Mixed-Technology System-Level Simulation

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ABSTRACT

We employ Modified Nodal Matrix representation, piecewise linear modeling of non-linear devices, and piecewise characterization of signals to accomplish the simulation of mixed technology systems. Piecewise simulation modeling for both optoelectronic and mechanical devices is used to decrease the computational task and allow for a trade-off between accuracy and speed. The extraction from device level simulation of circuit models, which characterize high level effects in optoelectronic or mechanical devices, allows for the inclusion of these effects into traditional circuit representations for the device. This technique improves the overall simulation accuracy without compromising the efficiency of the simulator. The additional advantage of using the same technique to characterize electrical and mechanical models allows us to easily merge both technologies in complex devices that interact in mixed domains.

Keywords: MEM, MOEMS, Mixed Technology, Piecewise Modeling, Simulation, Simulation Mixed Domains

1. INTRODUCTION

The need to support modeling of various technology domains in an OMEM (optical micro-electro-mechanical) design leads us to evaluate the impact of having heterogeneous signals in a common simulation framework. An OMEM design environment needs to support electronic, mechanical, and optical components at the very least, with the possibility of extensions to other domains, such as thermal, chemical, and RF. Not only do we have to characterize the sets of interactions between components of different technologies, we also have to consider the performance of the simulation environment, which depends on the simulation method and the type of signal characterization chosen.

We classify the signals in a "mixed signal" environment by whether their temporal behavior is continuous or discrete. Modules where analog effects must be analyzed to accurately model their characteristic behavior fall in the first category. Discrete signal modules where the behavior can be effectively characterized by a finite set of states fall in the second category. For instance, the electronic driver section in a laser array and the mechanical sub-system in a MEM device are typical examples of analog modules. On the other hand, digital electronic and control blocks in a system-on-a-chip (SOC) are examples of discrete signal modules.

It is also important to classify signals based on their relative frequency or rate of operation. This has a significant impact on the computational requirement for the simulation. In a common simulation environment, the high-speed signals will determine the degree of time granularity required for the simulator engine to characterize the dynamics of the system. And, the low-speed signals will determine the length of the simulation run required in order to observe the complete behavior of the system. In a mixed-technology OMEM system, it is common to find a difference of several orders of magnitude between the rates of high speed optical and slower mechanical signals.

Therefore, in order to effectively and efficiently model mixed signal systems there are two issues that must be decided. The first is the underlying model of simulation: continuous or discrete; and the second is the characterization of the information which must be carried between modules in the signals.

Our approach for simulation in a mixed signal environment has been implemented and is being tested on our mixed technology simulator *Chatoyant*. *Chatoyant* is a multi-level, multi-domain CAD tool that has been successfully used to design and simulate free space optoelectronic interconnect systems [1]-[5]. Static simulations analyze mechanical tolerancing, power loss, insertion loss, and crosstalk, while dynamic simulations are used to analyze data streams with techniques such as noise analysis and bit error rate (BER) calculation. Optical propagation models are based on two techniques: Gaussian and diffractive scalar. Gaussian models give fast and accurate results for macro-scale systems and systems that exhibit limited diffraction. Slower diffractive scalar models are used when diffraction effects dominate the system. A *4f*-optoelectronic link modeled in *Chatoyant* is shown in Figure 1. The center of the figure shows the system

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being modeled, a 3x3 VCSEL array propagating through a two-lens relay system to a 3x3-detector array. Across the top, we show the Gaussian beam profile of one beam of the array as it propagates through space. On the right, we show optical signals as they strike the detector array, while, on the bottom of the figure, we show a waveform and eye-diagram from one of the nine data channels. The details of these analyses can be found in [1]-[5].

Chatoyant is based on a methodology of system level architecture design. In this mixed-technology environment the system is decomposed into component modules that are individually characterized and joined together by the mutual exchange of information. This is in contrast to simulators based on potential/field gradients or finite element analysis. The nature of the information carried in the signals is a function of the components themselves: optical, electrical, mechanical, etc. An object-oriented framework, Ptolemy [6] is used to provide this degree of abstraction for the simulation of such systems.

The actual approach for our modeling of mixed signal multi-domain systems is a discrete event driven simulation model, which operates over the global system. We choose the "Dynamic Data Flow" (DDF) Ptolemy simulation method as our discrete event engine. Timing information is added to support multiple and run-time-rate variable streams of data flowing through the system. In this model of computation, the simulation scheduler creates a dynamic schedule based on the flow of data between the modules. In other words, the order of execution of modules is set during run time. This allows modeling of multi-dynamic systems where every component can alter the rate of consumed/produced data at any time during simulation. The scheduler also provides the system with buffering capability. This allows the system to keep track of all the particles arriving at one module when multiple input streams of data are involved.

The information flow is handled using a "message class". The parameters that characterize the signals are encapsulated in the message class to be sent and received throughout the system. The message class also carries time information for each message in the stream of data. This allows for the dynamic insertion and deletion of samples at any time in the system by any component. Modules that operate on multiple data streams of different rates use this time information to maintain the order in the stream of incoming data. To maximize our modeling flexibility, our signals are composite types, representing the attributes of force, displacement, velocity and acceleration for mechanical signals, voltages and impedances for electronic signals, and wavefront, phase, orientation and intensity for optical signals. The composite type is extensible, allowing us to add new signal characteristics as needed.

Because the frequency response for electronic and mechanical signals are extremely low when compared with the optical signal carrier, the analysis of optical signals can be performed at each discrete event in the time-base of the signal modulation frequency. This simplification offers an efficient way to integrate our optical analysis together with electrical/mechanical modeling. The same concept can be applied when thermal analysis in the system is considered. In this case the dynamics of the thermal propagation in material is so slow when compared with electronic or mechanical responses that the analysis can be performed using essentially steady state behavior for the thermal field in the system.

On the other hand, the interaction of the electronic and mechanical responses in a device must be treated using a different approach because their response times are comparable relative to the modulation frequencies of the signals. In the following sections we described how we use piecewise modeling for the signals in the system. Together with a nodal analysis representation for each sub-system within a component and the modeling of non-linear devices using piecewise linear

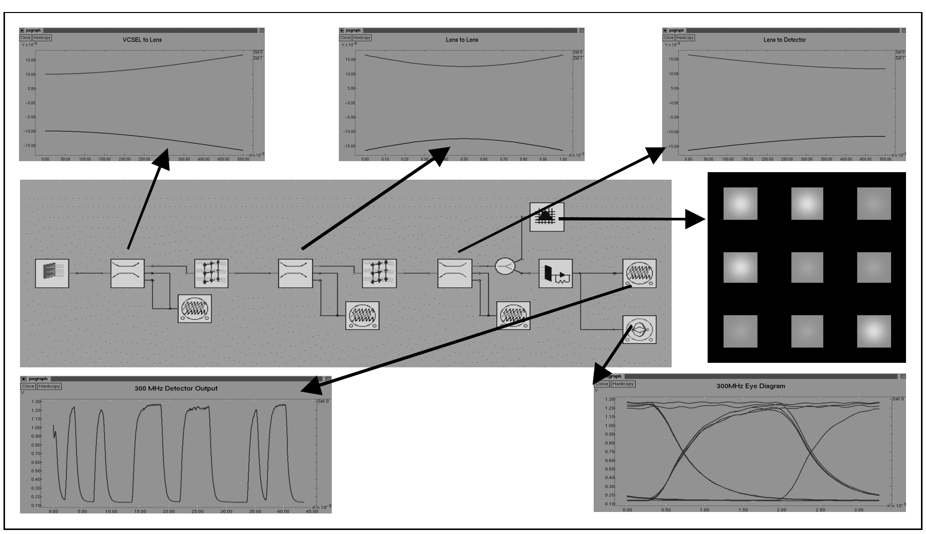

Figure 1: Chatoyant analysis of *4f* system

techniques, we have developed a computationally efficient methodology to integrate electronic an mechanical simulation in the system.

Before the discussion of individual signal and component models and to further understand the development of our mixed signal methodology, we first introduce our device and component modeling methodology.

2. COMPONENT LEVEL SIMULATION

We make a distinction between device level and component level modeling. Device level models focus on explicitly modeling the processes within the physical geometry of a device such as fields, fluxes, stresses, and thermal gradients. Conversely, in component level models these distributed effects are characterized in terms of device parameters and the models focus on the relationships between these parameters and state variables (e.g., optical intensity, phase, current, voltage, displacement, or temperature) as a set of linear or non-linear differential equations (DE). In the electronic domain, these are called "circuit models."

Component level (which in the electrical domain is called circuit-level) modeling techniques can be used for mechanical, optical, and electronic device modeling, but, for most models, the degree of accuracy does not match that required for performance analysis of real devices. Fast transient phenomena, dependencies on the physical geometry of the device, and large signal operation are generally not well characterized by these kinds of models.

On the other hand, device level simulation techniques, offer the degree of accuracy required to model fast transients (e.g., optical chirp, electrical overshoot, and mechanical contact), fabrication geometry dependencies, as well as steady-state solutions in the devices. However, modeling these processes requires specialized techniques and large computational resources. Further, these simulations produce results that are generally not compatible with the specialized simulators required for other domains. For instance, it is difficult to model the behavior of a laser in terms of carrier population densities, and at the same time, the emitted light in terms of its electro-magnetic fields.

There are two basic techniques to deal with this problem of device simulation vs. component simulation. The first is the use of two levels of simulation, a device level simulation for each unique domain, coupled to a higher level component simulation that coordinates the results of each. The idea is analogous to the technique of using a digital simulation backbone to tie together analog simulations for mixed signal VLSI.

However, for the case of device and circuit co-simulation, this technique has all the drawbacks previously mentioned for the device level simulation and the additional computational resources to coordinate both simulators and make them converge to a common point of operation.

Rather, our approach is to increase the accuracy of the component level (circuit) models. That is, to incorporate the transient solution and other second order effects, of the device analysis within the component level simulation. This is accomplished by creating component models for these higher order effects and incorporating them into the component model of the device. Different methodologies can be used to translate the device level expressions that characterize the device operation into a set of temporal linear/non-linear differential equations. The advantage of having this representation is that we can simulate mechanical, electronic, and optoelectronic models in a single mixed-domain component level simulator.

3. PIECEWISE LINEAR SIMULATION METHOD

For simulation, we perform a numerical analysis, in order to solve the linear/non-linear DE set necessary to obtain an accurate solution, and use piecewise linear (PWL) modeling to overcome the iteration process encountered in the integration technique used in traditional circuit simulators. Linearizing the behavior of the non-linear devices by regions of operation simplifies the computational task to solve the system. This also allows us to trade accuracy for speed. Most importantly, PWL models for these devices allow us to integrate mechanical, electrical and optical components in the same simulation.

Our modeling is accomplished as shown in Figure 2. We perform linear and non-linear sub-block decomposition of the circuit model of the device. This decomposes the design into a linear multi-port sub-block section and non-linear sub-blocks. The linear multi-port sub-block can be thought of as characterizing the interconnection network or parasitics while the non-linear sub-blocks characterize the active devices.

Then, Modified Nodal Analysis (MNA) is used to create a matrix representation for the device, as shown in Figure 3. In this electrical circuit example, **[S]** is the storage element matrix, **[G]** is the conductance matrix, **[x]** is the vector of state variables, **[b]** is a connectivity matrix, **[u]** is the excitation vector, and **[I]** is the current vector.

The linear sub-block elements can be directly matched to this representation, however the non-linear elements first need to undergo a further transformation. We perform piecewise modeling of the active devices for each non-linear sub-block. When we form each non-linear sub-block, a MNA template is used for each device in the network. The use of

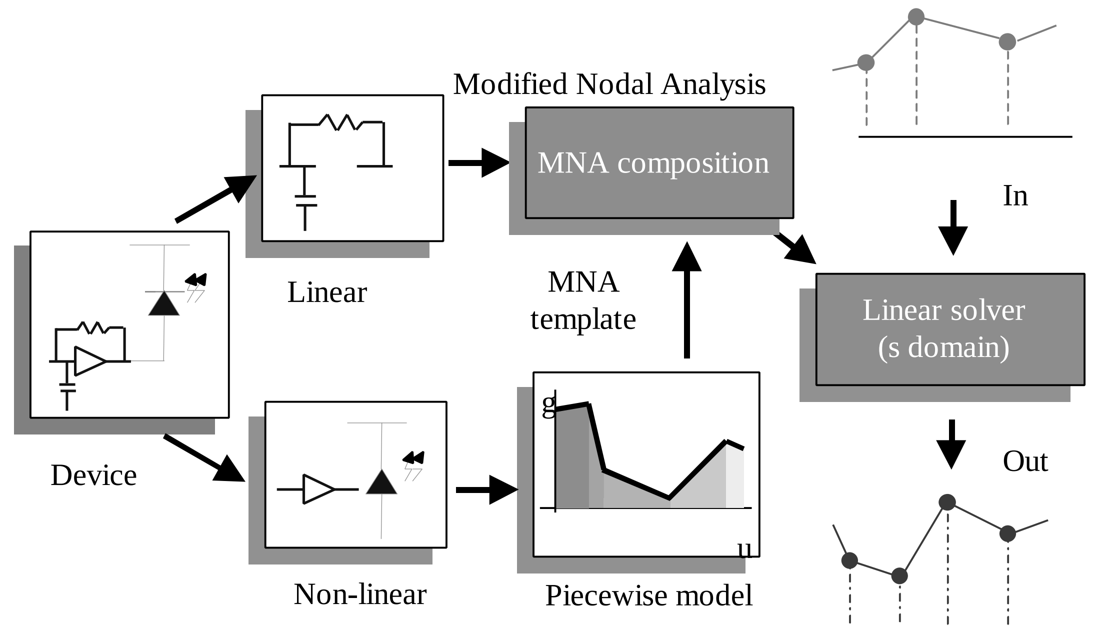

Figure 2 Piecewise modeling for MOEMS devices

piecewise models is based on the ability to change these models for the active devices depending on the changes in conditions in the circuit, and thus the regions of operation.

The templates generated can be integrated to the general MNA containing the linear components adding their matrix contents to their corresponding counterparts. This process is shown in Figure 3 for the **[S]** matrix. This same composition is done for the other matrices. The size of each of the template matrices is bounded to the number of nodes connected to the non-linear element.

Once the integrated MNA is formed, a linear analysis in the frequency domain can be performed to obtain the solution of the system. Constraining the signals in the system to be piecewise in nature allows us to use simple transformations to and from the time domain without the use of costly numerical integration.

During each time step in the simulation, the state variables in the module will change and might cause the active devices to change their modes of operation. Therefore, we re-compute and re-characterize the PWL solution caused by changes between piecewise models. Depending on the number of segments used in the piecewise linear model, on average

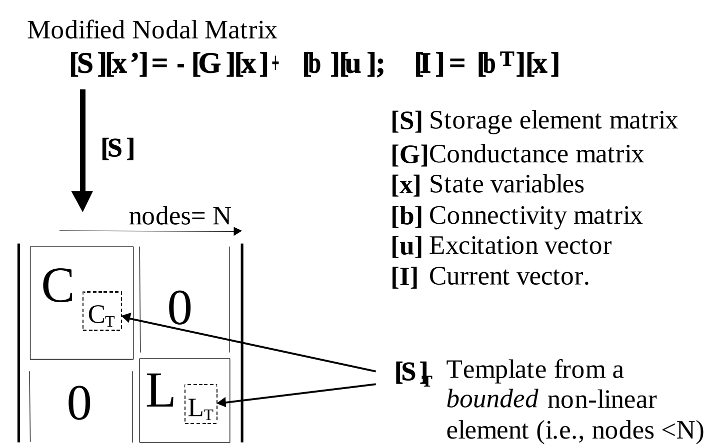

Figure 3 MNA representation and Template integration

there will be a large number of time steps during which the system representation is unchanged, justifying the computational savings of this technique.

4. MEM'S MODELING USING PWL TECHNIQUES

The general module for solving sets of non-linear differential equations using PWL can be used to integrate complex mechanical models. The model for a mechanical device can be summarized in a set of differential equations that define its dynamics as a reaction to external forces and given to the PWL solver for evaluation.

In the field of MEM modeling, there has been an increasing amount of work that uses a set of Ordinary Differential Equations (ODEs) to characterize MEM devices [7][8][9]. ODE modeling is used instead of techniques such as finite element analysis to reduce the time and amount of computational resources necessary for simulation. The model uses non-linear differential equations in multiple degrees of freedom and in mixed domains. The technique models a MEM device by characterizing its different basic components such as beams, plate-masses, joints, and electrostatic gaps, and by using local interactions between components.

Our approach to modeling mechanical elements is to reduce the mechanical ODE representation to a form matching the electronic counterpart, seen in the equation in Figure 3. This enables the use of the piecewise linear technique previously discussed for simulating the dynamic behavior of electrical systems.

With damping forces proportional to the velocity, the motion equation of a mechanical structure with viscous damping effects under a vector of external forces **F** is [10]:

1) $$[\mathbf{F}] = [\mathbf{K}][\mathbf{U}] + [\mathbf{B}][\mathbf{V}] + [\mathbf{M}][\mathbf{A}],$$

where **[K]** is the stiffness matrix, **[U]** is the displacement matrix, **[B]** is the damping matrix, **[V]** is the velocity matrix, **[M]** is the mass matrix, and **[A]** is the acceleration matrix. Similar to the electrical modeling, the expression represents a set of linear ODEs if the characteristic matrices **[K]**, **[B]** and **[M]** are static and independent of the dynamics in the body. If this is not the case, (e.g., aerodynamic load effects) then they represent a set of non-linear ODEs.

Obviously, knowing that the velocity is the first derivative and the acceleration is the second derivative of the displacement, the above equation can be recast to:

2) $$\mathbf{F} = [\mathbf{K}]\mathbf{U} + [\mathbf{B}]\mathbf{U}' + [\mathbf{M}]\mathbf{U}''$$

To reduce the above equation to a standard form, we use a modification of Duncan's reduction technique for vibration analysis in damped structural systems [11]. This modification allows for the general mechanical motion equation above to be reduced to a standard first order form, similar to the one in Figure 3, which allows for a complete characterization of a mechanical system.

3) $$\begin{bmatrix} \mathbf{0} & \mathbf{M} \\ \mathbf{M} & \mathbf{B} \end{bmatrix} \begin{bmatrix} \mathbf{U}'' \\ \mathbf{U}' \end{bmatrix} + \begin{bmatrix} -\mathbf{M} & \mathbf{0} \\ \mathbf{0} & \mathbf{K} \end{bmatrix} \begin{bmatrix} \mathbf{U}' \\ \mathbf{U} \end{bmatrix} = \begin{bmatrix} \mathbf{0} \\ \mathbf{I} \end{bmatrix} \mathbf{F}$$

Using substitutions, the equation 3 is rewritten as:

4) $[\mathbf{Mb}]\mathbf{X}' + [\mathbf{Mk}]\mathbf{X} = [\mathbf{E}]\mathbf{F}$ **,** where the new state variable vector $\mathbf{X} = \begin{bmatrix} \mathbf{U}' \\ \mathbf{U} \end{bmatrix}$

Each mechanical element (beam, plate, etc.) is characterized by a template consisting of the set of matrices **[Mb]** and **[Mk]**, composed of matrices **[B]**, **[M]**, and **[K]** in the specified form seen above. If the dimensional displacements are constrained to be small and the shear deformations are ignored, the derivations of **[Mb]** and **[Mk]** are simplified and independent of the state variables in the system. Additionally, the model for elements is formulated assuming a one-element idealization (e.g., two nodes for a beam). Consequently, only the static resonant mode is considered. Multiple-element idealization can be performed combining basic elements to characterize higher order modes.

The generalization of our discussion of single element mechanical systems to an assembly of elements or mechanical structure is fairly straightforward. The general expression, seen in Equation 4, will characterize the structure defined by a set of nodes, where each element shares a subset. The next step, as in the electronic case, is the merging of individual templates together to create the general matrix representation for the complete structure. However, a common coordinate reference frame must be used for this characterization of mechanical structures, since every template or element is characterized in a local reference system. The process of translation of these local templates to the global reference system can be described by [10]:

5) $\boldsymbol{S} = \boldsymbol{A}^T \overline{\boldsymbol{S}} \boldsymbol{A}$,

where, $\boldsymbol{A}$ represents the translation matrix from local displacements to global displacements (a function of the structure's geometry), $\overline{\boldsymbol{S}}$ represents the local template, and $\boldsymbol{S}$ is the corresponding global representation. The next step is the addition of these global representations into the general matrix form, using the matrices' nodal indexes as reference.

The final step in this method involves the use of a traditional non-linear solver to find the solution for the matrix sets. The use of a PWL general solver in this phase would decrease the computational task even more and allow for a trade-off between accuracy and speed. The additional advantage of using the same technique to characterize electrical and mechanical models allows us to easily merge mechanical, optical, and electronic technologies in complex devices that interact across mixed domains.

5. EXAMPLES

5.1 Piecewise Linear Modeling of CMOS circuits

To show the speed and accuracy of the PWL approach for electronics, we performed several experiments comparing our results to that of Spice 3f4 (Level II). The test was a multistage amplifier with a significant number of drivers. PWL models were tested versus Spice at 10 and 1000 MHz. Figure 4 shows that the speed-up achieved for the same number of timepoints is at least two orders of magnitude faster than Spice. Accuracy was within a 10% RMS error. These results show that PWL models are well suited to perform accurate and fast simulations for the typical multistage CMOS drivers and transimpedance amplifiers widely used in optoelectronic applications.

5.2 Piecewise Linear Modeling of Mechanical Beams

As an example of our mechanical technique, we present the response of an anchored beam in a 2D plane (x-y plane) with an external force applied on the free end. The template for the constrained beam is composed of the following matrices [10]:

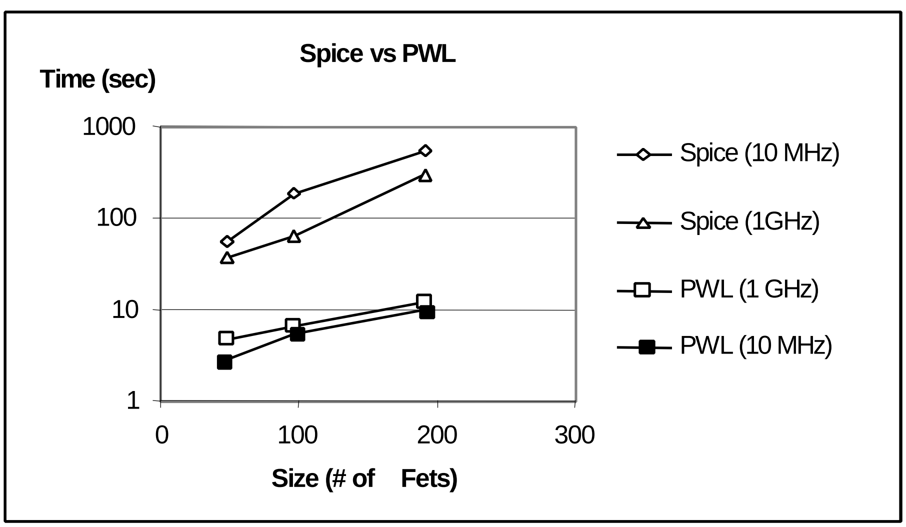

Figure 4 Spice vs. PWL models in a system of multiple FETs (f=100/1000 MHz).

$$K = \frac{EI_z}{l^3}\begin{bmatrix} \frac{Al^2}{I_z} & 0 & 0 \\ 0 & 12 & -6l \\ 0 & -6l & 4l^2 \end{bmatrix};\ M = \frac{?Al}{420}\begin{bmatrix} 140 & 0 & 0 \\ 0 & 156 & -22l \\ 0 & -22l & 4l^2 \end{bmatrix};\ B = d\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix};$$

where, E is Young's modulus, I_z is the inertia momentum in z, A is the area of the beam, l is the length, r is the density of the material, and d is the viscosity factor in the system acting over x and y components (2D plane).

The analysis of this element is obtained using the piecewise linear technique presented above. Constraining the input/output signals to a piecewise linear wave, the time domain response is completed in one step, without costly numerical integration. To test our results, a comparison against NODAS [7] was performed. Figure 5 shows the frequency response and corresponding resonant frequencies for this constrained beam (183µm length, 3.8 µm width, poly-Si) from both our PWL technique and NODAS. The transient response to 1.8 nN non-ideal step (rise time of 10 µsec) rotational torque is also simulated. The rotational deformation to this force is shown in Figure 6. The difference between the results from both techniques is within 2.9 %. NODAS uses SABER, a circuit analyzer performing numerical integration for every analyzed point, which results in costly computation time. Our linear piecewise solver is computational intensive during the eigenvalue search, however, this procedure is performed only one time, at the beginning of the simulation run. We believe that this will result in a more computationally efficient simulation. However, as previously mentioned, the accuracy of the analysis depends in the granularity of the piecewise characterization for the signals used in the system, which can increase computation time.

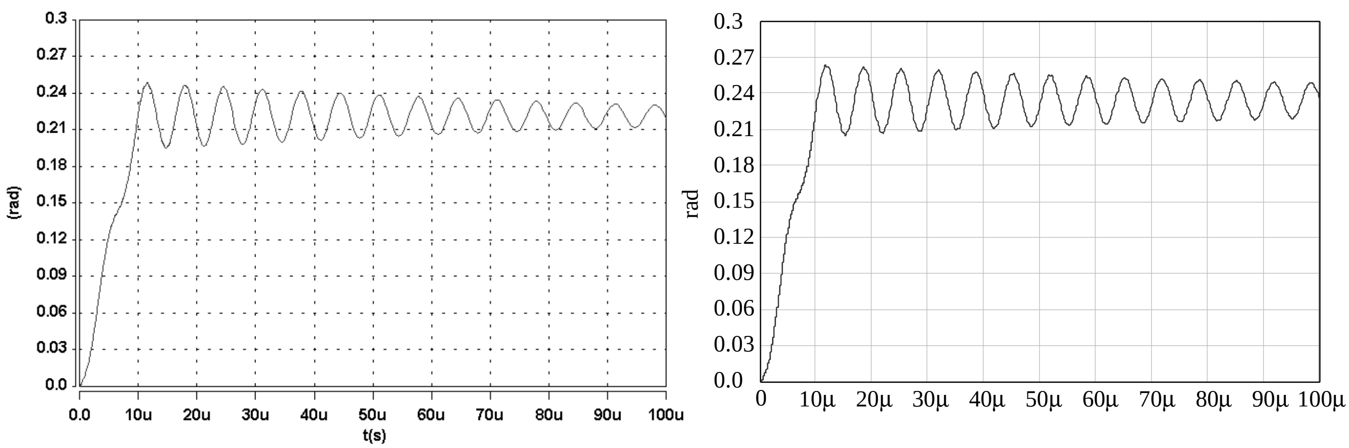

Figure 5: Transient Response of a Beam: (a) NODAS (b) Chatoyant

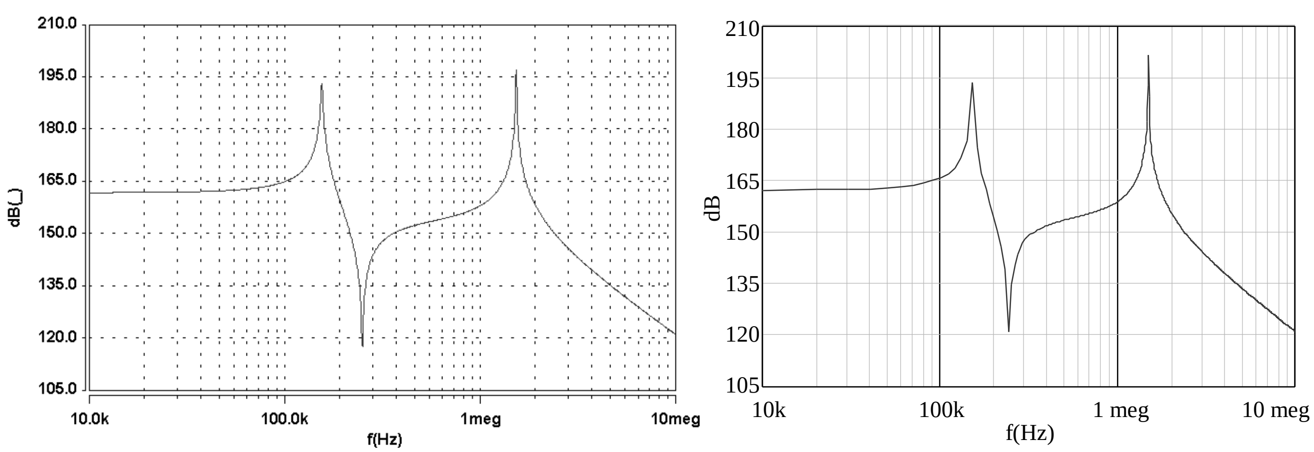

Figure 6: Frequency Response of a Beam: (a) NODAS (b) Chatoyant

6. FUTURE WORK

One way to characterize device level behavior of the electro-optical conversion in devices such as Vertical Cavity Surface Emitting Laser (VCSEL) and Multiple Quantum Well modulators (MQW) is by using rate equations. Rate equations represent the dynamic conservation of the total population of carriers in an optical device. Photons are considered particles and the variations of their population indicate an emitting or absorbing process in the device.

The dynamic representation of change in population in the device can be converted to a set of equivalent ordinary differential equations that depend on electrical parameters as well. This allows the inclusion of these non-linear opto-electronic effects into the existing circuit representation characterized in the interconnection and driving circuits. The PWL analyzer could then be used to solve the system and provide us with the required higher order effects, such as the turn-on transients in VCSEL based systems.

7. SUMMARY AND CONCLUSIONS

We are integrating new PWL modeling and simulation methods into our existing optoelectronic CAD tool *Chatoyant*. The use of modified nodal analysis together with piecewise linear modeling in a discrete event simulation environment provides for a single mixed-technology system-level design tool where the user can trade off the degree of accuracy of the analysis vs. simulation time.

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