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

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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

<table>
<thead>
<tr>
<th>Electronics</th>
<th>Optoelectronics</th>
<th>Optics</th>
<th>Thermal</th>
<th>Packaging Mechanics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional Models</td>
<td>Analytic Models</td>
<td>Lens law, Image formation</td>
<td>Power density</td>
<td>Area, Volume</td>
</tr>
<tr>
<td>Logic, Timing</td>
<td>First order layout, Gaussian beam propagation</td>
<td>First order thermal expansion coeff.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transistor, (SPICE)</td>
<td>Physical Models, Experimental data fitting</td>
<td>Ray tracing, Physical optics, Tolerancing</td>
<td>Finite Element analysis</td>
<td>(Auto-Cad)</td>
</tr>
</tbody>
</table>
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:
  \[
  \begin{bmatrix}
  y \\
  \theta
  \end{bmatrix} = \begin{bmatrix}
  A & B \\
  C & D
  \end{bmatrix} \begin{bmatrix}
  x \\
  \theta
  \end{bmatrix}
  \]

- Functional:
- Parametric:
  \[
  P_e = \frac{1}{2} \text{erfc} \left( \frac{(S/N)^{1/2}}{2^{1/2}} \right)
  \]
### Characteristics of Signals

<table>
<thead>
<tr>
<th>Electronic Signals</th>
<th>Optical Signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>amplitude-phase</td>
<td>amplitude-phase</td>
</tr>
<tr>
<td>signal spectrum</td>
<td>signal spectrum</td>
</tr>
<tr>
<td>noise spectrum</td>
<td>noise spectrum</td>
</tr>
<tr>
<td>modulation</td>
<td>modulation</td>
</tr>
<tr>
<td>pulse width / spectrum</td>
<td>pulse width / spectrum</td>
</tr>
<tr>
<td>power</td>
<td>power</td>
</tr>
<tr>
<td>coherence</td>
<td></td>
</tr>
<tr>
<td>light spectrum</td>
<td></td>
</tr>
<tr>
<td>polarization</td>
<td></td>
</tr>
<tr>
<td>spatial distribution</td>
<td></td>
</tr>
<tr>
<td>spatial mode content</td>
<td></td>
</tr>
</tbody>
</table>

### Characteristics of Devices

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

### 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

### Abstractions of Devices

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

\[ I_{\text{abs}}(V) = \frac{I_{\text{mod}}(V)}{1 + \frac{I_{\text{mod}}(V)}{I_{\text{s}}(V)}} \]


Generic MQW Modulators

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{\text{mod}})</td>
<td>10 V</td>
<td>Bias voltage</td>
</tr>
<tr>
<td>(\Delta V)</td>
<td>10 V</td>
<td>Driving Voltage</td>
</tr>
<tr>
<td>(P_{\text{om}})</td>
<td>10mW</td>
<td>Incident Optical Power</td>
</tr>
<tr>
<td>(P_{\text{abs}})</td>
<td>0.8 - 0.2 mW/detector</td>
<td>Absorbed Optical Power</td>
</tr>
<tr>
<td>(\eta_{\text{MQM}})</td>
<td>0.22 - 0.53 A/W</td>
<td>Power Responsivity</td>
</tr>
<tr>
<td>(I_s)</td>
<td>244 - 799 W/cm²</td>
<td>Absorption Saturation Intensity</td>
</tr>
<tr>
<td>(k)</td>
<td>0.19 - 0.30</td>
<td>Slope of Absorption/Intensity Curve</td>
</tr>
<tr>
<td>(A)</td>
<td>400 - 1600 µm²</td>
<td>Area of Modulator</td>
</tr>
</tbody>
</table>

Absorbed vs. Incident Optical Power (W/M²)

\[ \Delta V = \min \left[ \frac{2 \left( \frac{N_{\text{st}} - 1}{R_{\text{p}} P_{\text{optic}}} \right) V_{\text{DD}}}{3 \pi C_{\text{p}}' \left( \frac{R_{\text{p}}}{R_{\text{t}} + 1} \right) V_{\text{DD}}} \right] \]

Receivers
### Receiver Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N&lt;sub&gt;st&lt;/sub&gt;</td>
<td>2-3</td>
<td>Number of Stages</td>
</tr>
<tr>
<td>Δ&lt;sub&gt;V&lt;sub&gt;o&lt;/sub&gt;</td>
<td>3 V p-p</td>
<td>Output voltage swing</td>
</tr>
<tr>
<td>P&lt;sub&gt;optic&lt;/sub&gt;</td>
<td>10&lt;sup&gt;µ&lt;/sup&gt;W</td>
<td>Input Optical Power</td>
</tr>
<tr>
<td>BR</td>
<td>100-500MHz</td>
<td>Bit Rate</td>
</tr>
<tr>
<td>R&lt;sub&gt;e&lt;/sub&gt;</td>
<td>0.5 A/W</td>
<td>Detector Responsivity</td>
</tr>
<tr>
<td>C&lt;sub&gt;p&lt;/sub&gt;</td>
<td>170ff</td>
<td>Sum of capacitances of photodiode, input of first stage, and parasitics to first stage</td>
</tr>
<tr>
<td>f&lt;sub&gt;1&lt;/sub&gt;</td>
<td>10&lt;sup&gt;9&lt;/sup&gt;Hz</td>
<td>Amplifier fabrication technology parameter</td>
</tr>
<tr>
<td>V&lt;sub&gt;DD&lt;/sub&gt;</td>
<td>5 V</td>
<td>Power supply</td>
</tr>
</tbody>
</table>

### Voltage Swing vs. Bit Rate

![Graph showing voltage swing vs. bit rate]

- P<sub>optic</sub> = 100<sup>µ</sup>W

### 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

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Examples:

* lambda: 3.5e-07, spotsize: 2e-06, spacing: 2e-06
Waist Radius: 1e-06, Rayleigh Range: 3.69599e-06,
Input array is a 5x5 positions are from -4e-06 to 4e-06 space of 6e-06
len array of 4 with focal length 2.5e-05, diameter 1e-05 space of 6e-06
Image from 1089 (33 x 33) detectors of size 2e-06 spaced 2e-06 apart*

Examples:

* lambda: 7e-07, spotsize: 0.001, spacing: 0.002
Waist Radius: 0.0005, Rayleigh Range: 1.122,
Input array is 16x16 with max intensity 255 initial positions are -0.015 to 0.015
spaced 8 (8 meters) 4096.001 (4 detectors per source) target2.epsi file the same parameters were used

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