MODELING AND SIMULATION OF MIXED TECHNOLOGY MICRO SYSTEMS

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ABSTRACT

Chatoyant is a system level opto-electro-mechanical CAD tool developed to meet the needs of mixed technology systems designers. In this paper, we present the modeling techniques we have implemented in Chatoyant for system level design of mixed technology micro-systems composed of optical, electrical and mechanical components.

I. INTRODUCTION

For integrated micro-systems composed of optical, electrical, and mechanical components, the need to model large numbers of linear and non-linear components with sufficient accuracy to analyze cross-talk, noise, and tolerancing in a interactive environment leads to the requirement of an efficient yet accurate mixed-technology simulation technique that crosses the domains of optics, electronics and mechanics.

We have developed Chatoyant to support modeling and simulating of micro-opto-electro-mechanical systems including micro-optical and mechanical components [1,2]. Chatoyant is built upon the object-oriented simulation engine Ptolemy [3]. Chatoyant's component models are written in C++ with sets of user defined parameters for the characteristics of each module instance. 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.

The Ptolemy simulation method used in Chatoyant is called "Dynamic Data Flow" (DDF) with the modification that timing information is added to each message to support multiple and run-time-rate variable streams of data flowing through the system, which is essential for multiple domains.

Component models are based on three modeling techniques. The first is a "derived model" technique. That is, analytic models based on an underlying physical model of the device. These can be very abstract "0th-order" models, or more complex models involving time varying functions, internal state, or memory. The second class of models is based on empirical measurements from fabricated devices. These models use measured data and interpolation techniques to directly map input signal values to output values. The third technique is reduced order or response surface models. For these models, we use the results of low level simulations, such as finite element solvers, or simulators, and generate a reduced order model, which covers the range of operating points for the component by producing a polynomial curve fit, or simple interpolation over the range of operation. We have successfully used all three of these methods in the creation of four component libraries. The Optoelectronic Library includes vertical cavity surface emitting lasers (VCSELs), multiple quantum well (MQW) modulators, and p-i-n detectors. The Optical Library contains components such as refractive and diffractive lenses, lenslets, mirrors, and apertures. The Electrical Library includes CMOS drivers and transimpedance amplifiers, and the Mechanical Library contains scratch drive actuators and other electro-static devices.

In the remainder of this paper, we present our techniques for system level modeling, followed by the methodologies and examples for electrical and mechanical modeling. We conclude with a discussion and an example of our optical signal modeling.

II. SYSTEM LEVEL MODELING

The simulation of mixed-technology micro systems involves signals of very different structures with varied dynamics. The use of the object-oriented Ptolemy framework permits a large degree of abstraction for the simulation of such systems. This is in contrast to simulators based on potential/field gradients or finite element analysis. In Ptolemy's abstraction framework, the system is decomposed into component modules that are individually characterized and joined together by the mutual exchange of information. The nature of this information can be optical, electrical, mechanical, or any combination of these.

The information flow is handled using a "message class", a heterogeneous interface that allows for the transmission of a token, or particle, of data information between components. The advantage of using such a class is that one single message contains optical, electrical, or mechanical information, and each

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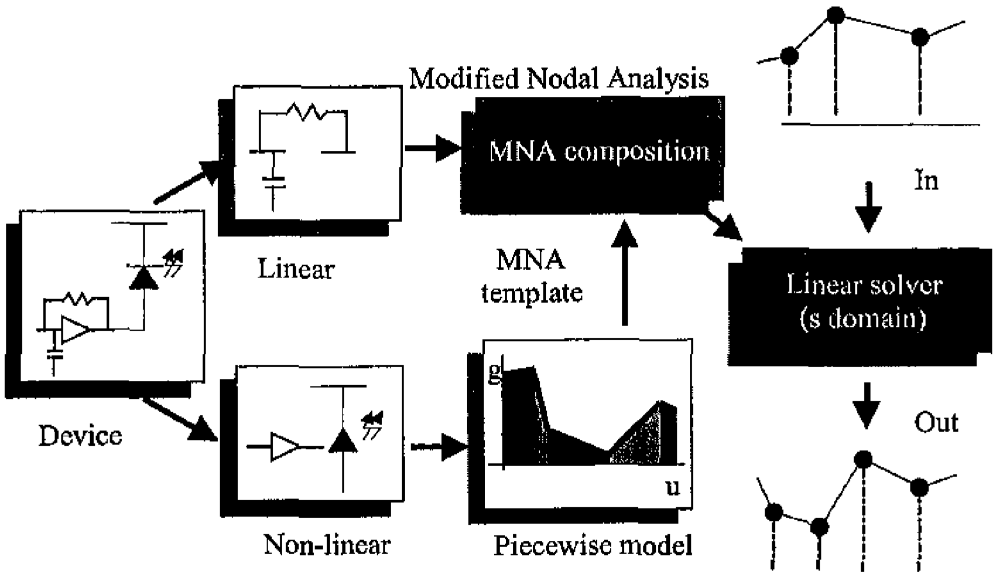


Figure 1 Piecewise modeling for mixed-technology devices

component type-checks the data, extracting the relevant information. 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 by any component, as discussed below.

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 the modules' execution is set during run time. This allows modeling of multi-dynamic systems where every component can alter the rate of consumed/produced data 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.

Before the discussion of individual signal models and to further understand the development of our system-level simulation tool, we first introduce our device and component modeling methodology.

A. 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 [4]. 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 [5,6].

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 [4,7]. 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 that are solved during simulation.

The advantage of having this representation is that we can simulate mechanical, electronic and optoelectronic models in a single mixed-domain component level simulator.

B. 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 [8,9]. 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 allows us to integrate mechanical, electrical and optical components in the same simulation.

Our modeling is accomplished as shown in Figure 1. 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 parasitic while the non-linear sub-blocks characterize the active devices.

Then, Modified Nodal Analysis (MNA) [10] is used to create a matrix representation for the device, shown in Figure 2. 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 but the non-linear elements need to first 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 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 2 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

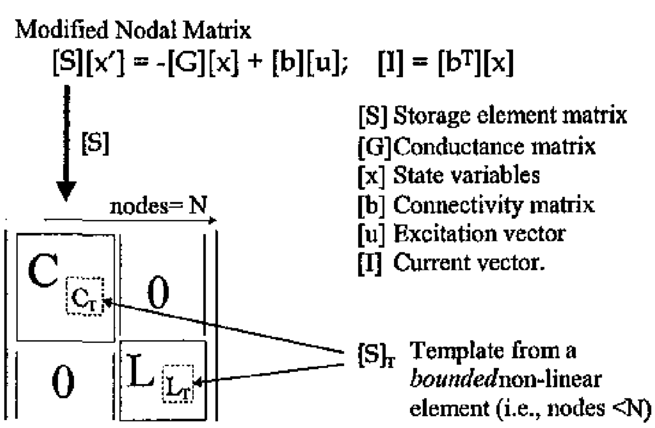


Figure 2 MNA representation and Template Integration

solution caused by changes between piecewise models. Depending on the number of segments used in the piecewise linear model, on average there will be a large number of time steps during which the system representation is unchanged, justifying the computational savings of this technique.

III. PWL MODELING EXAMPLES

To illustrate our PWL modeling technique we demonstrate modeling of some simple electrical and mechanical components.

A. Example PWL Modeling of CMOS circuits

To show the speed and accuracy of the PWL approach for electrical components, we performed several experiments comparing our results to that of Spice 3f4 (Level II).

Figure 3(a) shows the performance of a single CMOS amplifier under large signal input. The source used for the test was a pure sinusoid where the frequency was 1GHz. For this test we used the static (zero bias) capacitance values directly from the Spice level II models. The main difference in the results can be seen as a drift in phase. Fitting the model equations to the dynamic behavior of the parasitic capacitances would decrease the relative error.

Figure 3(b) shows the overshoot expected from the cascade of two inverters as an effect of the high frequency path created through the parasitic effective capacitance, Cgd and its size compared to the drain-source capacitance, Cds. The overshoot level is affected by the ratio Cgd/Cds and so will be as good as our estimation of Cds. In our tests a theoretical value for Cds of 6 fF was used and the overshoot level was within 10% of the Spice value.

B. Mechanical Modeling Using PWL Techniques

The general method for solving sets of non-linear differential equations using PWL can also 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.

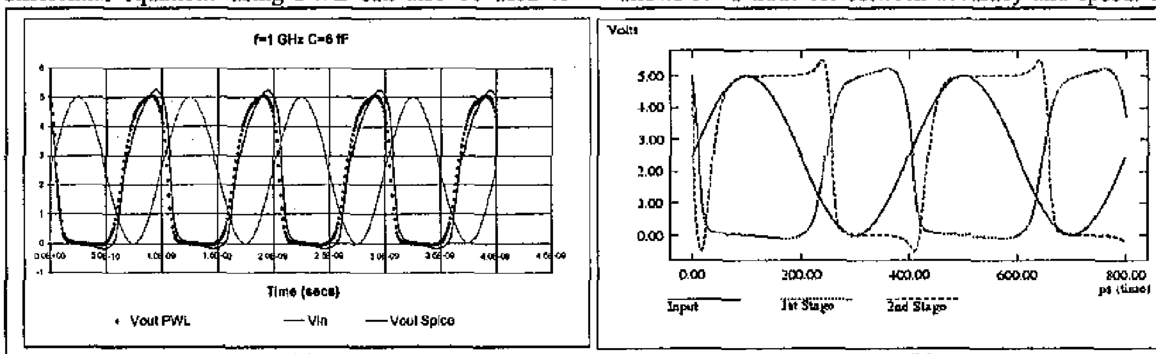
In the field of MEM modeling, there has been an increasing amount of work that uses a set of Ordinary Differential Equations (ODEs) [11,12] to characterize MEM devices. ODE modeling is used instead of techniques such as finite element analysis, to reduce the time and amount of computational resources 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 then using local interactions between components.

As an example, consider the standard equation that describes the dynamics of a beam under a vector of external forces F:

$$[F] = [K][U] + [B][V] + [M][A],$$

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. 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, then they represent a set of non-linear ODEs. Typically, this beam is only a part of a bigger device made from components that will be characterized using similar expressions. The interaction between components will be constrained to the joint points and also described using similar matrix expressions that interact across mixed domains.

The final step in this method involves the use of a traditional non-linear solver to find the solution for the matrix sets. Our use of a PWL general solver in this phase decreases the computational task even more and allows for a trade-off between accuracy and speed. The



(a) (b)

Figure 3 (a) PWL and Spice output for inverter under capacitive load and frequency of 1GHz. (b) PWL simulation of two inverters showing overshoot at 600MHz.

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.

C. Dynamic Simulation of a Single Constrained Beam

As example of our mechanical technique, we present the response of an anchored beam in a 2D plane with an external force applied on the free end. 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 [13] was performed. Table 1 shows the resonant frequencies and Figure 4 shows the transient response (rotational deformation) to a 1.8 nN non-ideal step (rise time of 10 μsec) rotational torque for this constrained beam (183μm length, 3.8 μm width, poly-Si) from both our PWL technique and NODAS. The comparison between our results and NODAS's are very close. 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.

	Resonant Frequencies	
	f_1	f_2
NODAS	154.59KHz	1.52MHz
PWL simulator	150.04KHz	1.48MHz

Table 1 Resonant frequencies

IV. MODELS FOR MICRO-OPTICAL SYSTEMS

For macro-scale systems, on the order of tens of millimeters to meters, we support Gaussian propagation, which characterizes an optical signal as a Gaussian beam. Not having to perform an explicit integration of the optical wavefront at each component results in an accurate simulation with a fast computation time.

However, as we extend our tool to support micro systems, where we are required to model diffractive propagation effects through the refractive and diffractive components (e.g., lenses, apertures, gratings, and mirrors), Gaussian propagation breaks down and a diffractive propagation method must be used. For our diffractive modeling, we have used scalar propagation techniques, due to our intuition that these models will be accurate in the optical MEM domain, and have a smaller computation time than the full vector method. We have chosen to implement the Rayleigh-Sommerfeld formulation, using a 96-point Gaussian quadrature method for our integration technique [14]. This choice gives us the diffractive accuracy that we require for micro systems in a reasonable computation time for an interactive simulation tool.

We have been able to interface our Rayleigh-Sommerfeld scalar model into the fiber based software package, BPM_CAD [15]. Chatoyant creates an output file of the complex wavefunction in BPM_CAD's specialized format. Our tool can also read this format for the fiber to free-space interface. As an example, we simulate a 850nm VCSEL ($1/e^2$ waist is equal to 5μm) propagating 150 μm in free space, and interface these results with 10 μm single mode fiber (index difference of .006, length of 1500 μm) in BPM_CAD. Using Snell's law, the acceptance angle of this fiber is 6.3 degrees. To illustrate the relationship of the acceptance angle to the mechanical tolerancing for the system, we show how tilting the end of the fiber effects the propagation of light down the fiber. In Figure 5, we show results as the beam is propagated down the fiber, for the case of perfect alignment and when the fiber is tilted by an offset of 1,

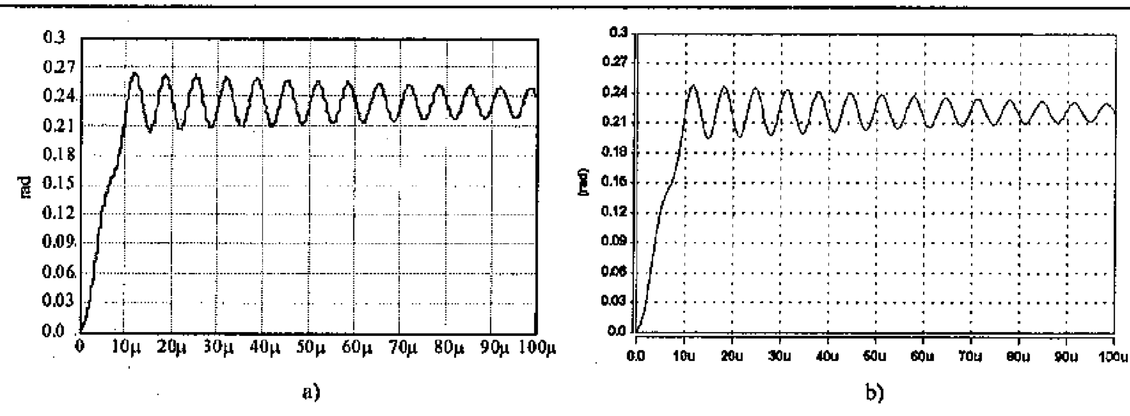


Figure 4 Transient Response of a Beam: (a) Chatoyant (b) NODAS

4, and 7 degrees. Also shown in Figure 5 is the VCSEL beam after it has propagated through free space. Notice that the waist of the Gaussian beam changes as enters the fiber due to the index change. For the 0 degree offset case, the Gaussian beam at the free-space fiber interface is almost the mode field diameter of the fiber (10.5 μm), therefore, the beam propagates well in this fiber. However, as the mechanical rotation is applied, the beam enters the fiber at a tilt, resulting in the beam bouncing back and forth on the core/cladding interface. It is seen in the 4 degree offset case, that as the tilts get larger, some of the beam is not captured in the core and is lost through the cladding. When we get above the acceptance angle of the fiber, hardly any of the beam is left to propagate down the fiber, as seen in the last case of the figure.

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REFERENCES

1. S. P. Levitan, et al., "Chatoyant: a computer-aided design tool for free-space optoelectronic systems," Applied Optics, Vol. 37, No. 26, September, 1998, pp. 6078-6092.

2. S. P. Levitan, et al., "Computer-Aided Design of Free-Space Opto-Electronic Systems," DAC, Anaheim, CA, June 1997, Best Paper Award, pp. 768-773.

3. J. Buck, et al., "Ptolemy: a framework for simulating and prototyping heterogeneous systems," Int. J. Computer Simulation, Vol. 4, 1994, pp. 155-182.

4. J. Morikuni, S. Kang, Computer –Aided Design of Optoelectronic Integrated Circuits and Systems, Prentice-Hall, Inc., New Jersey, Chapter 6, 1997.

5. E. M. Buturla, et al., "Finite element analysis of semiconductor devices: the FIELDAY program," IBM Journal of Research and Development, vol. 25, 1981, pp. 218-231.

6. M. R. Pinto, et al., "PISCES II – Poisson and continuity equation solver," Stanford Electronics Laboratory Technical Report, Standard University, September 1984.

7. P. C. H Chan and C. T. Sah, "Exact equivalent circuit model for steady-state characterization of semiconductor devices with multiple energy-level recombination centers," IEEE Transactions of Electronic Devices, Vol. ED-26, 1979, pp. 924-936.

8. R. Kielkowski, SPICE, Overcoming the obstacles of circuit simulation, McGraw-Hill, Inc., chapter 4, 1994.

9. S. Kim, et al., "Time-Domain Macromodels for VLSI Interconnect Analysis," IEEE Tran. on CAD of Integrated Circuits and Systems, Vol. 13, No. 10, pp. 1257-1270, October 1994

10. J. Vlach and K. Singhai, Computer Methods for Circuit Analysis and Design.

11. J. Clark, et al., "Nodal Analysis for MEMS Simulation and Design," Proc. Modeling and Simulation of Microsystems Workshop, Santa Clara, CA, April 6-8, 1998.

12. J. E. Vandemeer, et al., "Hierarchical Representation and Simulation of Micromachined Inertial Sensors," Proc. Modeling and Simulation of Microsystems Workshop, Santa Clara, CA, April 6-8, 1998.

13. J. E. Vandemeer, "Nodal Design of Actuators and Sensors (NODAS)", M.S. Thesis, (Department of Electrical and Computer Engineering, Carniege Mellon University, Pittsburgh, PA., 1997).

14. T. P. Kurzweg, et al., "Optical Propagation Methodologies for Optical MEM Systems," MSM 2000, San Diego, CA, March 27-29, 2000.

15. Optiwave Corp., http://www.optiwave.com/

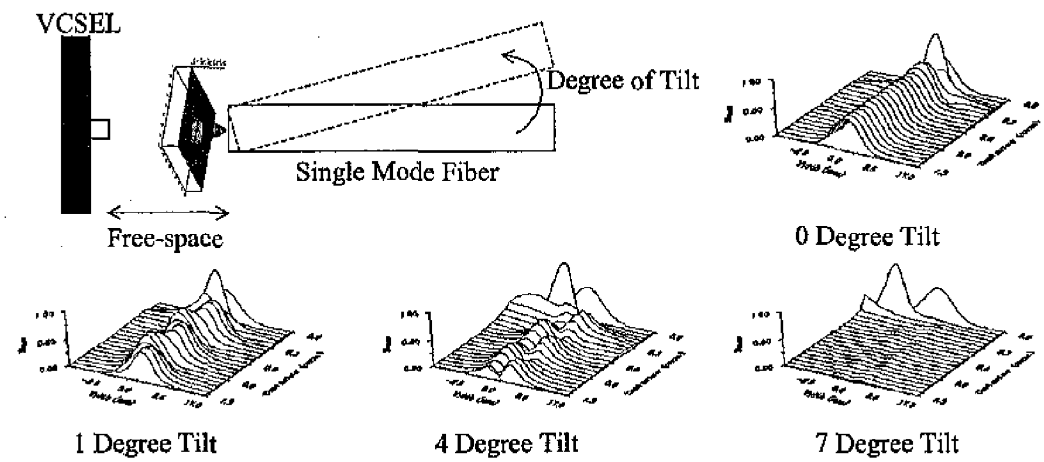

Figure 5 Free-Space/Fiber Interface