Simulation and Modeling of Optoelectronic Devices, Circuits and Systems

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ABSTRACT

Holographic optical elements fabricated from DuPont's OMNIDEX™ photopolymer have been demonstrated in a variety of product prototypes in which optical interconnect and semiconductor optoelectronic devices are integrated. With the emergence of Fibre Channel, Gigabit Ethernet, and Asynchronous Transfer Mode (ATM) applications, the simulation and modeling of passive and active elements is required for effective component, device, and system design. This capability is even more crucial for a surprising class of 'low frequency' portable wireless and consumer products, as well as for 'gigabit' digital microprocessors. For all of these applications, optical, electrical, and mechanical subsystems must be concurrently addressed. During this talk, both the applications and the simulation and modeling issues central to practical product development are presented and reviewed. For space constraints, however, this paper will emphasize modeling and simulation of the laser diode due the critical role that it plays in optical product design.

INTRODUCTION

As the limitations of today's semiconductor and fabrication technologies become apparent, optical interconnect is rapidly emerging as an attractive alternative to conventional electronic interconnection schemes. The use of optics for signal transmission offers many advantages over electronic approaches, including higher speed, lower electromagnetic interference (EMI), reduced crosstalk, higher isolation, and lower signal skew. While the largest application of optical interconnects has been long-distance fiber-optic telecommunications, optical interconnects have also been successfully implemented over smaller distances, such as between computers, boards, and even chips (Figure 1).

Modeling and simulation play a key role in the silicon electronics industry. Computer-aided design (CAD) tools exist today that enable the design and simulation of million-transistor VLSI chips, multi-component PC boards, and even complete electronic systems. Such capability is crucial for first-pass design; without these tools, multiple design and fabrication iterations are required in order to optimize design and system parameters, a process which severely impacts cycle time and end-product cost.

In contrast, the field of optoelectronics is still in relative infancy and very few modeling or simulation tools exist. As is the case for electronics, however, CAD tools for the design and analysis of optical interconnect systems, circuits, and devices are critical to the development of the technology. In this paper, we will discuss several approaches to this problem and present some of the solutions that have been developed. Much of this paper will emphasize the laser diode as it is typically the most difficult element to model in optoelectronic links and systems. The impact of this work is global, as it demonstrates the problems that all new technologies encounter in the design and manufacturing environments.

BACKGROUND

The approaches depicted in Figure 1 are largely guided-wave or fiber-optic schemes. Various products are geared toward inter-machine optical interconnects, as illustrated in Figure 1(b). These products include both parallel optical links as well as serial ones. Parallel links typical include arrays of transmitters and receivers connected by fiber-optic ribbon cable, whereas serial links contain a single transmitter and receiver connected by a single fiber-optic cable. Figure 1(d) utilizes not a fiber, but an optical waveguide, to interconnect chips within a board.

In contrast, optical interconnect can also be performed without using a guiding medium, but rather by propagating the light through free space. Typically, this approach uses air or an optically transparent substrate as the transmission medium, and holograms to steer and guide the light (Figure 2). Because of the significant loss that occurs when coupling light from the optical source into a fiber or waveguide, guided-wave optical interconnect implementations tend to be fairly power intensive and require elaborate packaging schemes. Since coupling the optical source to the transmission medium is a non-issue for free-space interconnects, lower power, more efficient systems are possible. As a result, free-space optical interconnect links have potentially higher manufacturability and lower cost than equivalent guide-wave approaches.

Regardless of the mode of transmission (guided wave or free space), an optical interconnect link consists of three parts: the transmitter (optical source), the transmission medium, and the receiver (optical detector). The optical source is an electro–optic converter, changing electrical energy into optical energy.

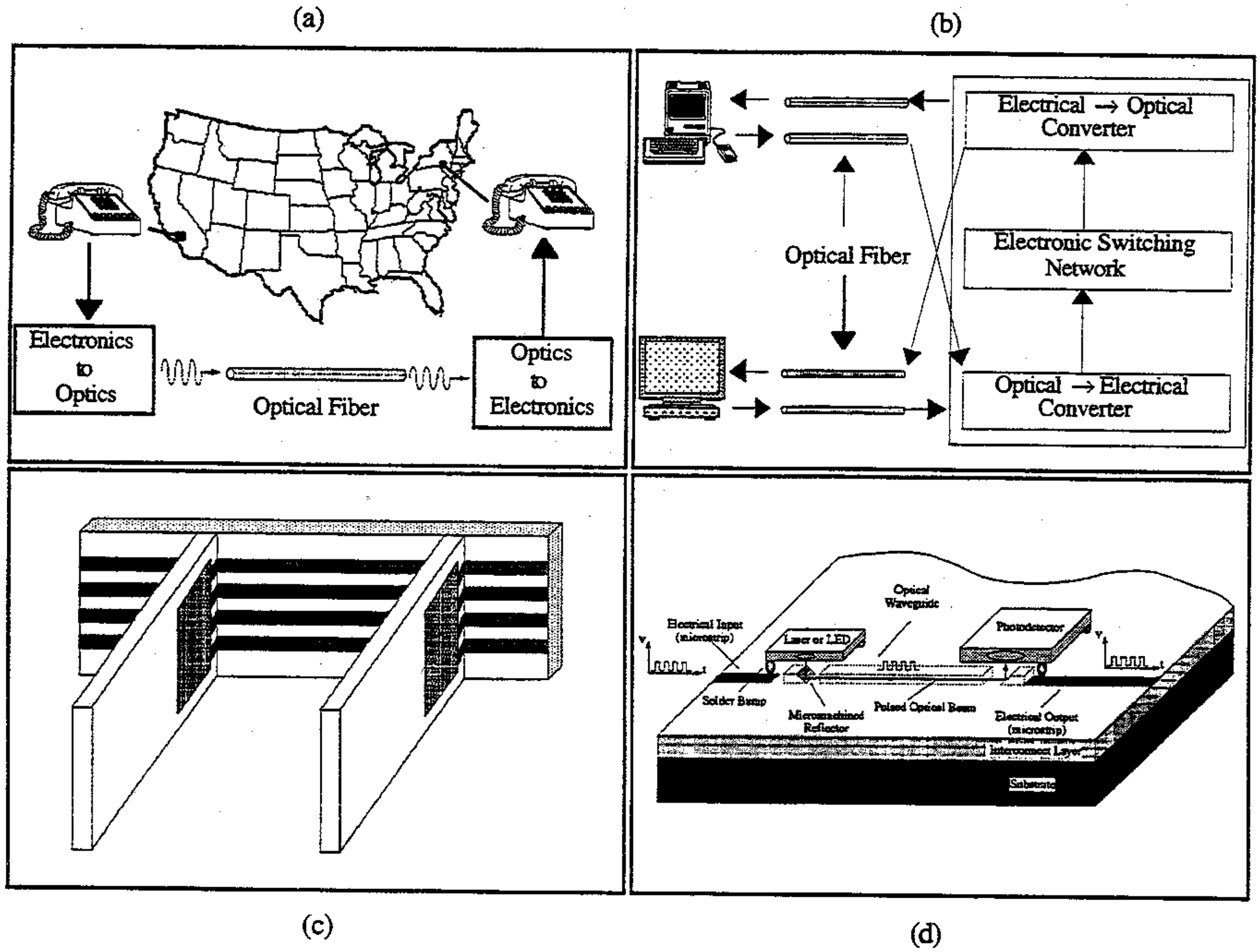

Figure 1: Optical interconnect over various scales and distances:
(a) Long-distance fiber-optic telecommunications
(b) Computer-to-computer network-level optoelectronics
(c) Board-to-board optical interconnect, optical bus, optical backplane
(d) Chip-to-chip optical interconnect, optoelectronic MCM

Typically, the optical source takes the form of a laser diode or an LED. The transmission medium can be a guided-wave material, such as an optical fiber or waveguide, or in a free-space implementation, it can be a combination of holograms, air, and/or an optically transparent substrate. Finally, the optical receiver is an opto-electronic converter, changing the light back into an electrical signal. The receiver usually consists of a photodetector in conjunction with an electronic preamplifier. The transmitter and receiver usually have pre- and post-processing (electronic) circuits, respectively, to serve as interfaces between the optical devices (laser, photodetector) and the transmitting and receiving electronics. A typical link would consist of a digital logic circuit connected to a laser driver circuit (to convert digital logic signals to levels needed to drive the laser), a laser diode, a transmission medium, a photodetector (to convert the light into a current), electronic pre and postamplifiers (to convert the current to a usable voltage), and finally, a digital logic circuit. Optical interconnect can also play a significant role in analog and RF implementations.

MODELING AND SIMULATION OF OPTICAL INTERCONNECTS

In order to successfully design an optical interconnect or optoelectronic link, it is necessary to be able to model and simulate the optical source (laser or LED), the transmission medium (guided wave or free space), and the optical detector. Unfortunately, while many models exist for the simulation of conventional electronic circuits and systems, very few exist for the design of optoelectronic circuits and systems. In general, simulation can be performed at three basic levels. The first is at the device level; in this approach, the fundamental device/semiconductor and electromagnetic (Maxwell's) equations are discretized and solved by finite difference methods. The second approach to simulation is at the circuit level; tools such as SPICE are good examples of analysis at this level. The third level of simulation involves behavioral, functional and system simulation. At this level, elements in a system are viewed essentially as "black boxes." The designer does not care what is inside the box, but rather what output will be generated for a given input. The laser diode is traditionally the most difficult portion of the optical interconnect link to model; thus, due to space constraints, the remainder of this paper will focus on the modeling and simulation of laser diodes.

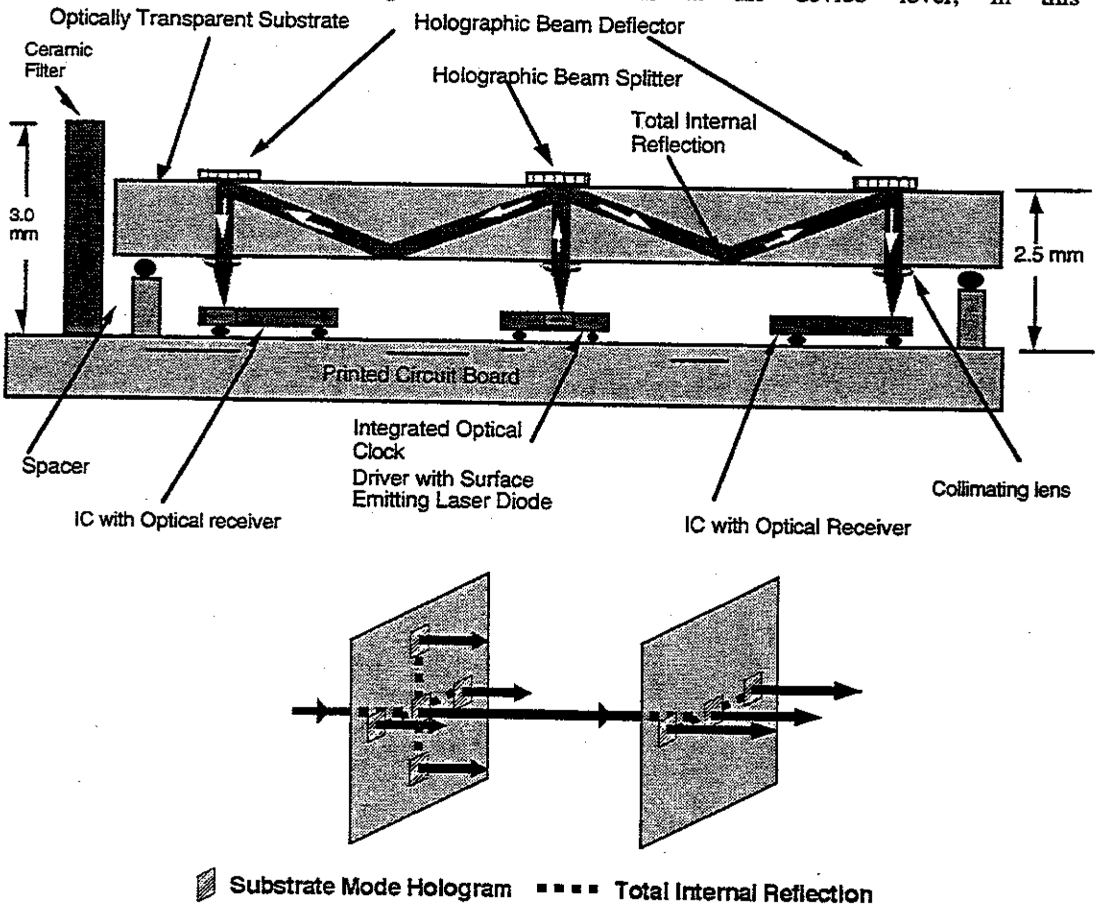

Figure 2: Free-space optical interconnect link with an optically transparent substrate as the transmission medium (top) and with air as the transmission medium (bottom).

The fundamental behavior of a laser diode is described by the laser rate equations which describe the dynamic nonlinear relationship between electrons and photons in the laser cavity:

$$\frac{dN}{dt}=\frac{I}{q}-\frac{N}{\tau_n}-G_0(N-N_0)S$$

$$\frac{dS}{dt}=\beta\frac{N}{\tau_n}+G_0(N-N_0)S-\frac{S}{\tau_s}$$

In these equations, N and S are the electron and photon populations in the laser cavity, respectively; I is the injected current, q is the electronic charge, τ_n and τ_s are the electron and photon lifetimes, respectively, β is the spontaneous emission coupling coefficient, N_o is the electron transparency population, and G_o is the gain coefficient. The rate equation formulation is the most common representation of laser behavior. The input to a laser diode is the current I and the output is light. The output light power is proportional to the photon density S; thus, to solve for the amount of optical output power (light) for a given input current, it is necessary to solve for S in the above coupled, nonlinear differential equations.

EQUIVALENT-CIRCUIT MODELING

The level of model complexity and the nature of the input parameters (physical, material, and geometrical) suggest that the rate equation model be solved at the circuit level. Indeed, these equations and parameters bear some similarity to existing circuit-level models for MOSFETs, BJTs, transmission lines, and the like. We have implemented such a model in a SPICE-like simulator for edge emitting laser diodes. It is natural to inquire how optical properties are modeled with an electronic simulator. Since a circuit simulator is essentially a differential equation solver, the rate equations can be solved with such a tool by mapping the electron and photon densities into node voltages (such as V_n and V_s). When simulation is complete, it is up to the user to interpret V_n and V_s as their true quantities.

Outputs for DC and transient circuit simulations are depicted in Figures 3 and 4, respectively.

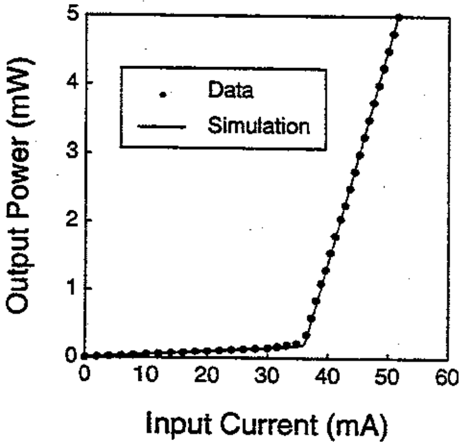

Figure 3: Laser diode light-current characteristic. Data taken from Rohm RLD-83MF edge-emitting laser.

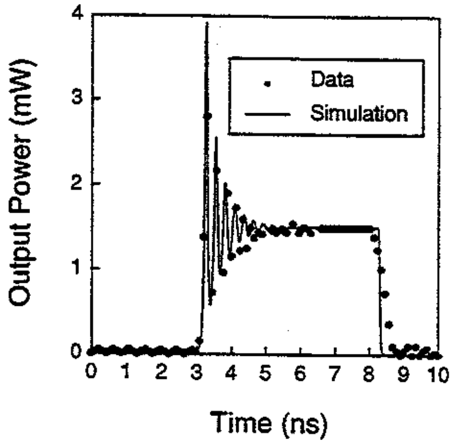

Figure 4: Laser diode transient characteristic. Data taken from Rohm RLD-83MF edge-emitting laser.

Several salient features are evident. First, in the DC simulation, it is clear that the optical output is nearly zero for current inputs less than some critical value; this is called the threshold current and is approximately 35 mA in the example of Figure 3. Once the injected current exceeds threshold, the power increases roughly linearly at a slope which is defined as the differential quantum efficiency. This quantity is traditionally expressed in units of mW/mA and is a measure of the electrical-to-optical conversion efficiency. In the transient simulation, the optical output power exhibits an oscillatory or ringing behavior. While this appears similar to parasitic electronic effects, it is actually a fundamental aspect of laser behavior. This phenomenon is referred to relaxation oscillation, and has its origins in the dynamic exchange of energy between the electron and photon densities in the laser cavity during turn on. This is analogous to the exchange of energy between the inductor and capacitor in an RLC circuit. Physically, turning on the laser creates an abrupt rise in the electron population which then causes a dip in the photon population as light is emitted. This is countered by another build-up of electrons which in turn causes another decrease in the photon population, a process which repeats itself iteratively until the number of photons (and hence, the optical output power) reaches some steady-state value. Since this phenomenon occurs only upon laser turn on, for high-speed modulation, a static bias current is usually run through the laser to keep it turned on. Obviously, this bias current is chosen so that it is larger than the threshold current.

As seen in Figures 3 and 4, the rate-equation model predicts laser behavior quite well. However, the rate equation model requires many physics-based input parameters which tend to be difficult to extract. In addition, if one is using a commercial device, access to geometrical and physical parameters is often not possible. For these reasons, it is often desirable to use an empirical or numerical laser diode model, similar to the HP Root FET model. In the "table-based" technique, a device is characterized over several regimes of operation, and large amounts of data are measured. The numerical model usually consists of polynomials, or similar functions, with arbitrary constants. The measured data are used to adjust the arbitrary constants until the numerical equations match observed device behavior. Unlike an equivalent-circuit model (such as the Gummel-Poon BJT model, or the Statz MESFET model), the resulting table-based model has no physical meaning whatsoever; there are no input parameters, such as those found in a .MODEL card, and very little can be adjusted to predict the behavior of modified devices. However, table-based models do predict, very accurately, device behavior in the regimes over which the device data were measured. Thus, numerical modeling is useful when a device that has been obtained externally (e.g., commercially) is to be included into a circuit design. Similar to the table-based approach, an empirical model uses circuit elements that mimic the behavior of the device in question. The actual values of the circuit elements, which have no physical significance, are determined by characterizing the device and using parameter extraction.

VERTICAL CAVITY SURFACE EMITTING LASER (VCSEL) MODELING

Lasers operate on the principle of positive feedback; light is passed through an amplifying medium then reflected back upon itself by a partially reflective mirror (Figure 5). This process repeats itself over and over, the light becoming more and more powerful with each iteration. Since one mirror is partially reflective, with each pass through the system, a portion of the light exits the laser cavity.

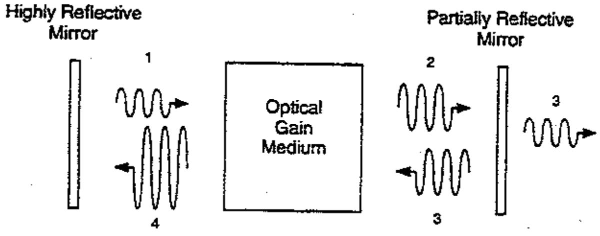

Figure 5: Basic principle of laser operation.

Conventional semiconductor lasers, or "laser diodes," are often referred to as "edge emitters" because the optical output is emitted from the side, or edge, of the device. (The device depicted in Figures 3 and 4 (Rohm RLD-83MF) was an edge-emitting laser). The semiconductor laser is typically fabricated by first growing epitaxial layers of material on a semiconductor substrate (GaAs, InP, etc.) then processing the resulting wafer and metalizing it. One of these epitaxial layers is engineered to provide optical gain to any light that passes through it and constitutes the gain medium depicted in Figure 3. Once the epitaxial growth is complete, a finished wafer of lasers results, somewhat analogous to a silicon wafer of ICs prior to its slicing into individual dice. In order to create the reflective mirrors depicted in Figure 5, the wafer is sliced, or "cleaved" into individual devices (Figure 6). Because the growth of the laser epitaxial layers was chosen to occur along predetermined crystallographic planes, cleaving the wafer results in optically reflective surfaces which serve as the laser mirrors. This process is similar to that taken by a diamond cutter who "cleaves" a dull surface along appropriate crystal planes and transforms it into a brilliant, optically reflective one.

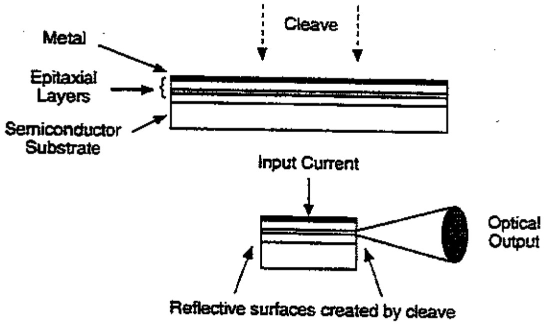

Figure 6: Edge-emitting laser diode.

The fundamental operation of the VCSEL is virtually identical to that of the edge-emitting laser diode; that is, the VCSEL operates on the principle of an optical gain medium and reflective mirrors. However, the VCSEL and edge emitter physical device structures are radically different. The basic principle of Figure 5 still holds true even for VCSELs; however, instead of using cleaving to create mirrored facets, VCSELs use alternating layers of epitaxial materials with alternating indices of refraction (Figure 7).

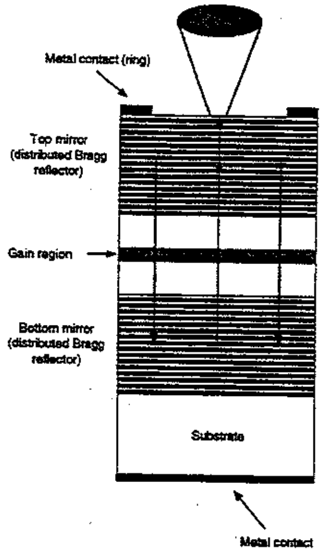

Figure 7: Generic VCSEL structure.

When engineered correctly, these layers form a distributed Bragg reflector, the reflective properties of which are well-known. When these layers are precisely tailored, the Bragg reflector at the bottom of the device acts like a mirror and can be designed with a reflectivity greater than 99%. This is extremely important in view of the much shorter gain region clearly evident when comparing Figures 6 and 7. (The gain region of a VCSEL can be several orders of magnitude shorter than that of an edge emitter). Because of the extremely low gain provided by the VCSEL, the mirrors must present minimal optical loss (i.e., low transmissivity, high reflectivity), making design of the Bragg mirrors critical. The top mirror, on the other hand, is obviously designed with a lower reflectivity to allow some light to exit the cavity. Clearly, since the VCSEL mirrors are on above and below the gain medium (rather than to the left and right as for the edge emitter), light will exit the VCSEL from the top, rather than the edge/side of the device.

VCSELs have many advantages over edge emitters. They are smaller and more compact. Because they emit light from the surface, they can be tested and probed at the wafer level; in contrast, each edge emitter must be cleaved and packaged before it can be tested. Furthermore, the VCSEL optical output beam is circular and of much higher quality than the edge emitter's elliptical beam. The current required to operate the VCSEL can be over an order of magnitude lower than that of an edge emitter resulting in lower power dissipation.

Finally, as a result of these features, VCSELs have the potential for much lower cost than edge emitters. Thus, the ability to model VCSELs is critical to the design and analysis of optical interconnect links and optical systems.

Since the *basic* operational principles of VCSELs and edge emitters are identical, the rate equation description previously described and applied to the Rohm RLD-83MF edge emitter can also be applied to a certain extent to VCSELs. Although VCSELs *do* exhibit behavior different from that of edge emitters in various situations, over certain regimes of operation the rate equation model works quite well. We applied our equivalent-circuit laser model to a VCSEL; the results are depicted in Figures 8 and 9.

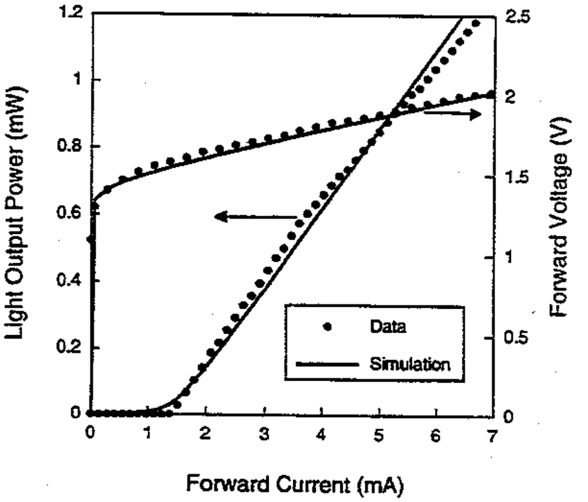

Figure 8: VCSEL light-current-voltage response.

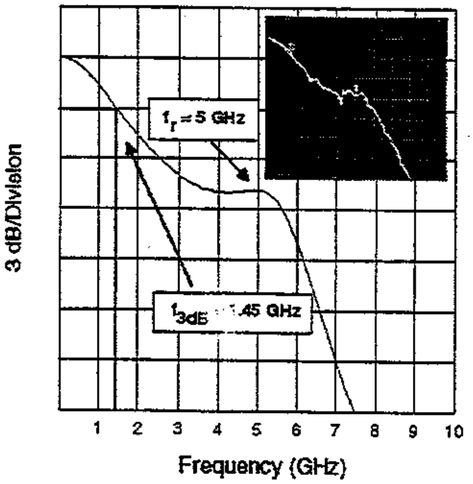

Figure 9: VCSEL light-current-voltage response.

Although VCSELs and edge emitters share many common features, the VCSEL does exhibit certain unique behavior. For example, although the VCSEL threshold current varies far less with temperature than the edge emitter, the VCSEL is susceptible to a decrease in output power at high currents. Because of the extremely short effective optical path length of the VCSEL, typically only one longitudinal optical mode can be supported. Since both the gain and the longitudinal mode (i.e., the lasing wavelength) shift with temperature, the output power inevitably decreases. Also contributing to this phenomenon is the VCSEL leakage current; as the temperature increases, it becomes more difficult to confine injected electrons to the active region. Since the VCSEL gain is proportional to this electron population, the gain, and hence the output power, decreases with temperature. These thermal features cannot be modeled with the simple edge-emitting laser model presented in the previous sections. We have augmented these models to reflect the increased thermal sensitivity of VCSELs and illustrate a simulation in Figure 10.

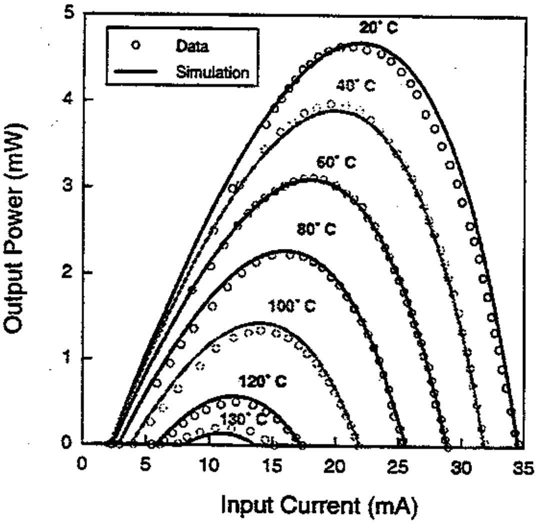

Figure 10: Simulation of VCSEL thermal properties.

CONCLUSIONS

Central to the design and analysis of any system is the ability to model and simulate the system's constituent components before assembly. Optoelectronic systems are no exception. In this paper, we have described several optical interconnect and communication systems and have emphasized the need for accurate, compact models for design analysis. Because the laser diode is the most difficult optical link element to model, we have chosen to highlight several laser diode models in this paper. We illustrated several models, for both edge-emitting laser and VCSELs, which have greatly enhanced our ability to design optoelectronic systems.