VCSEL Device and System Design for Manufacturing

Multi-level modeling solution

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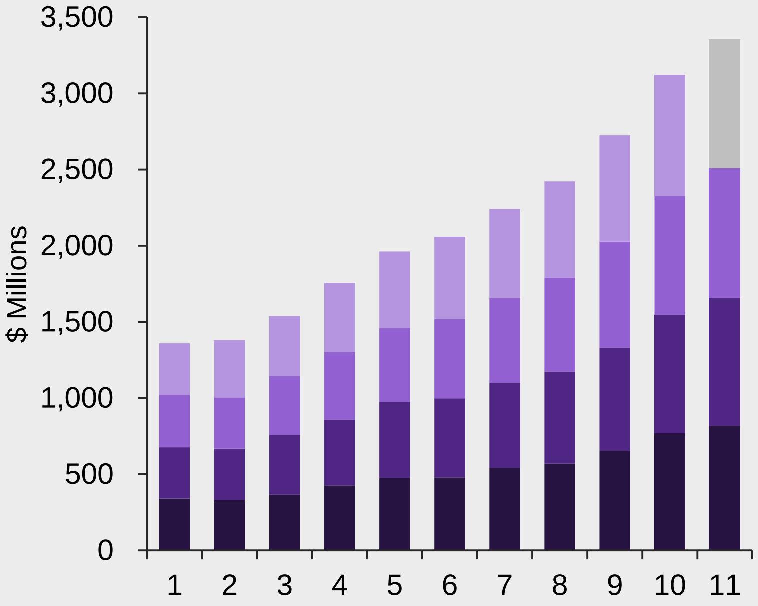
Synopsys Today: From Silicon to Software

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

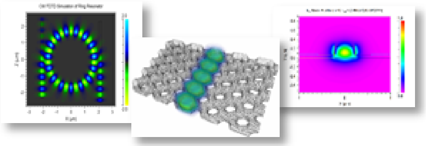
SYNOPSYS®

Synopsys Sees Optics and Photonics as a Key Enabling Technologies

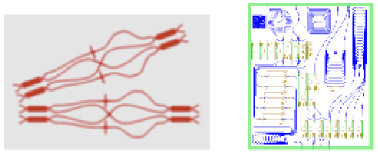
Entered the Field in 2010

- 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

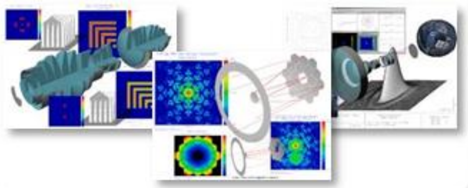
RSoft - Photonics Design
Design and simulation of optical telecomm devices, nano-scale optical structures, circuits and systems



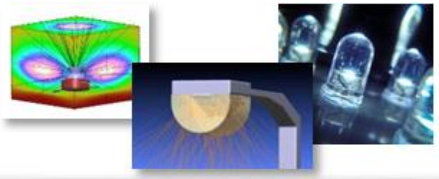
PhoeniX OptoDesigner - Photonic Integrated Circuit Design
Physical layout and verification for photonic integrated circuits



CODE V - Imaging Design
Lens optimization, analysis, tolerancing and fabrication support



LightTools - Illumination Design
Virtual prototyping, simulation, optimization and visualization of illumination optics



LucidShape - Automotive Lighting Design
Design and real-time simulation of automotive forward, rear and signal lighting

Outline

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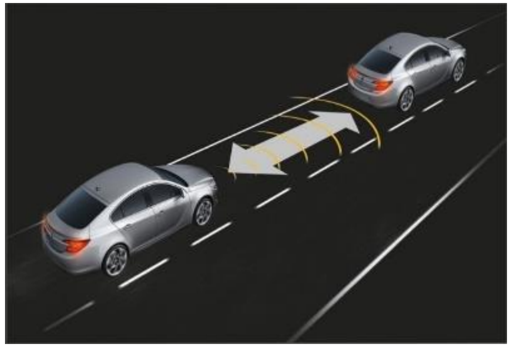
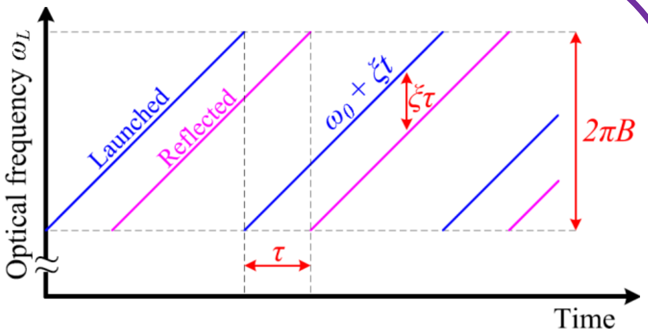
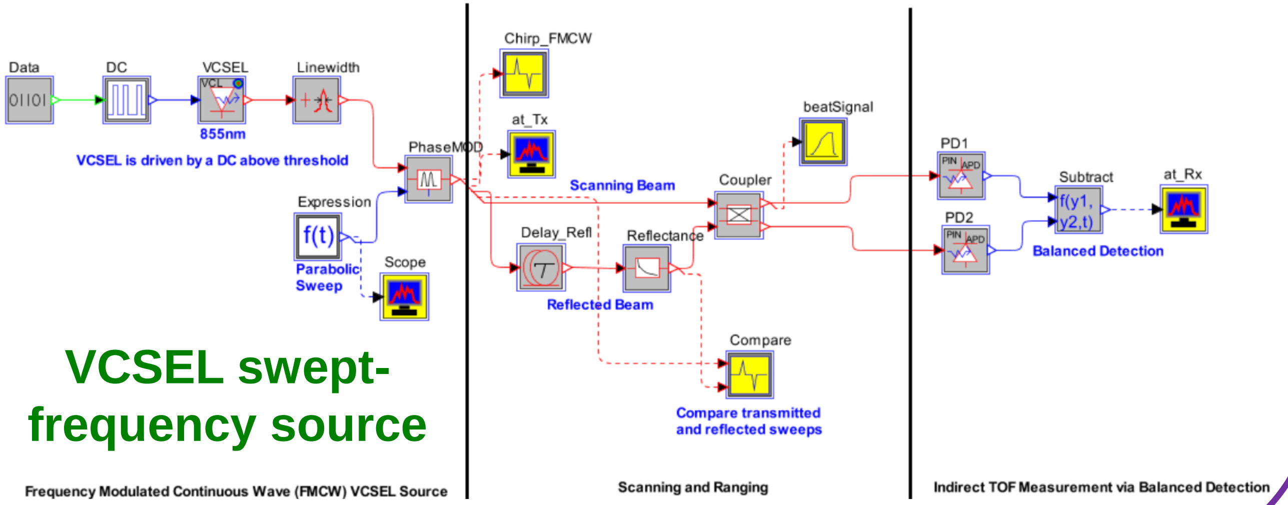
History and Application(s)

ToF and LiDAR

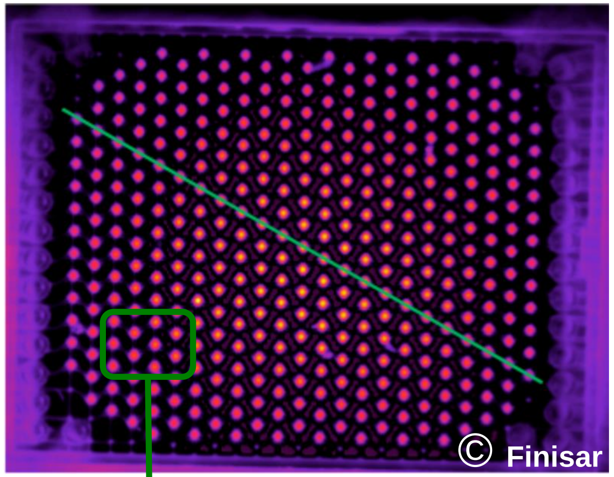


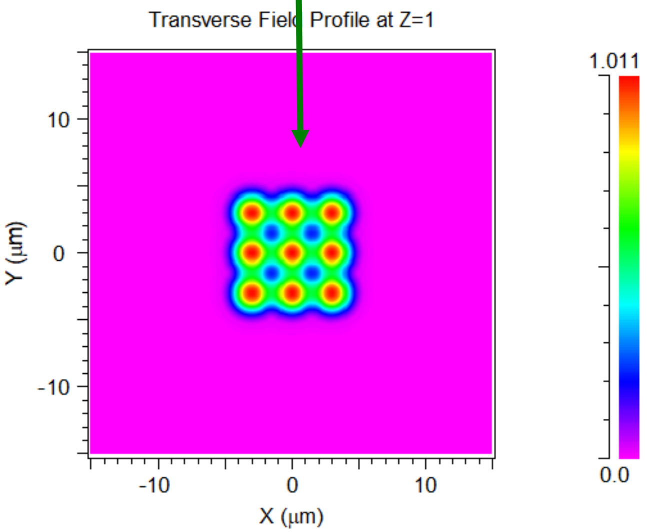


Modeling Indirect Time-of-Flight Case Study in OptSim



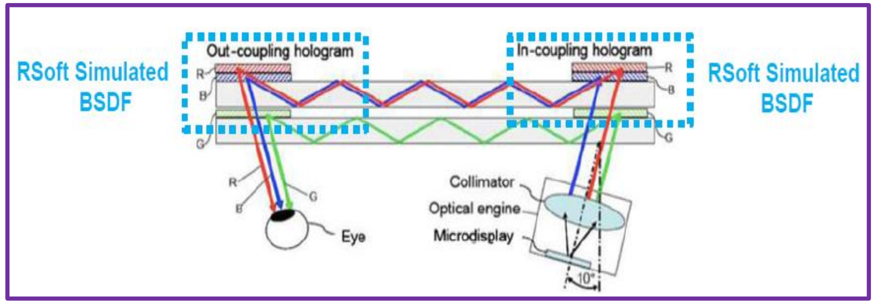
FaceID: VCSEL arrays



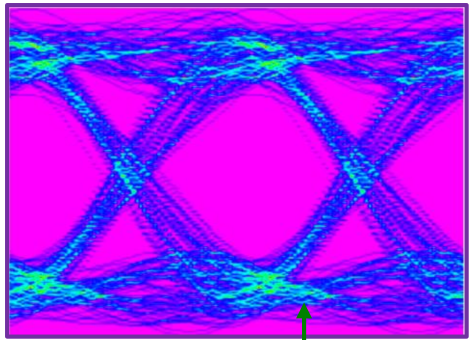


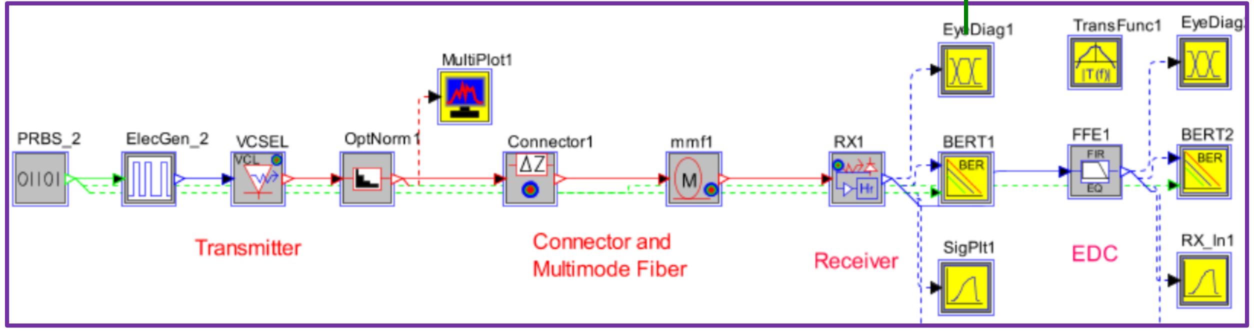
History and Application(s)

AR/VR



High-speed Transceiver





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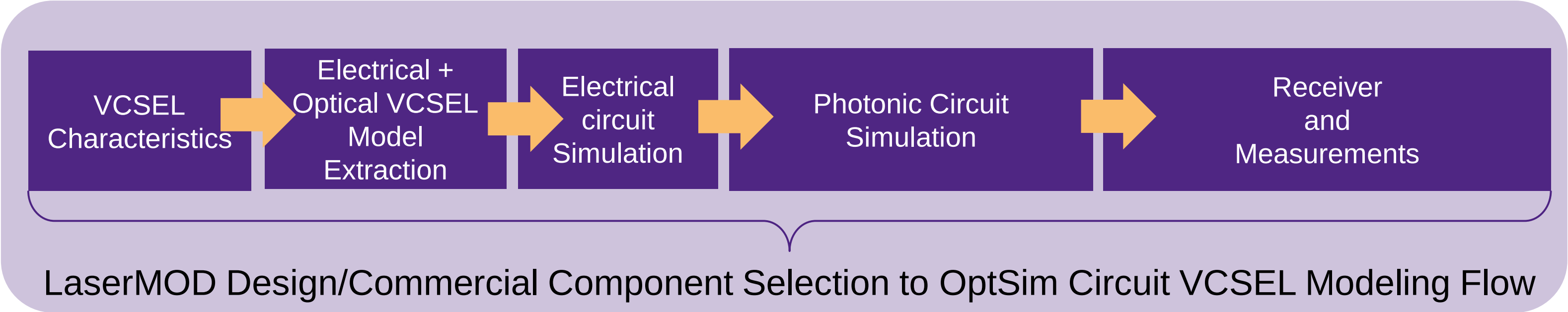
Problems to Solve

- 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

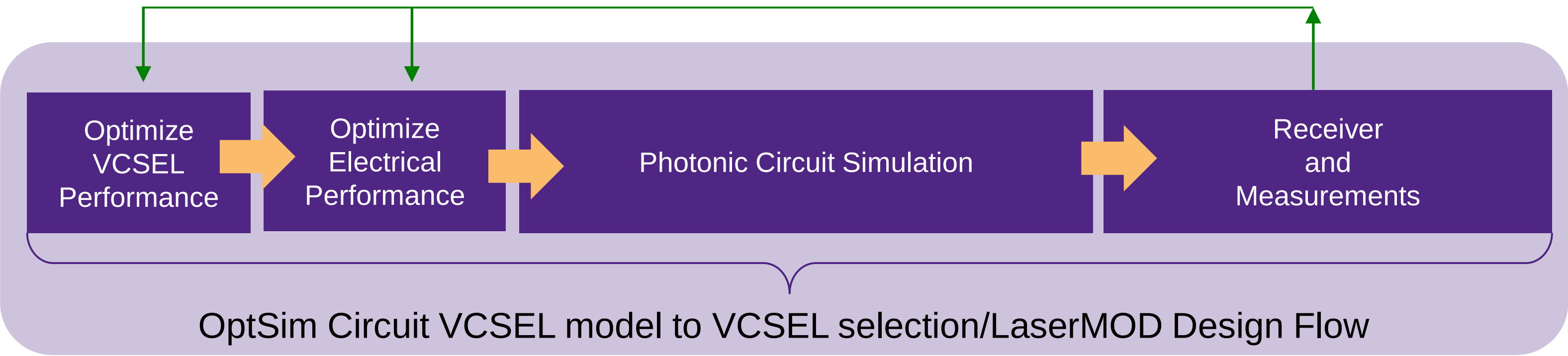
Design Objectives and the Choice of Flow

Two possible approaches

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



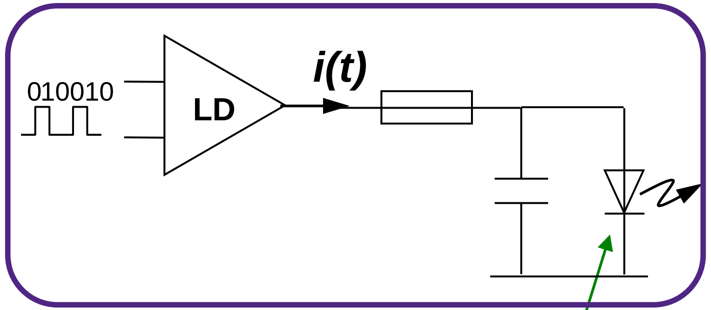
2. Top-down: Starting with targeted system performance, evaluate VCSEL selection/design:



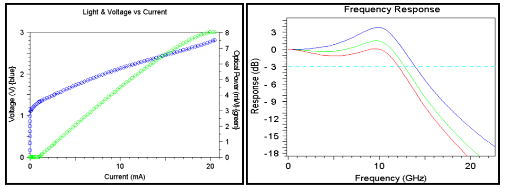
Example: Optical System Design Flow

ToF System for LiDAR

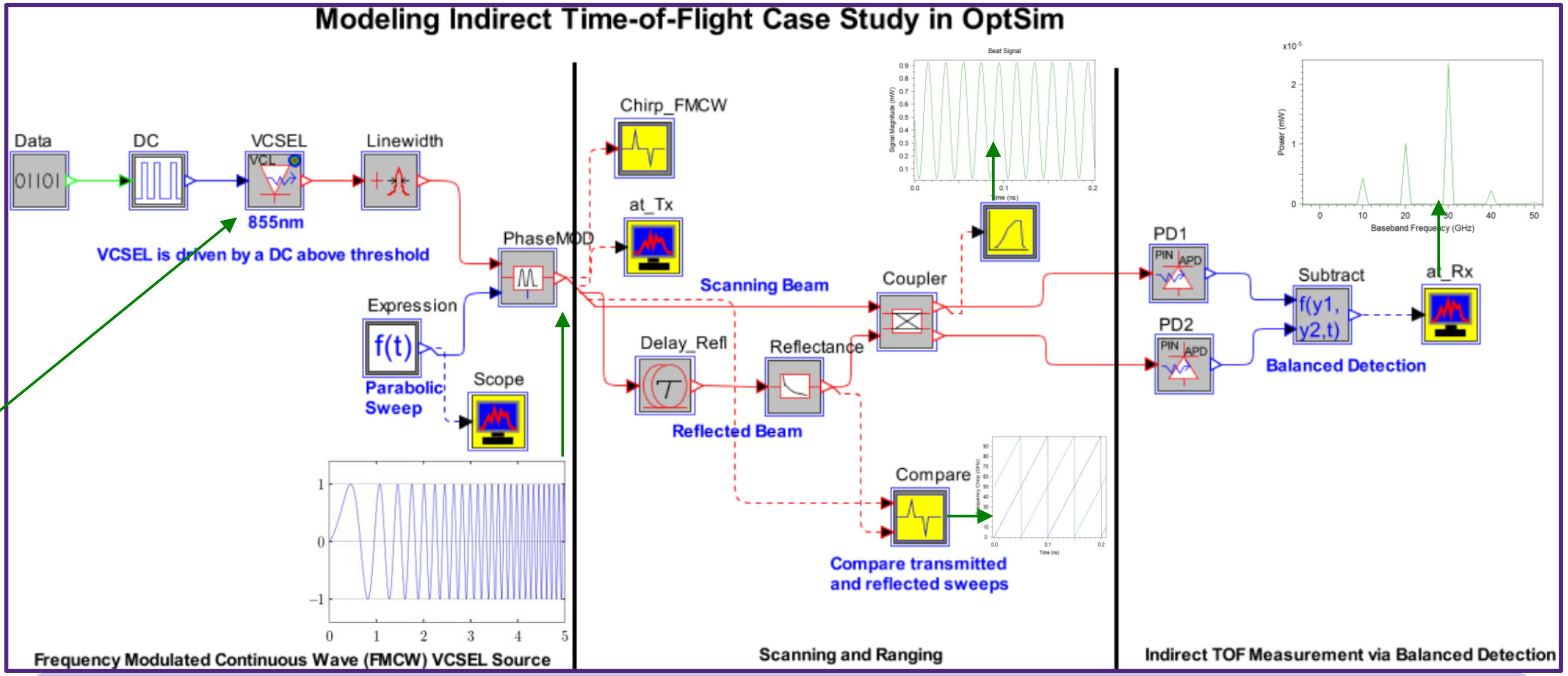
SPICE modeling



Electrical+Optical VCSEL Model Extraction



VCSEL Characteristics



- VCSEL Characteristics
- Electrical + Optical VCSEL Model Extraction
- Electrical circuit Simulation
- Photonic Circuit Simulation: Multipath Interference
- Receiver and Measurements

LaserMOD OptSim Circuit VCSEL Modeling Flow

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VCSEL: Circuit- and System-level Modeling

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

VCSEL Parameter	Parameter Dependency
Threshold current	Photon lifetime, carrier lifetime, gain coefficient, carrier transparency number
Output power	Output power coupling coefficient, Photon lifetime, carrier lifetime, gain coefficient, carrier transparency number, test current
P-I Slope	Photon lifetime, Output power coupling coefficient
Turn-on Delay	Photon lifetime, carrier lifetime, gain coefficient, carrier transparency number, test current
Thermal gain constant	Gain constant and Empirical fitting parameters
Temperature dependent transparency number	Carrier transparency number and Empirical fitting parameters
Thermal leakage current	Leakage current factor, temperature, and Empirical fitting parameters

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

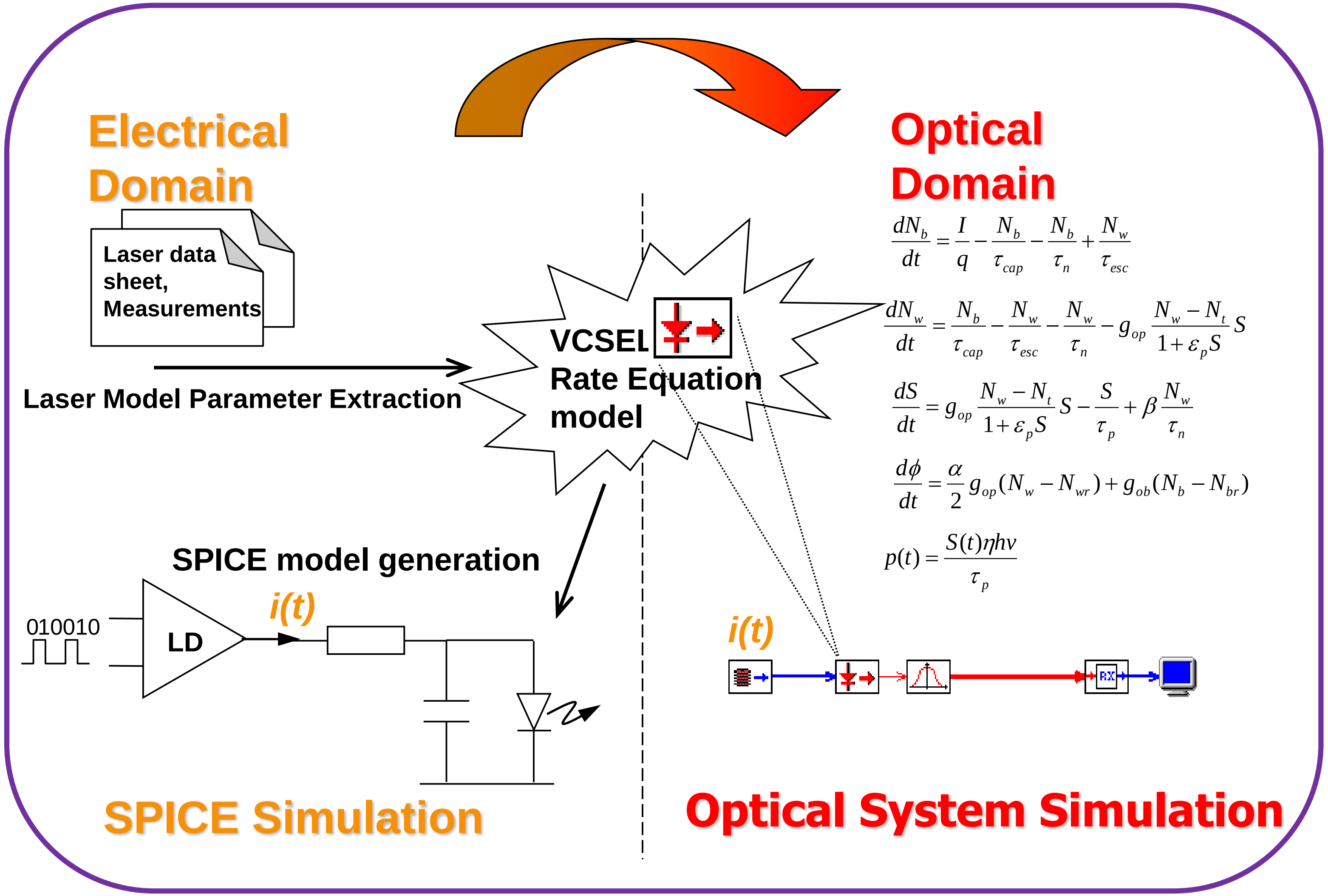
- Co-packaged optics require driver electronics be on the same chip

- 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?

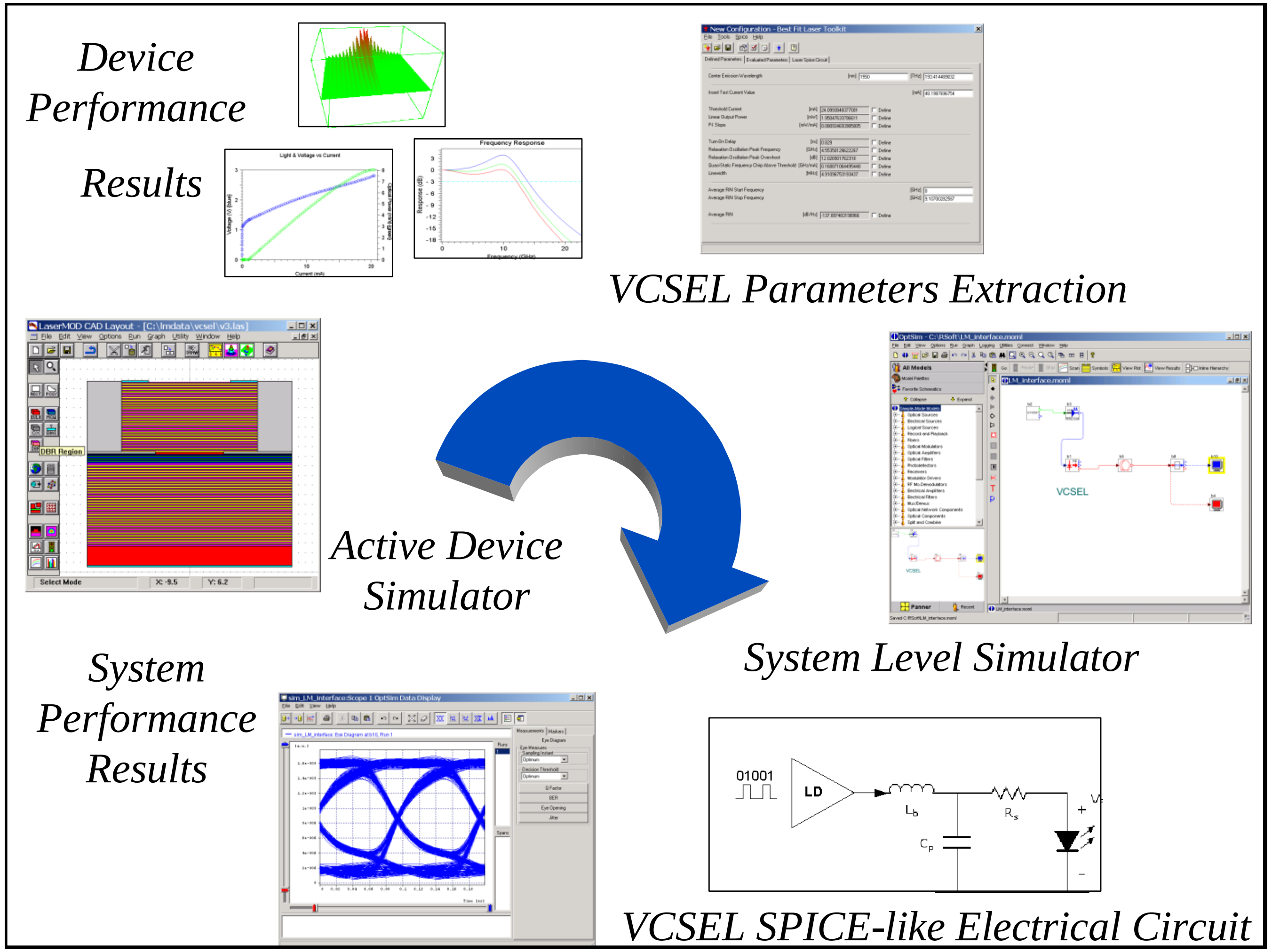
SYNOPSYS®

Starting from a Datasheet



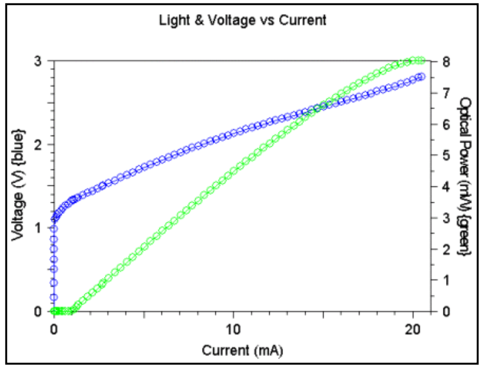
- Rate-equation laser model parameters extracted from data sheet information
- Rate-equation laser model converted into an equivalent circuit (SPICE or equivalent circuit simulation tool format) that can be simulated in the electrical domain
- Identical rate-equation laser model shared between electrical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

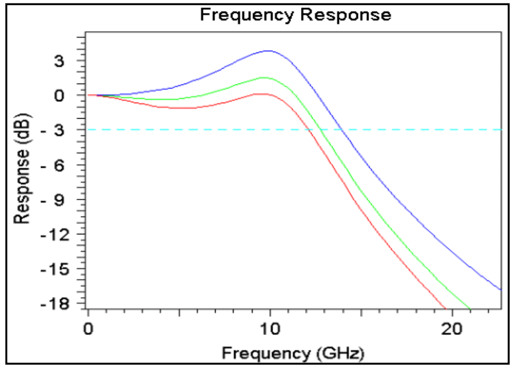
Starting from a Device Model



- 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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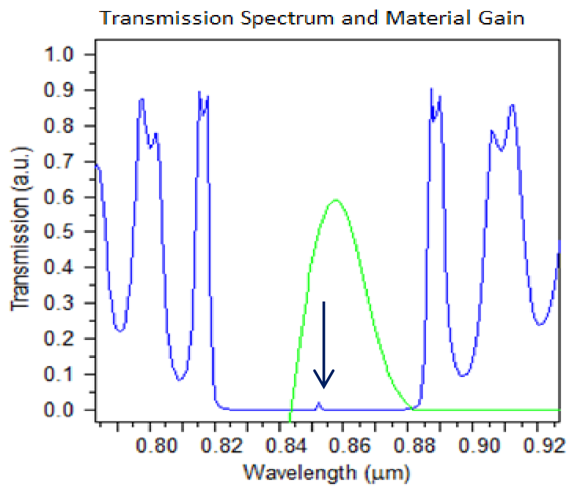
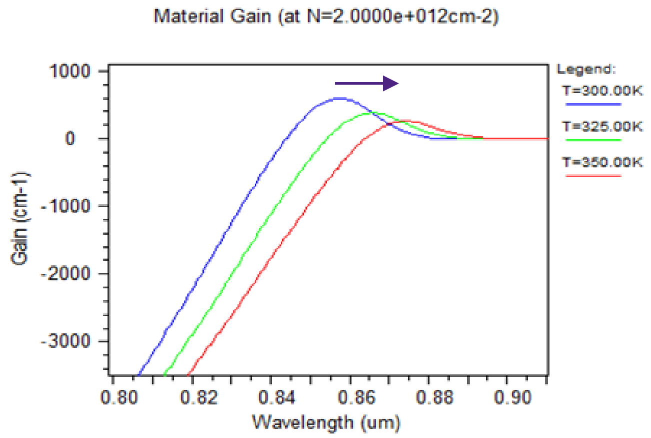
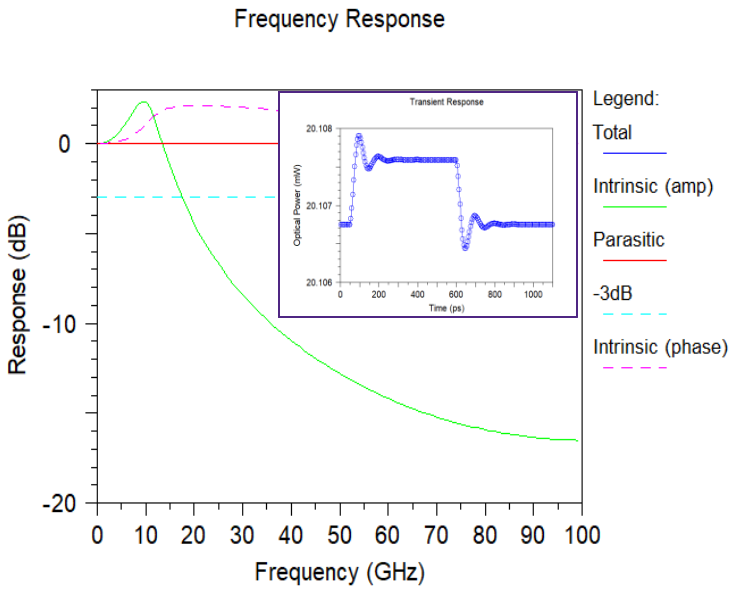
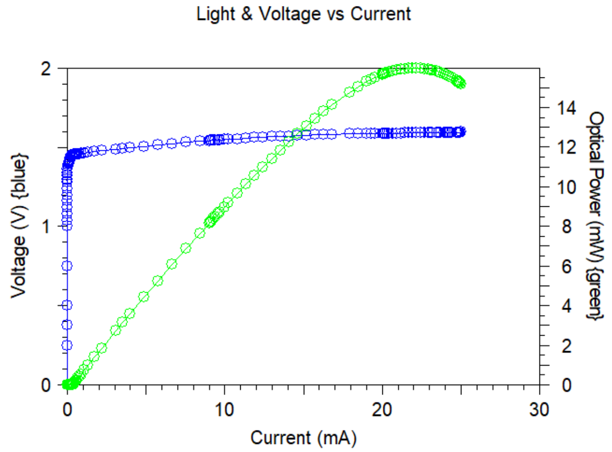
Device Level Simulation of VCSELs

- **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**

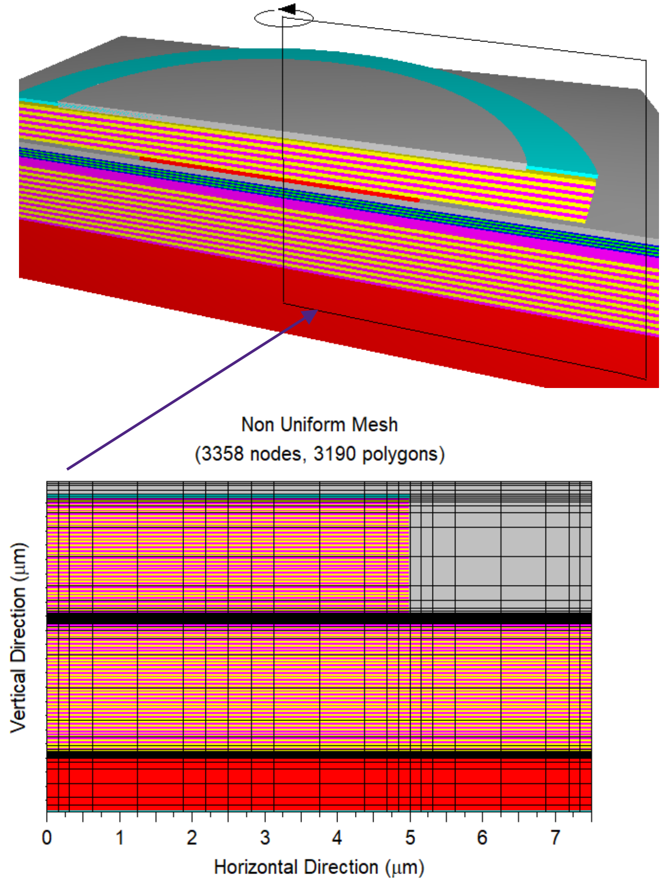




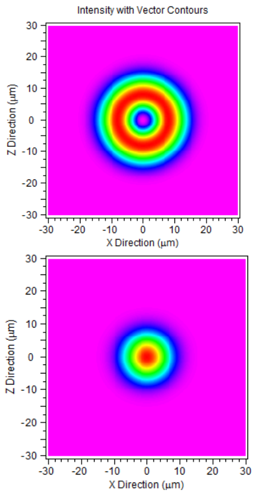


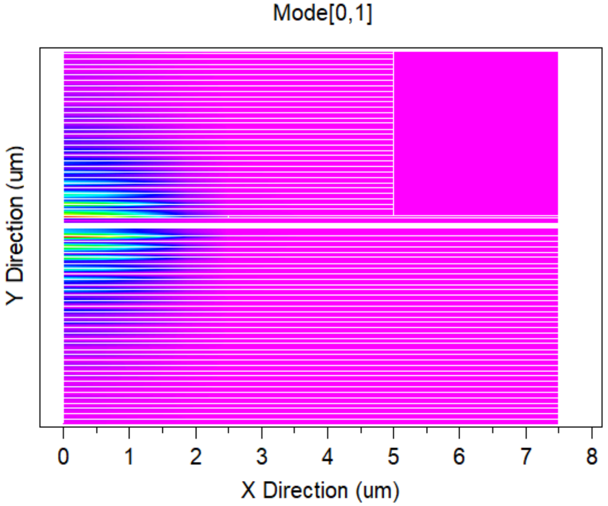


Device Level Simulation of VCSELs



- **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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- 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

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