VCSEL Device and System Design for Manufacturing
Multi-level modeling solution

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Synopsys Today: From Silicon to Software

FY18 Revenue: $3.121B
Employees: >13,854
Patents: 3,201
Offices: 116

- #1 electronic design automation tools & services
- Broadest IP portfolio and #1 interface, analog, embedded memories & physical IP
- ‘Leader’ in Gartner’s Magic Quadrant for application security testing
Synopsys Sees Optics and Photonics as a Key Enabling Technologies

Entered the Field in 2010

- Acquired Optical Research Associates, Brandenburg, and RSoft Design Group
  - Full spectrum of optical and photonic design solutions and services

- Expanded portfolio for photonic IC design by acquiring PhoeniX Software in 2018
  - Complete PIC design flow from a single vendor with one support channel

- Largest dedicated optics and photonics software development and support team
Outline

• Introduction: History and Applications
• Design Objectives and Choice of Design Flow
• VCSEL: Circuit- and System-level Modeling
• VCSEL: Device-level Modeling
• Conclusion
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History and Application(s)

ToF and LiDAR

VCSEL swept-frequency source

FaceID: VCSEL arrays
History and Application(s)

AR/VR

High-speed Transceiver

[Image: AR/VR application diagram]

[Image: High-speed Transceiver component]

[Image: RSoft Simulated BSDF diagrams]
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Problems to Solve

- Predictive models capturing thermal, electrical and optical behavior needed to enable design for manufacturing (DfM)
- Modeling presents several challenges:
  - Interdependence of physical parameters makes parameter extraction difficult
  - Thermal effects, packaging parasitics must be accounted for
  - Manufacturing variability results in performance variations. Must be able to predict performance bounds for given tolerances
  - Driver circuit dynamics play crucial role in modulation bandwidth and power output
  - Often optical and electrical design teams are different but inter-dependent
  - Interference from reflections affect power distribution and phase noise
Design Objectives and the Choice of Flow

Two possible approaches

1. Bottom-up: Starting with known VCSEL specs, evaluate system performance:

   VCSEL Characteristics → Electrical + Optical VCSEL Model Extraction → Electrical Circuit Simulation → Photonic Circuit Simulation → Receiver and Measurements

   LaserMOD Design/Commercial Component Selection to OptSim Circuit VCSEL Modeling Flow

2. Top-down: Starting with targeted system performance, evaluate VCSEL selection/design:

   Optimize VCSEL Performance → Optimize Electrical Performance → Photonic Circuit Simulation → Receiver and Measurements

   OptSim Circuit VCSEL model to VCSEL selection/LaserMOD Design Flow
Example: Optical System Design Flow

ToF System for LiDAR

LaserMOD OptSim Circuit VCSEL Modeling Flow

1. **VCSEL Characteristics**
2. **Electrical + Optical VCSEL Model Extraction**
3. **Electrical Circuit Simulation**
4. **Photonic Circuit Simulation: Multipath Interference**
5. **Receiver and Measurements**
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VCSEL: Circuit- and System-level Modeling

- Interdependence of parameters makes modeling and parameter extraction a complex challenge

<table>
<thead>
<tr>
<th>VCSEL Parameter</th>
<th>Parameter Dependency</th>
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</thead>
<tbody>
<tr>
<td>Threshold current</td>
<td>Photon lifetime, carrier lifetime, gain coefficient, carrier transparency number</td>
</tr>
<tr>
<td>Output power</td>
<td>Output power coupling coefficient, Photon lifetime, carrier lifetime, gain coefficient, carrier transparency number, test current</td>
</tr>
<tr>
<td>P-I Slope</td>
<td>Photon lifetime, Output power coupling coefficient</td>
</tr>
<tr>
<td>Turn-on Delay</td>
<td>Photon lifetime, carrier lifetime, gain coefficient, carrier transparency number, test current</td>
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<tr>
<td>Thermal gain constant</td>
<td>Gain constant and Empirical fitting parameters</td>
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<tr>
<td>Temperature dependent transparency number</td>
<td>Carrier transparency number and Empirical fitting parameters</td>
</tr>
<tr>
<td>Thermal leakage current</td>
<td>Leakage current factor, temperature, and Empirical fitting parameters</td>
</tr>
</tbody>
</table>
VCSEL: Circuit- and System-level Modeling

• VCSEL behavior is highly sensitive to drive conditions and operating temperature. Modeling must capture
  - Driving scheme, parasitics, thermal dependence of gain and carrier leakage, device self-heating, phase-noise like impairments from multipath interference (reflections)

• Datasheets mostly give measured behavior, not all physical parameters available. Device geometries are often unknown to system designers (i.e., can’t use a device modeling tool)

• VCSEL arrays are often driven by common electronics, loading and power-delivery analyses vital

• Co-packaged optics require driver electronics be on the same chip

• Electronics designers often not comfortable with photonic models, and their EDA tools don’t have photonic components

• How to facilitate inter-domain modeling? How to extract physical parameters from datasheet parameters?
Starting from a Datasheet

- Rate-equation laser model parameters extracted from datasheet information
- Rate-equation laser model converted into an equivalent circuit (SPICE or equivalent circuit simulation tool format) that can be simulated in the electrical domain
- Identical rate-equation laser model shared between electrical and optical simulation includes both electrical and optical characteristics
- Effective aid to laser driver design
- Simulation of the TRUE driving conditions of the laser
Starting from a Device Model

- OptSim uses LaserMOD results:
  - L-I curve
  - S21 curve – frequency response
  - Material Gain versus Temperature and Carrier density

- Through optimization OptSim can extract the VCSEL rate equation parameters necessary to simulate at the system-level

- Rate-equation VCSEL model converted to electrical equivalent circuit model for EDA
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Device Level Simulation of VCSELs

• Design flow begins with alignment of material gain and cavity resonances
  – Transmission spectrum of VCSEL cavity indicates location of modes
  – Alignment with material gain determines Quantum Well and Cavity properties

• Steady-state simulation of the physics produces the LIV curves
  – Material gain will red-shift with temperature increase (due to self-heating)
  – This leads to roll-off of the L-I curve, since cavity resonances shift only slightly

• Transient simulation produces the time and frequency responses
  – Determines the 3dB bandwidth
  – Relaxation oscillation frequency
  – Turn-on delay
  – Capacitance and Resistance vs Voltage

• Creation of Circuit Model For System and Circuit Level Simulation
Device Level Simulation of VCSELs

• Rigorous simulation of the discretized structure on a mesh
  – Geometric definition of the device structure
  – Specification of material system, alloy composition, and doping

• Cylindrical symmetry may be exploited to reduce computational time
  – The vertical & radial directions are meshed
  – Physics solved in cylindrical coordinates, so the solution is a “body of revolution”

• Gain / optics / thermo-electric transport must be solved self-consistently
  – Quantum Well Gain solved via the K•P method (8x8 band)
  – Photon Rate Equations and Cavity modes via Finite Element Method (FEM)
  – Poisson, Continuity Equations, and Lattice Heat equation

• Gives spatial solution of physics throughout the device
  – carrier densities (spatial hole burning), temperature profiles,
  – current contours, recombination, …

• Provides steady state and dynamic performance analysis
  – LIV curves (roll-off), near fields, far fields,
  – transient and frequency responses, … , and circuit models
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Conclusion

• Diverse range of VCSEL applications demands mixed-level, multi-domain modeling

• Co-simulation between optical system simulation tool (e.g. OptSim) and EDA tools (e.g. HSPICE, Spice, ADS, and Spectre) with option of using device-level laser modeling tool (e.g. LaserMOD) lead to manufacturing-oriented design cycle

• Device and circuit designers can optimize designs for maximum overall system performance

• System designers can determine system performance based on highly accurate device and circuit models and optimize system designs according to actual components to be used in system

• Greatest accuracy in end-to-end device/circuit/system simulation and design for best performance, and reduction in cost and time-to-market
Thank You