Computer-Aided Design of Free-Space Opto-Electronic Systems

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Abstract

*The integration of new optoelectronic **devices** into practical **systems** has been impeded by the fact that researchers have been unable to evaluate how these devices can be used to make components, and then how these components can be used to build systems. We address this need with an Opto-Electronic system prototyping tool based on Ptolemy.*

Introduction

Free-Space Opto-Electronic (FSOE) Systems will become key components of the next generation of computers and communications networks. Prototypes of these systems have been proposed, designed and constructed for the last 20 years. However, these systems have only existed in university and industry laboratories. To date, they have not seen general use. One of the reasons for this phenomena is that the time and effort involved in designing and building these systems, even as prototypes, is prohibitively expensive. Aside from some work in the area of CAD for fiber networks [4][1][10] these designs are currently performed essentially by hand. Therefore, the ability to make the kinds of design trade-offs necessary for production-quality systems is lacking.

The current “state of the art” for these analyses is to first perform basic characterizations of the devices built in the laboratories and then to use those models and a set of ad-hoc procedures to generate end-to-end system performance estimates. This painstaking technique results in rough approximations which must be refined by actually prototyping each of the particular systems under consideration. The result is that few FSOE systems have been designed, and fewer still have been built. This is in sharp contrast to the growth of rapid prototyping systems in the electronic domain, where the path from concept to system is often as short as a few weeks.

A simple example FSOE system is shown in Figure 1. This shows inputs and outputs of the system as digital electronic signals. Also shown are the electronic power signals for the electronic and optoelectronic units. A laser system is shown as a power source for the opto-electronic conversion module, which in this case would imply that the electronic to optical conversion is done by a a modulation technique rather than the use of direct sources such as laser diodes. A generic

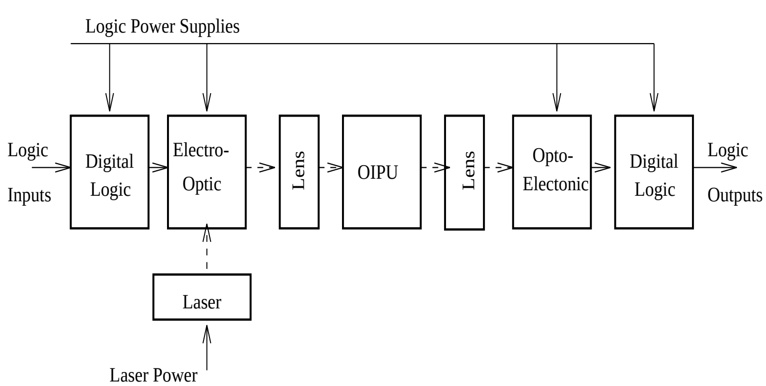


Figure 1: FSOE System

optical interconnection and processing unit (OIPU) is also shown. This could be a simple optical shuffle interconnection network, an optical memory sub-system, or some computational block which could be further described in lower levels of abstraction and decomposition [7][11].

In this paper we address the need for a computer aided design system for these hybrid opto-electronic information processing systems. There are three steps required to accomplish this goal. First, we must define the appropriate levels of abstraction for optoelectronic systems, analogous with the behavioral, logical, and electrical abstraction levels associated with digital electronic design. Second, we must characterize the necessary simulation models for these levels of abstraction. Third, we must integrate a multi-level simulation system that can use these models to perform the analysis required to close the synthesis / analysis design loop.

The rest of this paper is organized as follows. We first present a discussion of the space of optoelectronic system design. We follow that with a discussion of the abstractions which must be made in order to perform hierarchial design. We then discuss the models needed at these levels of abstraction focusing on two kinds of models: functional and parametric. We then give examples of some of our models for both signals, in particular models of light, and components. We follow with examples of functional simulation using Ptolemy[3]. We conclude with a discussion of the direction we see for this emerging discipline.

Optoelectronic System Design

One question which we must answer is: Can a single system support the various kinds of design that take place using very different system models, and implementation domains? The design of optoelectronic systems span the domains of free-space optics, optical fiber systems, integrated optics, as well as, high speed analog / digital electronics. A second question is: Can a single system support the multiple design tasks required for system level design? This includes the traditional functional design of systems, as well as the physical design of three dimensional hardware and the component design of electronic and optical devices. Our claim is that an integrated *system* design tool is both desirable and possible.

We can consider the process of optoelectronic systems design from our experience with CAD for electronic systems. Design is an iterative process of synthesis, or creation, followed by analysis, or evaluation with each iteration of this synthesis / analysis loop expanding pieces of the final design into a design hierarchy of components or sub-systems. The design of optoelectronic systems must additionally include explicit input / output analysis of the components at each level of the decomposition hierarchy as well as defining the technology that would be used for each component at that level. After those decisions are made, the components themselves can be refined. One view of the functionality space for such a CAD system is shown in Table 1. It incorporates a number of design disciplines, as well as examples of some of the design tasks required at different levels of design.

Therefore, to support optoelectronic systems design we must define the appropriate abstractions of optoelectronic systems, provide models for sub-systems in terms of those abstractions, and create analysis tools which use those models to help the designer perform the trade-offs, optimizations, and technology choices necessary to achieve high-quality systems with a moderate investment of design time.

Table 1: Abstractions of Optoelectronic Systems

Electronics	**Optoelectronics**	**Optics**	**Thermal**	**Packaging Mechanics**
Functional Models	Analytic models	Lens law, Image formation	Power density	Area, Volume
Logic, Timing		First order layout, Paraxial Gaussian beam propagation	First order thermal expansion coeff.	
Transistor, (SPICE)	Physical Models, Experimental data fitting	Real-ray tracing, Physical optics modeling, Optimization, tolerancing	Finite Element analysis	(Auto-Cad)

Abstraction

Figure 2 shows a “Basic Block” as an abstraction for general optoelectronic components. These are the basis of our abstraction mechanism. While this kind of black box model is very simplistic, it has several advantages. First, it is general enough to be used for decomposition. In other words, it is the analog of the “module” in digital electronic design. Second, it encompasses electronic, optoelectronic and optical components with the same abstraction. This allows the system designer to use a black box approach until he or she is ready to decide on the appropriate technology for each component of the system. Third, it explicitly models the electrical and optical *signal transformation*, of power, noise and physical attributes of the components. While this is often ignored in the early design phases of electronic systems, it is an essential aspect of many optoelectronic systems. As discussed below, in optics we also need to explicitly model *signal propagation* as well. By explicitly modeling propagation, we encompass the issues of dispersion, cross talk, noise, etc., which are essential for the design of a free space system.

As shown in Figure 2, each component in the system is modeled as an object which could take its inputs in either electronic or optical form, and generate its outputs in either form as well. Power for amplification or modulation could also be either electronic or optical. Clearly for most

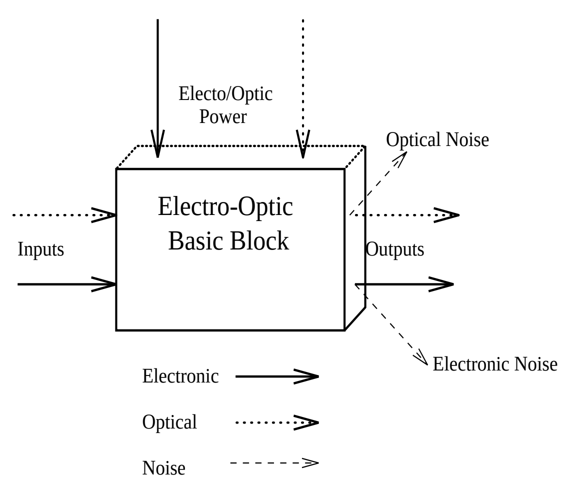


Figure 2: Basic Block

components, some of these paths would only exist in one form. For instance, a continuous laser source would only have an electronic power source and an optical output. While a liquid crystal spatial light modulator (SLM) could have electronic control inputs, optical data inputs, and optical data outputs, as well as an electronic power input.

Models

Tied to these basic blocks, we need three kinds of models *functional models*, *physical models*, and *parametric models*. Functional models are similar to those typical in digital electronic CAD. They allow us to answer the question: What does the system (as designed) do? We can use them for simulation and analysis of the behavior of the system operating on its input values and generating output values. The models themselves can exist at different levels of abstraction. Examples of high-level functional models are behavioral models. For instance, the equation:

$$\vec{F}(x, y, t_i) = \vec{a}(x, y, t_{i-k}) \wedge \vec{b}(x, y, t_{i-l})$$

states that the function of a block is to compute the logical *and* of two binary arrays that have values separated in space, and therefore in time. Other types of functional models are geometric optical models, as shown in Figure 3, which illustrates a shifting and masking operation, and optoelectronic device models, analogous to spice models for electronic devices.

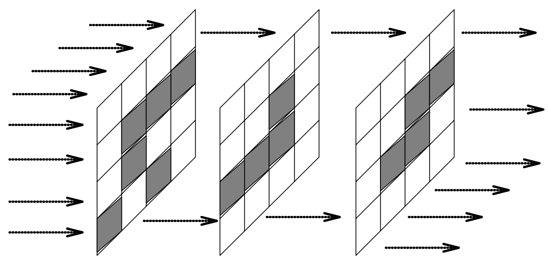


Figure 3: Functional Optical Model (SLM)

Physical models answer the question: What does the system look like? We need three dimensional physical models for the optical paths in the system, as well as more traditional "optical cad" for example, lens design.

The third types of models we need are parametric models. We need these models to answer the question: Can we build a system with the required specifications using the components we have chosen? For electronics, these would be parameters like the bandwidth, and power consumption of the components. Similarly, in optics we need to consider all the characteristics of the components that affect the quality of the information which flows through the system.

At each abstraction level which we choose to model, we need to define the input/output characteristics of the basic blocks in terms of "characteristic parameters". As examples, the characteristics of some optical components are shown in Table 2. Note that not all of these parameters are appropriate for all abstraction levels. Also, in order to perform analysis, we need to define a corresponding set of characteristic parameters for the electronic and optical signals that propagate in these systems. Some examples are shown inTable 3. In general, these parameters should be appropriate for engineering or design decisions, rather than at the level of fundamental physics. Based on the characteristic parameters of the signals that carry information between the components, we can then define the parametric models of the components in terms of the ways they *transform* the characteristic parameters of the signals. It is important to note that optical signals are inherently based on modulation of a “carrier” of light. The characteristics of this carrier are as important to model as the signal itself. Analogous to the way we to model components, we need have a flexible model for the *propagation* of optical signals as well.

Table 2: Properties of Optical Components

Device	**Properties**
Lens	material, λ, polarization, losses, reflection, MTF, PSF, phase map, geometry, aberration, absorption
Polarizing beam splitter	size, λ, contrast, S / P, angle, polarization
Spot array generator	λ, number of spots, distance, spot size, spot uniformity, spot spacing, geometry
Optical isolator	intensity out, intensity in, absorption, λ
Beam collimator	shape of input beam, λ, shape of output beam, polarization
Laser	power out, power in, λ, δλ, modes, duty cycle, CW, modulation, spot size, shape, solid angle, polarization

Table 3: Properties of Electronic and Optical Signals

Electronic Signals	**Optical Signals**
amplitude-phase	amplitude-phase
signal spectrum	signal spectrum
noise spectrum	noise spectrum
modulation	modulation
pulse width / spectrum	pulse width / spectrum
power	power
	coherence
	light spectrum
	polarization
	spatial distribution
	spatial mode content

Models of Light Propagation

Figure 4, based on [15], shows the full range of abstraction which could be used for modeling optical signal propagation. The most basic model is called Ray Optics, or geometrical optics where we use simple geometry and the normal of the propagating wave. Gaussian Beams are models of paraxial waves, a simplification of more general Wave Optics, which uses scalar waves to model propagation. More general is Electromagnetic Optics where the true E/M Fields are directly modeled. Finally, Quantum Optics or quantum electrodynamics are required to model propagation in certain non-linear optical materials. As shown below Ray optics are appropriate for the most basic models, while Gaussian beam optics models are more appropriate for typical FSOE applications.

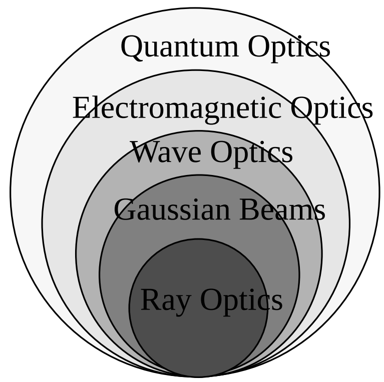


Figure 4: Models of Light

Geometric Propagation Models

If we assume that we have ideal sources, ideal components, that the dimensions of the components are much larger than the wavelength of light and we have no interactions based on intensity, frequency polarization or phase we can use the most basic model of propagation, geometric or Ray optics. We present a brief description of both optical signal propagation and ideal optical device models below. See [15] for a more complete description.

For this discussion we assume that light is propagating in the positive z direction. An ideal ray of light at any point along the z axis is characterized by its x, y position and its ρ and θ angles with the z axis in the x and y planes. The geometric transformations performed on this ray by its passing through linear, ideal optical components can be captured in the simple 2-d ray transfer matrix **M**:

$$\begin{bmatrix} y' \\ \theta' \end{bmatrix} = M \begin{bmatrix} y \\ \theta \end{bmatrix} \qquad \begin{bmatrix} x' \\ \rho' \end{bmatrix} = M \begin{bmatrix} x \\ \rho \end{bmatrix}$$

The value of the transformation matrix **M** for some common components are shown in Table 4. Analogous to the transformation matrices used in graphics and image processing, propagation through multiple or cascaded components can be modeled by a concatenation of multiplications. These geometric models give some insight into the physical (3d) configuration of optoelectronic systems. However, they do not handle many important issues essential to designing the non-ideal and non-linear devices needed for information processing systems.

Table 4: Ray Transfer Matrices

Component	Matrix M
Linear Component	$\begin{bmatrix} A & B \\ C & D \end{bmatrix}$
Propagation in space	$\begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix}$ for distance, d
Refractive Boundary	$\begin{bmatrix} 1 & 0 \\ 0 & \frac{n_1}{n_2} \end{bmatrix}$ for n_1 to n_2 boundary
Thin Lens	$\begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix}$ for focal length, f

Gaussian Propagation Models

For modeling non-ideal sources that generate wavefronts making small angles to the z axis, such as laser sources, we can use a Gaussian Beam approximation [9]. Here we minimally introduce parameters for the wavelength, λ, the *beam waist*, and the *intensity* of the light. Using the abstraction of a "beam" we can still model the propagation of the center of the beam using the algebra for geometric propagation of rays with the addition of equations for the transformations for the intensity and beam waist for each component. Further, we must add a notion of optical power. Optical power is the integral of the intensity of the beam over the area of incidence. In the ideal case, beams are narrow and physically far apart. In practical systems, beams disperse, and arrays of beams travel through common components. The beams are detected by arrays of detectors where practical constraints on component sizes and spacing makes overlap of beams non-negligible and leads to cross talk.

In order to understand the nature of the models at this level of abstraction, we present some of the defining equations for Gaussian beam propagation. The intensity of a Gaussian beam as a function of radial and axial position is given by:

$$I(r,z) = I_o\left[\frac{W_0}{W(z)}\right]^2 \exp\left[-\frac{2r^2}{W^2(z)}\right]$$

The beam waist radius, *W,* defined as the radial distance where the intensity has fallen to $1/e^2$ of the peak, is:

$$W(z) = W_0\left[1 + \left(\frac{z}{z_0}\right)^2\right]^{1/2}$$

The beam divergence is characterized by z_0, the Rayleigh range, and is related to the initial waist W_0 and the wavelength λ by:

$$z_0 = \frac{\pi W_0^2}{\lambda}$$

The transformation of the beam waist performed by various components can be modeled by using a complex variable: $q = z + jz_0$ where z is the distance to the beam waist. For each component that the Gaussian beam traverses, the new q parameter, for both the location of the new waist and new Rayleigh range is given by:

$$q' = \frac{Aq + B}{Cq + D}$$

That is, for each optical component, the complex variable q is transformed by the same ABCD parameters of the corresponding ray transform matrix, **M**, as is the center of the beam itself. Using these equations we can model light from individual lasers, arrays of laser sources or modulators propagating through free-space or passive components, and being detected by active receivers.

However, the Gaussian beam approximation fails in several instances. In particular it is inaccurate, when the sources themselves do not generate a Gaussian intensity wavefront, when the direction of propagation of the light does not meet the paraxial criteria, and in general when diffractive effects must be considered. Further, the models assume that the beams themselves are not significantly clipped by the optical components through which they pass. In those cases, the equations for intensity, and beam waist break down [13]. This can occur for systems with arrays of microlenses where logical or physical constraints cause splitting or clipping of the Gaussian beams.

Device Models

To complete our description of electro-optic models we present some typical active device models for transmitters and receivers at a level of abstraction required for system level design and analysis.

Transmitters

Transmitters can be either based on an emitting source technology such as vertical cavity surface emitting lasers (VCSELs) [8] or a modulation technology such as multiple quantum well (MQW) modulators [14]. Figure 5 shows driver electronics and a MQW modulator reflecting a portion of the incident light, P_{om}, as modulated optical power, P_{optic}.

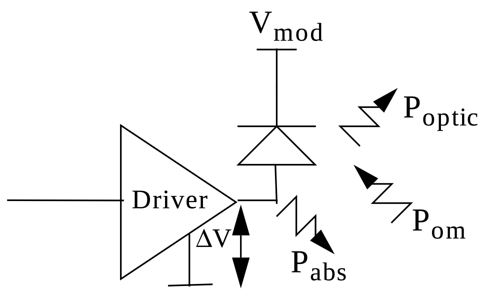


Figure 5: Generic Electro-Optic Modulator

Both reflective and transmissive modulators are possible. In either case the key parameter is the amount of optical power which is absorbed by the modulator as a function of the controlling voltage. Table 5 shows typical parameters for a MQW modulator [5]. The optical intensity modulation can be modeled by:

$$I_{abs}(V) = \frac{I_i k(V)}{1 + \frac{I_i}{I_s(V)}}$$

Figure 6 shows a plot of this equation for the values reported in [5]. This figure shows the power absorbed by the MQW modulators for modulation voltages of 10, 8, 6, 4, 2 and 0 volts, on the curves from top to bottom respectively.

Table 5: Generic MQW Modulator Parameters

Parameter	**Typical Value**	**Description**
V_{mod}	10 V	Bias voltage
ΔV	10 V	Driving Voltage
P_{om}	10mW	Incident Optical Power
P_{abs}	0.8 - 0.2 mW / detector	Absorbed Optical Power
η_{MQW}	0.22 - 0.53 A / W	Power Responsivity
Is(v)	244 - 799 W / cm^2	Absorption Saturation Intensity
k(v)	0.19 - 0.30	Slope of Absorption / Intensity Curve
A	400 - 1600 μm^2	Area of Modulator

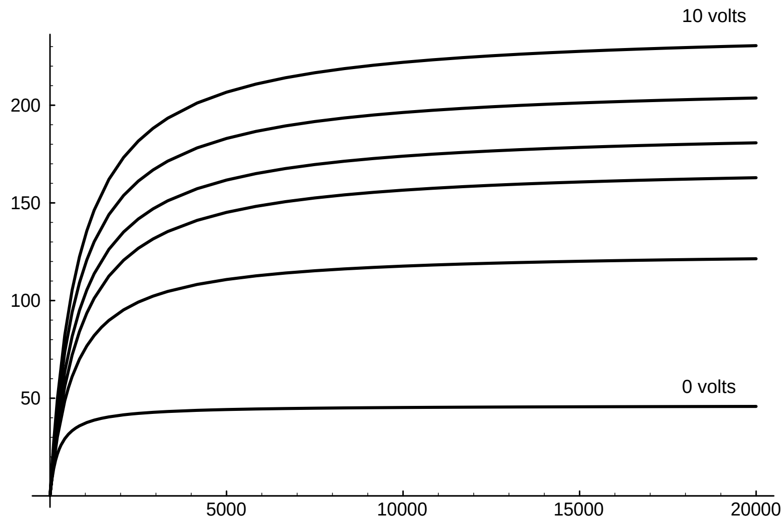


Figure 6: Absorbed vs. Incident Optical Power (W / M^2)

As can be seen in this plot, the modulation depth of these components marginal. However, they are very efficient in terms of the amount of electrical current due to the optical power absorbed that must be dissipated by the by driver electronics, given as η_{MQW}.

On the other hand, for laser diode emitters the key parameters are shown in Table 6. A plot of the electrical input to optical output power relation is shown in Figure 7 for diodes with 2.5 and 4 volt thresholds. Here we see a linear power conversion relationship between electrical and optical power.

Table 6: Generic Laser Diode Parameters

Parameter	Typical Value	Description
$V_{Threshold}$	2.5 - 4V	Bias voltage
$I_{Threshold}$	2mA	Bias current
η_{LI}	0.6 W / A	Light / Current conversion efficiency
λ	850 nm	Wavelength
S	5-10μm	Spot size
θ	8-15˚	Solid angle

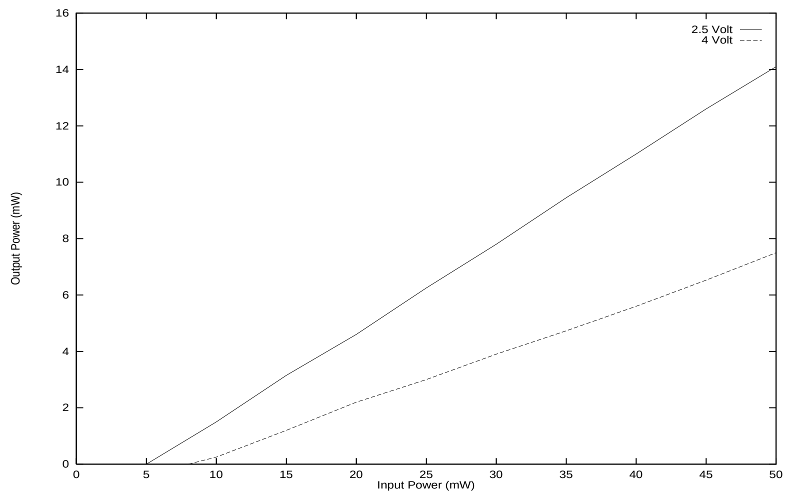


Figure 7: Laser Diode Power Out vs. Power In

Receivers

A generic single ended receiver is shown in Figure 8. The two components are a photo-diode and a multi-stage transimpedence amplifier. Typical values for the key parameters are given in Table 7. This gives the following parameterized equation for output voltage swing:

$$\Delta V_o = min\left[\frac{2^{(N_{st}-1)} R_T P_{optic}}{3\pi C_p f_t \left[\frac{BR}{f_t}\right]^{(N_{st}+1)}}, V_{DD}\right]$$

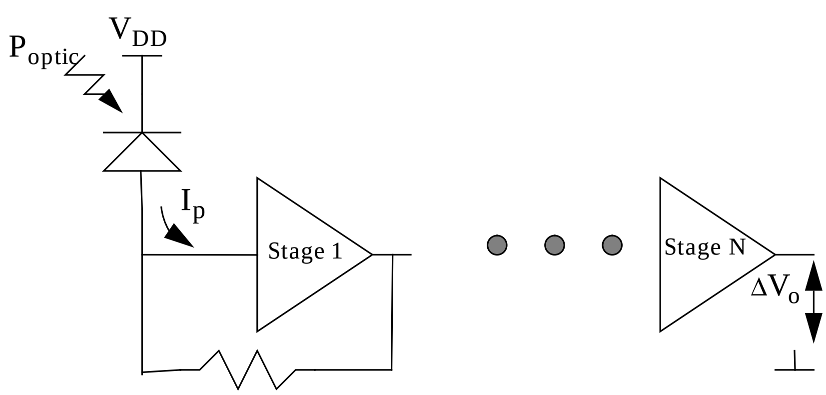


Figure 8: Generic Single Ended Receiver

Table 7: Generic Receiver

Parameter	Typical Value	Description
N_{st}	2-3	Number of Stages
ΔV_o	3 V p-p	Output voltage swing
P_{optic}	10µW-1mW	Input Optical Power
BR	100-500MHz	Bit Rate
R_T	0.5 A / W	Detector Responsivity
C_p	170ff	Sum of capacitances of photo diode, input of first stage, and parasitics to first stage
f_t	10^9Hz	Amplifier fabrication technology parameter
V_{DD}	5 V	Power supply

Figure 9 shows this equation plotted for a Bit Rate of 300MHz and a two stage transimpedence amplifier. The other parameters are from Table 7. Figure 10 shows the same equation plotted for 100µW of optical power and 1, 2, 3, and 4 stages of amplification.

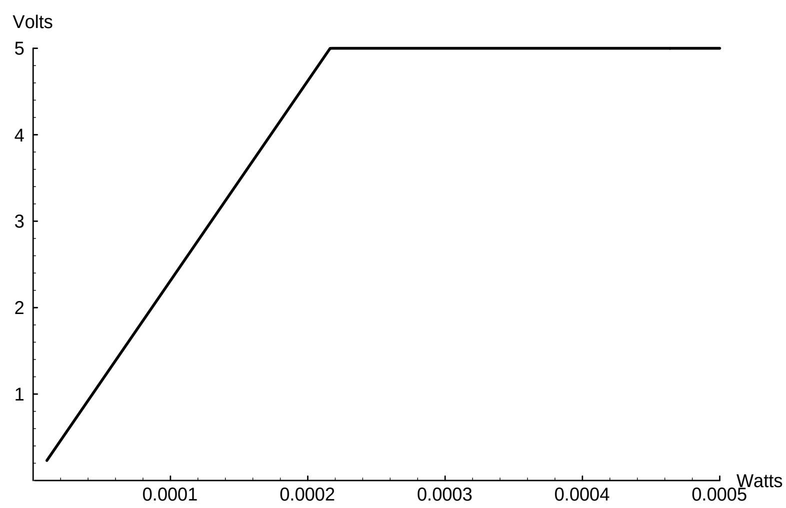


Figure 9: Voltage Swing vs. Optical Power

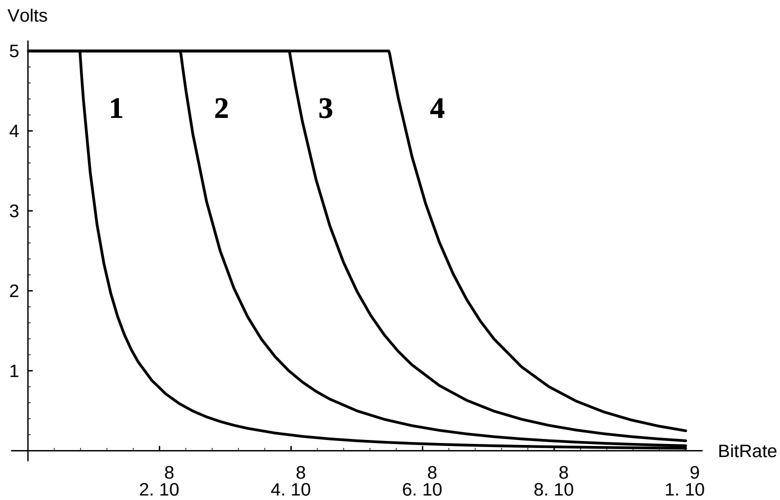


Figure 10: Voltage Swing vs. Bit Rate

Parametric Analysis

Once we have the input/output characteristics of the basic blocks (at whatever abstraction level) we can begin to perform the analysis to determine the input/output characteristics of the entire system. This kind of analysis is similar to current analog CAD tools which work in terms of frequency response, slew-rate, Q-factor, etc. [6].

Even in systems as abstract as Figure 1, we can assign parametric specifications for the components and therefore begin to characterize the system behavior. As an example of the type of analysis that might be done, the left side of Figure 11 shows the relationship of a signal waveform to the probability density functions, $p_m(x)$ of signal amplitude values for the logic levels zero and one, with the sum of all noise sources assumed to have a Gaussian distribution:

$$p(x) = \frac{e^{-(x-m)^2/\left(2\sigma^2\right)}}{\sqrt{2\pi}}$$

Here m is the mean value for the logic level and σ is the standard deviation of the distribution. If we consider a receiver in the opto-electronic sub-system that has a single threshold value at $\frac{m_1 - m_0}{2}$, the shaded area below the curves shows the probability of a bit error. That is, the probability of either a zero being detected as a one or a one being detected as a zero. Following the derivation in [16], for this system the relationship of the probability of a single bit error occurring, P_e, to the signal to noise ratio (S/N) is:

$$P_e = \frac{1}{2}\text{erfc}\left(\frac{(S/N)^{1/2}}{2\sqrt{2}}\right)$$

where **erfc** is the complementary error function. This defines the bit error rate (BER) of the system and is plotted against the signal to noise ratio (in dB) in Figure 12.

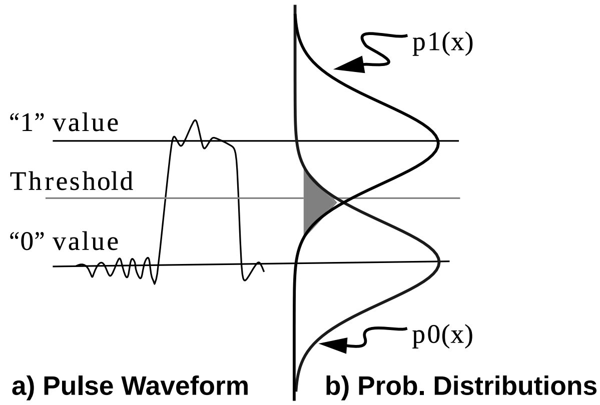


Figure 11: Parametric Model (BER)

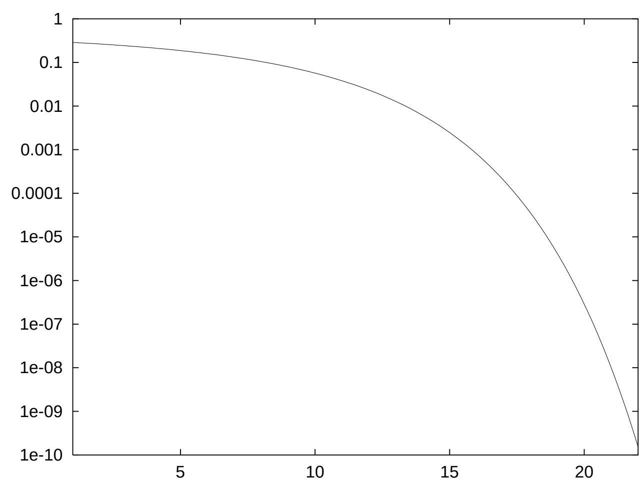


Figure 12: BER vs. S / N

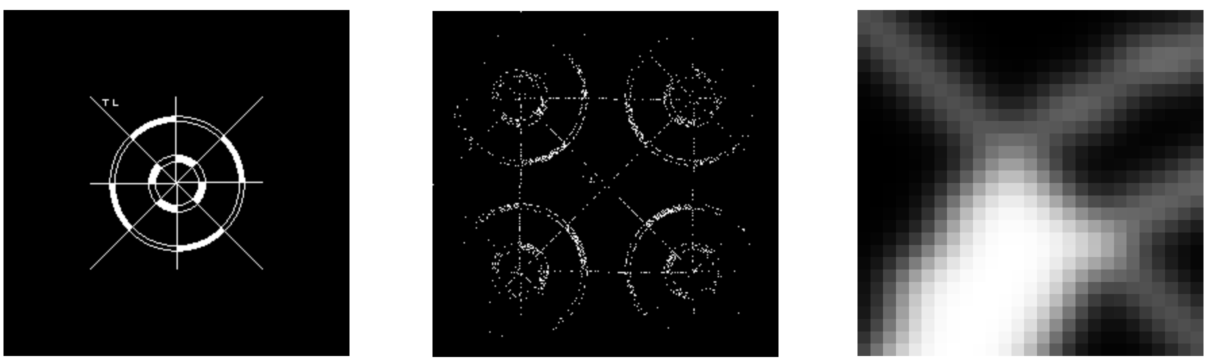
We should note that real systems have many noise sources (including those in the receiver itself) that are often not Gaussian. Cross-talk between signal channels is also a noise source. On the other hand, modulation and coding methods, as well as differential signaling, and other techniques can be used to reduce the bit error rate. These would all have to be modeled in the analysis system.

Functional Analysis Examples

To provide a simulation framework for the models we are developing, we are investigating the use of Ptolemy [3] which is a generalized simulation framework used for rapid prototyping of digital signal processing systems. By using a pre-existing framework, which already has support for system software, digital simulation, and signal processing we are building an integrated system which meets the needs of optoelectronic systems design.

Figure 13 was generated by using extensions to Ptolemy to support simple free space optical systems. Figure 13A is an input array of 128x128 light sources. Figure 13B shows a simulation of paraxial geometric rays to model the functionality of a 2x2 lenslet array performing a fan-out operation. The lack of density in the output is a result of using single light rays emanating from each source with small random angles. This model gives only the most basic functional information about how the lenses work.

As discussed above, in order to address issues such as power and cross talk, the simulation shown in Figure 13C moves to a lower level of abstraction using Gaussian beams. We can now perform more detailed analysis. This figure shows a small piece of the image as seen by an array of detectors integrating the power from each beam in the source array.



A B C

Figure 13: Optical Functional Simulation

Using the synchronous data flow domain (SDF) we have defined our own message class derived from the Ptolemy message class to support both geometric and Gaussian propagation. Some of the stars we have developed are shown in Figure 14. These include lenses, arrays of lenses, beam splitters, spatial shifting, superposition, inverting and masking operators. Also shown are image read, view, write and integrate stars. We note that the “black hole” is useful for performing type checking for our message class.

An example using these Ptolemy stars is shown in Figure 15. This figure depicts the use of Ptolemy components at the level of ray optics to simulate the optical symbolic substitution method presented by Brenner [2]. The input image Figure 15A is read in then split by an ideal beam splitter. The split images are then spatially shifted, with the amount and direction of shift determined by the search pattern. Next, the shifted images are superimposed upon each other, inverted and then masked with the mask pattern shown in Figure 15B; the mask pattern is also dependent upon the search pattern. Now that the search patterns are located, the image is re-split and spatially shifted according to a scribing pattern. Finally, the shifted images are superimposed to produce the output image shown in Figure 15C.

Figure 14: Electro-Optic Stars in the Ptolemy SDF Domain

A B C

Figure 15: Optical Symbolic Substitution using Ptolemy

Using Ptolemy has several advantages. In particular it provides a simple graphical user interface, a built in simulation engine, and a method for iteration. The real advantages we expect to realize with Ptolemy are its support for varied domains, simulation across those domains and access to existing signal processing libraries. Of course the disadvantage of using Ptolemy is that we are tied to another tool developer's code and have to live with their decisions.

Discussion

A key requirement of the design system is the ability to provide analysis tools at the opto-electronic systems level. At this level the design system must support parametric modeling and analysis of the sub-systems in order to allow the designer to perform design trade-offs in terms of both technology and architecture. This will improve the system design task in several important ways. It will enable a system architect to perform truly system-wide "what-if" analyses, rather than only analyzing a subset of the system constraints. Certain aspects of the system design are themselves very multi-disciplinary. System and device level packaging is one example, and the lack of a widely accessible tool to facilitate this design task and quantify the trade-offs is becoming quite apparent in the FSOE community. A tool which provides a conceptual interface to powerful modeling and optimization programs will enable those programs to be used by researchers and designers with little experience in that aspect of the design space.

One important issue in the discussion of these tools is their usefulness in light of the wide variety of commercially available single-discipline CAD tools (i.e., for analog or digital electronic circuit design, for geometrical or physical optical system design, for FEA thermal analysis, etc.). An effective FSOE system should concentrate on two main issues: 1) Identification of required design areas or tasks for which no useful CAD tool exists 2) Creation of system level interfaces to provide simple, rapid and more intuitive generation of the inputs to, and filtering/analysis of the outputs from these other tools.

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