Computer Aided Design of Free-Space Optoelectronic Interconnection (FSOI) Systems

S. P. Levitan[✣], P. J. Marchand[✦], M. A. Rempel[✣], D. M. Chiarulli[★], F. B. McCormick[✦]

Department of Electrical Engineering[✣] and Department of Computer Science[★]
University of Pittsburgh

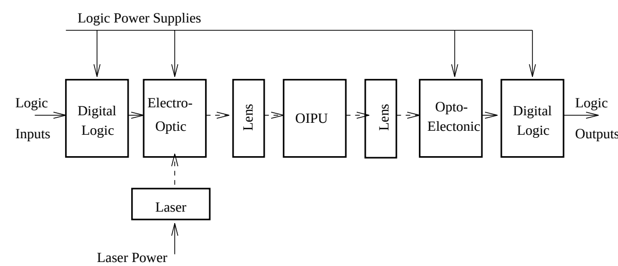
Department of Electrical and Computer Engineering[✦]
University of California, San Diego

National Science Foundation - MIP-9421777

Overview

We are building a Computer Aided Design tool for the simulation and analysis of optoelectronic interconnection systems.

- We Need Help!



Requirements

- What are the requirements for a CAD system to design hybrid optoelectronic information processing systems?
- Can a single system support various implementation domains?
  - Free space optics, Fiber waveguides, Integrated optics, Analog / Digital Electronics
- Can it support multiple design tasks?
  - Functional design, Physical design, Component design

System Abstractions

Electronics	**Opto-electronics**	**Optics**	**Thermal**	**Packaging Mechanics**
Functional Models	Analytic Models	Lens law, Image formation	Power density	Area, Volume
Logic, Timing		First order layout, Gaussian beam propagation	First order thermal expansion coeff.	
Transistor, (SPICE)	Physical Models, Experimental data fitting	Ray tracing, Physical optics, Toler-ancing	Finite Element analysis	(Auto-Cad)

Design Methodology

We need to define a design methodology:

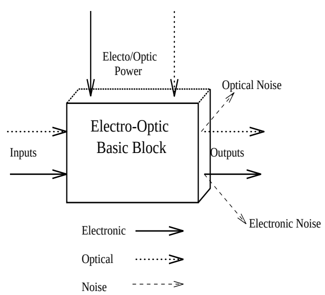
- Given a problem in what order / how do we design and analyze a solution?
  - Top Down
  - Bottom Up
  - Technology driven
  - Need driven

Three Steps

- Define the appropriate levels of abstraction
  - Analogous with *behavioral*, *structural*, *electrical*, and *physical* abstraction levels associated with digital electronic design
- Define models for components at these levels of abstraction
  - Need *Functional* models as well as *Parametric* models
- Build analysis and simulation tools to provide feedback to the designer to close the synthesis / analysis design loop.

Basic Block

- Inputs, Outputs, and Power can be in either Electrical or Optical domains (or both)
- Explicitly model power and noise

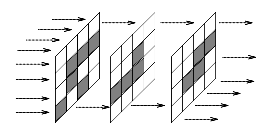


Models

Physical

$$\begin{bmatrix} y' \\ \theta' \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} y \\ \theta \end{bmatrix}$$

Functional



Parametric

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

Characteristics of 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

DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

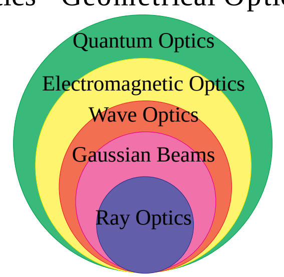
Characteristics of Devices

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

DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

Abstractions of Optical Signals

- Quantum Optics - Quantum Electrodynamics
- Electromagnetic Optics- E/M Fields
- Wave Optics - Scalar Waves
- Gaussian Beams - Paraxial Waves
- Ray Optics - Geometrical Optics



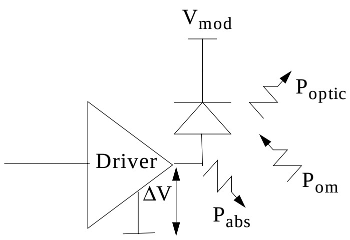
DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

Abstractions of Devices

- Electronic: C-code, VHDL, Spice
- Optical:
  - Rays: ABCD Ray Transform Matrix
  - Gaussian:
    - intensity
    - waist
    - wavelength
- Optoelectronic:?

DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

Modulators*



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

* C. Fan, et. al. "Digital free-space optical interconnections: a comparison of transmitter technologies", Applied Optics 34(7) pp. 3103-3115, 10 June 1995.

DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

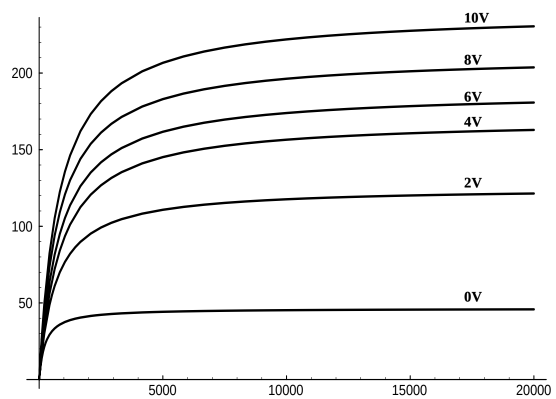
Generic MQW Modulators

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_{MQM}	0.22 - 0.53 A / W	Power Responsivity
Is	244 - 799 W / cm^2	Absorption Saturation Intensity
k	0.19 - 0.30	Slope of Absorption / Intensity Curve
A	400 - 1600 μm^2	Area of Modulator

DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

UNIVERSITY OF PITTSBURGH

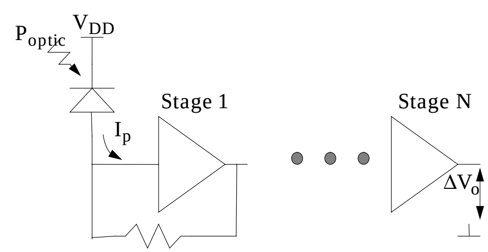
Absorbed vs. Incident Optical Power (W / M²)



DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

UNIVERSITY OF PITTSBURGH

Receivers



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

DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

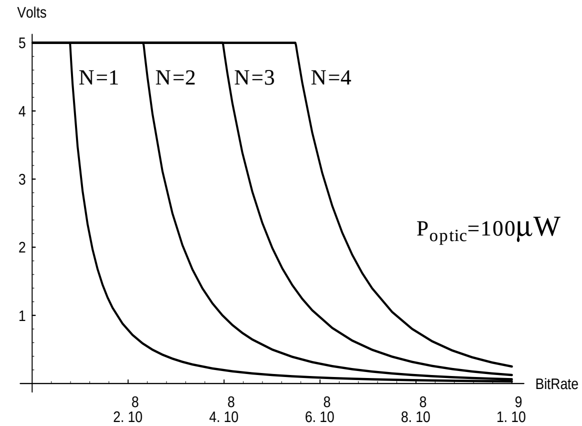
Receiver Parameters

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

DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

UNIVERSITY OF PITTSBURGH

Voltage Swing vs. Bit Rate



DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

UNIVERSITY OF PITTSBURGH

Ptolemy*

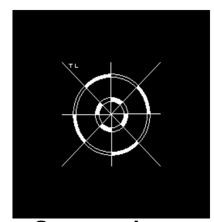
- Advantages:
  - Graphical User Interface
  - Built in Simulation
    - Method for Iteration
  - Support for Varied Domains
  - Simulation Across Domains
  - Access to Signal Processing Libraries
  - Large User Community
- Disadvantage:
  - Tied to Other Developer's Code

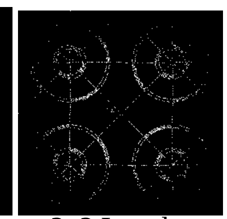
* J.Buck, S. Ha, E.A. Lee, and D. G. Messerschmitt, "Ptolemy: A Framework for Simulating and Prototyping Heterogeneous Systems," Int. Journal of Computer Simulation, special issue on "Simulation Software Development," January, 1994.

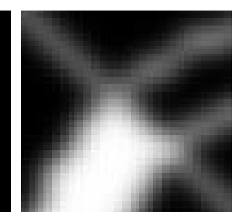
DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

UNIVERSITY OF PITTSBURGH

Simulation

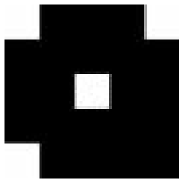

Source Array

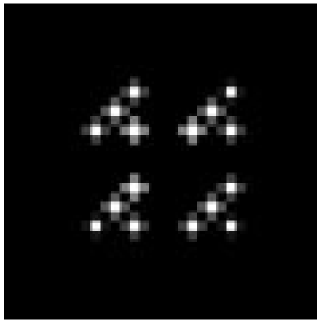

2x2 Lenslet


Gaussian

DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

Examples*

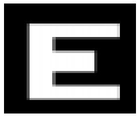


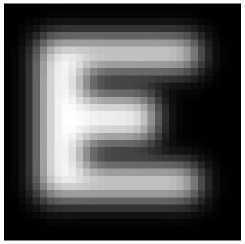


* lambda: 8.5e-07, spotsize: 2e-06, spacing: 2e-06 Waist Radius: 1e-06, Rayleigh Range: 3.69599e-06, Input array is a 5 5 positions are from -4e-06 -4e-06 to 4e-06 4e-06 space of 5e-05 lens array of 4 with focal length 2.5e-05, diameter 1e-05 space of 5e-05 Image from 1089 (33 x 33) detectors of size 2e-06 spaced 2e-06 apart*

DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

Examples*





* lambda: 7e-07, spotsize: 0.001, spacing: 0.002 Waist Radius: 0.0005, Rayleigh Range: 1.122, Input array is 16 16 with max intensity 255 initial positions are-0.015 -0.015 to 0.015 0.015 s 8 (8 meters) i 4096.001.001 (4 detectors per source)(target2.epsi file the same parameters were used)

DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

Summary - Future Work

- We are just getting started - we need help!
- Focus on free-space interconnections
- Define clear abstractions for
  - Signals
  - Transformations
- Integrate other tools
  - CodeV
  - Spice

DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003

DEPARTMENT OF ELECTRICAL ENGINEERING
348 BENEDUM ENGINEERING HALL
PITTSBURGH, PA 15261
+1-412-624-8000 FAX: +1-412-624-8003