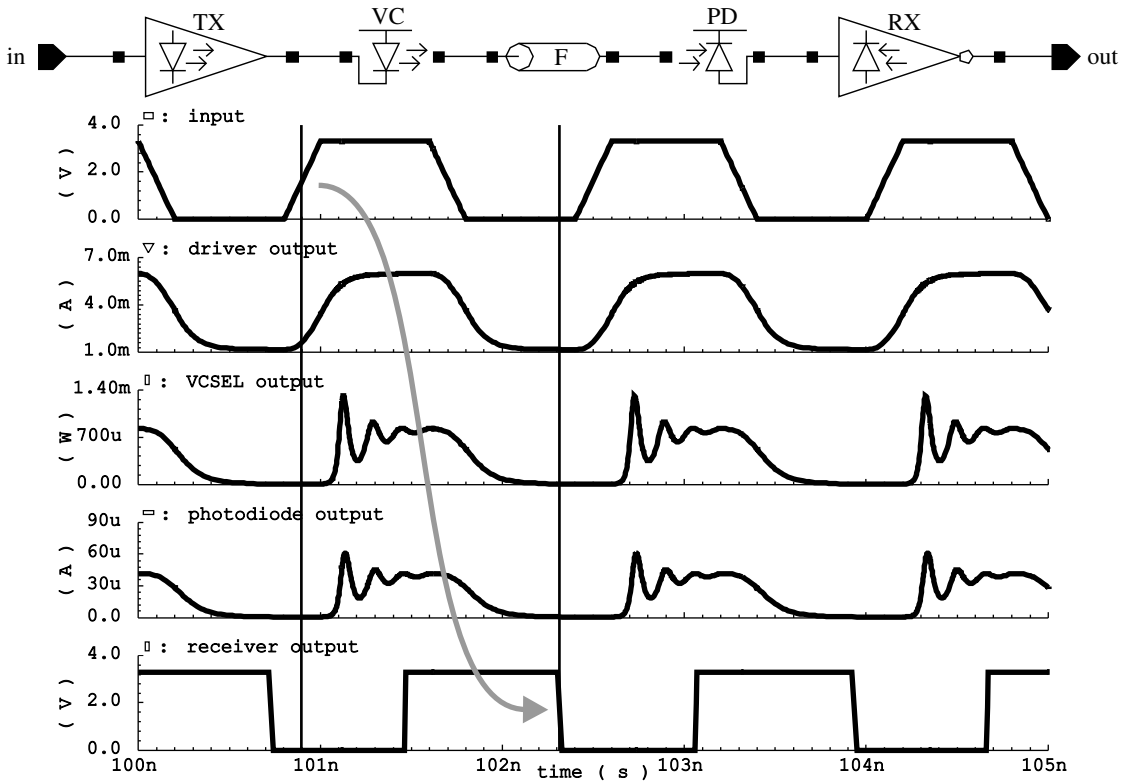

Figure 6. Sample setup of a transient simulation of an entire link. Note that the VCSEL model is instantiated with default parameters that give much worse results than a real device at this operating frequency should yield. Furthermore, we remark that the receiver is one of an inverting kind.

4. FUTURE WORK

VCSEL model and fiber coupling Using Matlab, we have written a tool to fit the parameters of the comprehensive VCSEL model of Mena[13] to measured data. The fitting process is based on two kinds of measurements:

- DC measurements, which yield the VCSEL light output power and the device voltage in function of the device current.
- S-parameter measurements, which can be transformed to describe, at a certain DC device current (the *bias*), how the incremental device impedance and the output light power respond to small current fluctuations at different frequencies.

The model parameters are fitted by a nonlinear multidimensional solver, which tries to minimize the least square error between the measurements and the model. While our current fitting effort accurately makes the model agree with real VCSEL DC measurements, the correspondence with the S-parameter curves is still less than satisfactory.

Recently, we came across some interesting current research work by Jungo at ETHZ that focuses on the characterisation and modelling of VCSELs.[19] While the rate equations that we currently implement only describe radial distributions of carriers and the optical field, his VCSEL modelling and simulation tool VISTAS supports azimuthal profile variations, allows to calculate VCSEL-fiber coupling efficiency, and takes VCSEL-specific noise effects into account.[20] We will look into VISTAS to use it for characterisation purposes, and port the applied model to Verilog-AMS.

Optical path models While the behavioural model for the optical path is relatively simple, the characterisation of attenuation and crosstalk is rather difficult. For each fiber section, next to fiber attenuation, we are confronted with different coupling losses (VCSEL-fiber, fiber-fiber and fiber-detector) and fiber bend losses that are difficult to quantify.

We have already received data on fiber bend losses which was retrieved using a ray-tracing program. This has resulted in a look-up table where the loss is listed in function of fiber NA and bending radius. This currently enables us to predict fiber loss of curved runs with moderate accuracy. We will attempt to follow the same approach for estimating crosstalk.

Thermal models Temperature is an aspect that greatly affects reliability of the optical link. For example, a drive circuitry array and VCSEL array dissipate relatively much power, but the operation of the VCSELs itself is quite temperature-sensitive. To take these effects into account, we will look for a way to integrate temperature calculation at the different temperature-sensitive devices given the power dissipations on the chip.

5. CONCLUSION

CAD tools for the design and the simulation of VCSEL-based waveguided optical interconnects are indispensable to accelerate system design and technology development of opto-electronic building blocks.

In order to construct a tool for assisting system designers to decide on product and parameter options for the different interconnect building blocks, we have started with the set-up of a design methodology for optical inter-chip interconnects. In the introduction, we identified three stages that are important in the development of this methodology. We henceforth kept our focus on the first stage: the implementation of a tool capable of predicting link properties given product and parameter choices for the link constituents.

In section 2, we described a simulation framework that can be used to extract these properties. We discussed in detail the framework design and the issues we have encountered while implementing behavioural models for the different link building blocks. We also discussed how the framework can support process-corner simulations and simulations taking statistical parameter fluctuations into account.

In section 3 a sample transient simulation illustrates the functioning of our implementation. Finally, section 4 discusses future issues that need to be resolved in order to enable an accurate link properties extraction.

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