Modeling, Extraction and Verification of VCSEL Model for IBIS AMI

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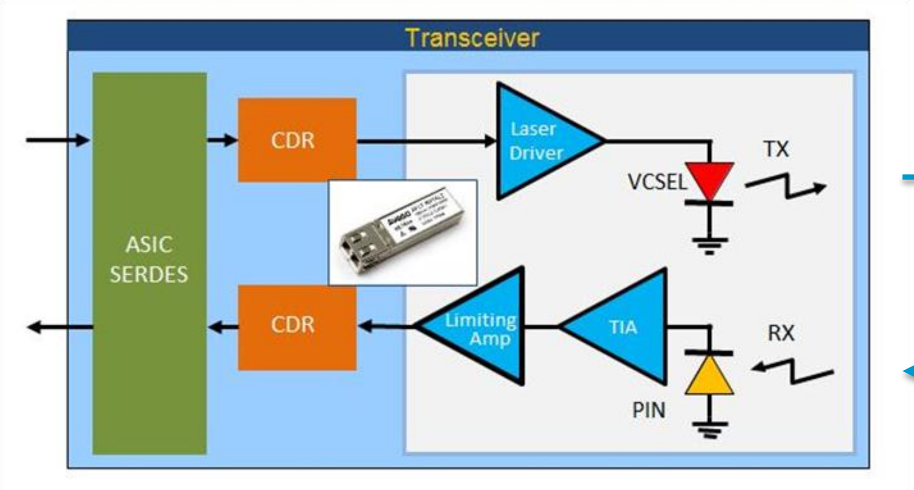
Outline

- Introduction
  - Optical Link Simulation
  - VCSEL(Vertical Cavity Surface Emitting Laser) simulation under IBIS-AMI
- VCSEL Modeling and Extraction
  - Thermal based modeling
  - Curve fitting algorithm
- VCSEL Verification
  - Test case including VCSEL device
  - The comparison between simulation and measured data

Introduction
Optical Link System and Simulation(cont.)

- Optical Link Simulation



optical fiber

optical fiber

Inside SerDes Tx & Rx

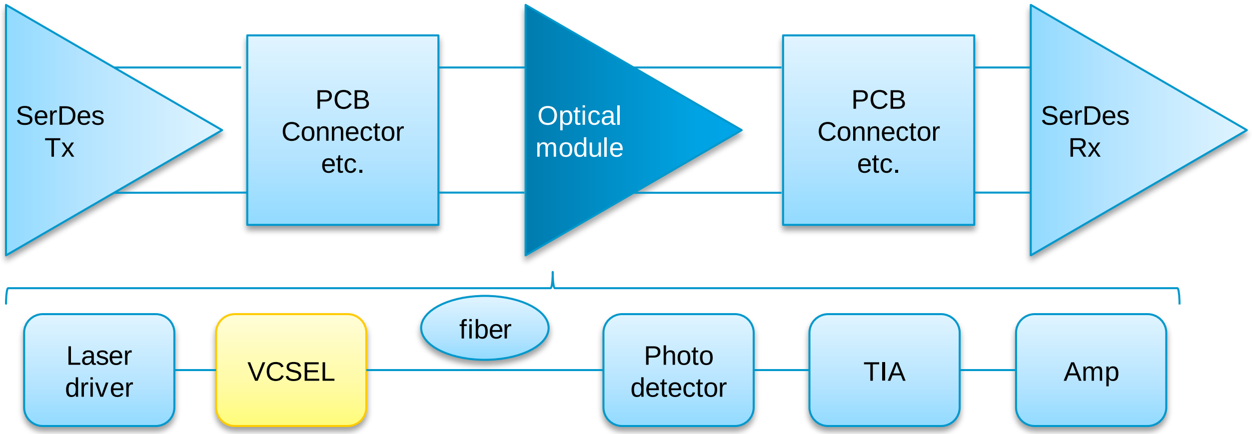
- Equalization (FFE, CTLE & DFE)
- Clock-data recovery (CDR)

Inside optical module

- Input voltage signal drives VCSEL to emit photons
- Photons propagate along optical fiber
- Photons are converted into photocurrent in PIN
- TIA converts current into output voltage

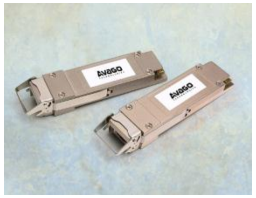
Introduction
Optical Link System and Simulation(cont.)

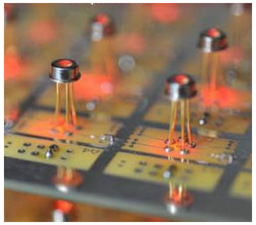
- Extending AMI to Optical Channel
  - Treat the entire optical module as a mid-channel repeater
  - Encapsulate all optical behaviors inside the optical model
  - Extend AMI simulation to include repeater



Introduction
VCSEL Basic

- VCSEL(Vertical Cavity Emitting Laser)
  - Characteristics
    - High Data Rate, up to 40GHz(state of art)
    - Low power cost(input ~ mA, output ~ mW)
    - Single-longitudinal-mode operation
    - Suitability for monolithic 2-D integration
  - Application
    - Very short range data transmission
    - Board to board data transmission



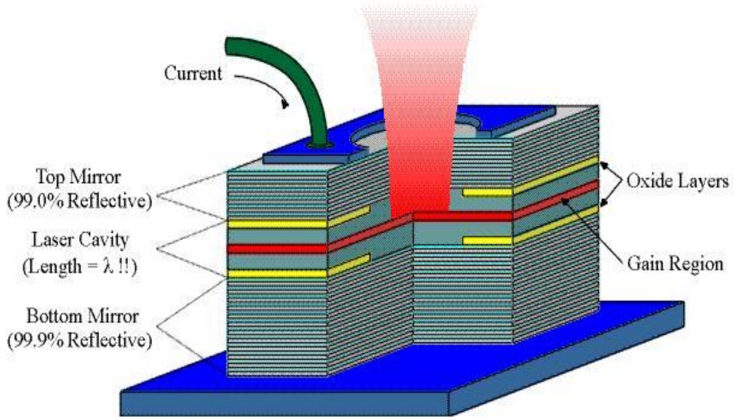


Introduction
VCSEL Basic

- VCSEL modeling
  - 3-D modeling and simulation
    – From the principle of laser point of view
    – Accurate but too complicated
  - SPICE simulation
    – As VCSEL is an optical device, SPICE model may not be the initial design, a new SPICE schematic is needed
    – Hard to communicate due to IP issue
  - IBIS-AMI(Algorithmic Modeling Interface)
    – Focusing on performance only
    – Treat the VCSEL as an algorithm unit

VCSEL Modeling and Extraction
VCSEL Modeling

- Modeling Principle
  - VCSEL’s performance vs. Thermal behavior
  - Data flow based
  - The relationship between input current(I) and output power(Po) under the effect of temperature(T)
  - Peripheral simulation
  - Working schematic



VCSEL Modeling and Extraction
VCSEL Modeling

- Rate-Equation-Based Thermal VCSEL Model
  - Transient Analysis

$$P_o = kS$$

$$\frac{dS}{dt} = -\frac{S}{\tau_p} + \frac{\beta N}{\tau_n} + \frac{G_o(N-N_o)S}{1+\varepsilon S}$$

$$\frac{dN}{dt} = \frac{\eta_i(I - I_{off}(T))}{q} - \frac{N}{\tau_n} - \frac{G_o(N-N_o)S}{1+\varepsilon S}$$

Rate Equation

$$I_{off}(T) = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4$$

$$T = T_o + (IV - P_o)R_{th} - \tau_{th}\frac{dT}{dt}$$

$$V = \begin{cases} (b_0 + b_1 T + b_2 T^2)(c_0 + c_1 I + c_2 I^2) \\ (c_0 + c_1 I + c_2 I^2 + c_3 I^3 + c_4 I^4 + c_5 I^5 + c_6 I^6) \\ AI + B\ln(1 + \frac{I}{C}) \end{cases}$$

  - Stationary Analysis

$$P_o = \eta(I - I_{tho} - I_{off}(T))$$

$$I_{off}(T) = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4$$

$$T = T_o + (IV - P_o)R_{th}$$

$$V = \begin{cases} (b_0 + b_1 T + b_2 T^2)(c_0 + c_1 I + c_2 I^2) \\ (c_0 + c_1 I + c_2 I^2 + c_3 I^3 + c_4 I^4 + c_5 I^5 + c_6 I^6) \\ AI + B\ln(1 + \frac{I}{C}) \end{cases}$$

VCSEL Modeling and Extraction
VCSEL Extraction

- Extraction Basics
  - <u>VCSEL's performance</u> ↔ <u>Parameter values in rate equations</u>

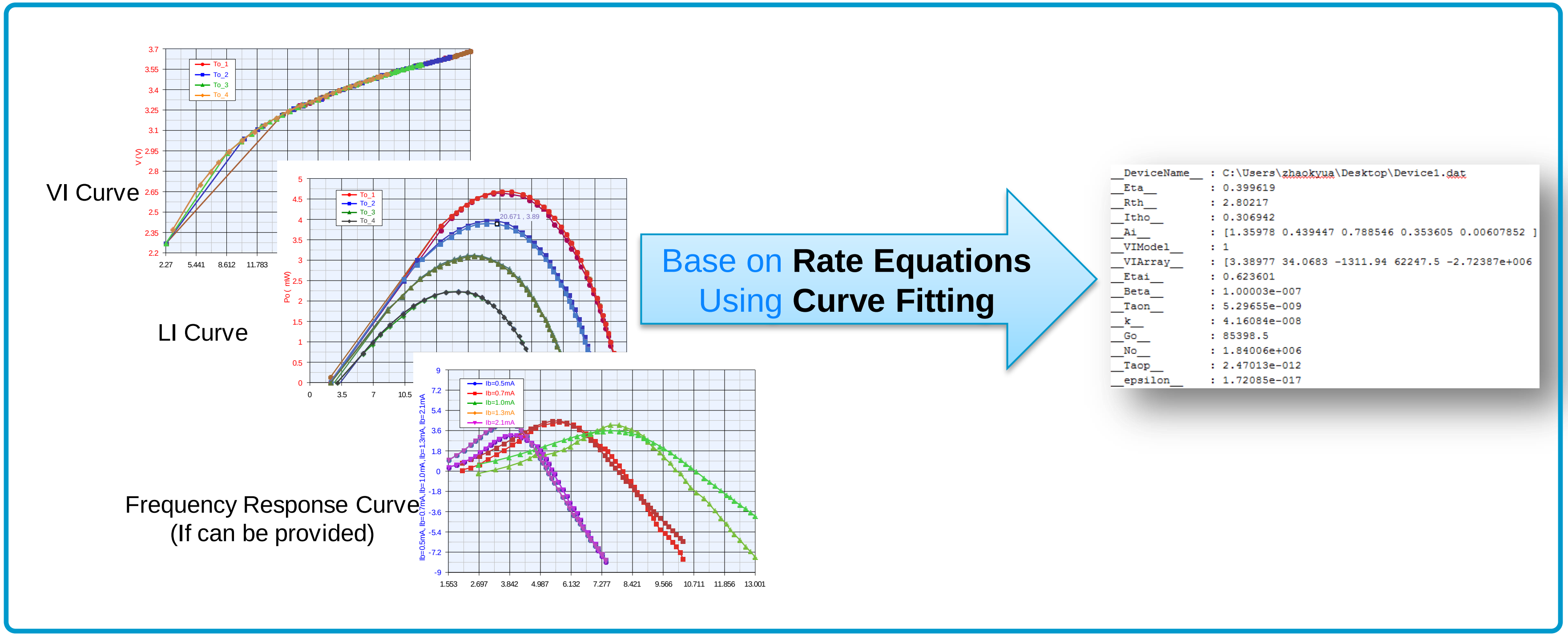
  - Measured curves
    - LI ~ Po(I; T)
      - Measured stationary, shows the relationship between input current and the output power under different ambient temperature
    - VI ~ V(I; T)
      - Measured stationary, shows the relationship between input current and the voltage for connection, also with effect of ambient temperature
    - Frequency response ~ H(w)
      - Measured stationary, shows the frequency response, reveals the signal transmission characteristics

VCSEL Modeling and Extraction
VCSEL Extraction

- Extraction Method
  - Curve Fitting Algorithm
    - LS curve fitting
      - Just solve the matrix equations
      - Suitable for simple relationship equations, such as the polynomial
      - Accurate and less time cost
    - Minimal gradient curve fitting
      - Try to find the certain set of values which can generate the smallest error
      - Suitable for more complex equations, especially with iterations
      - Need some pre-knowledge of the range of the parameters
      - More time cost for accuracy

VCSEL Modeling and Extraction
VCSEL Extraction

- Schematic



VCSEL Verification

- VCSEL Simulation
  - Parameter values in rate equations ↔ VCSEL's performance
  - Schematic

$$\frac{dN}{dt} = \frac{\eta_i (I - I_{off}(T))}{q} - \frac{N}{\tau_n} - \frac{G_o (N - N_o) S}{1 + \varepsilon S}$$

$$\frac{dS}{dt} = -\frac{S}{\tau_p} + \frac{\beta N}{\tau_n} + \frac{G_o (N - N_o) S}{1 + \varepsilon S}$$

$$I_{off}(T) = \sum_i a_i T^i$$

$$V = f(I, T)$$

$$T = T_o + (IV - P_o) R_{th} - \tau_{th} \frac{dT}{dt}$$

$$P_o = kS$$

```
__DeviceName__  : C:\Users\zhaokyua\Desktop\Device1.dat
__Eta__         : 0.399619
__Rth__         : 2.80217
__Itho__        : 0.306942
__Ai__          : [1.35978 0.439447 0.788546 0.353605 0.00607852 ]
__VIModel__     : 1
__VIArray__     : [3.38977 34.0683 -1311.94 62247.5 -2.72387e+006
__Etai__        : 0.623601
__Beta__        : 1.00003e-007
__Taon__        : 5.29655e-009
__k__           : 4.16084e-008
__Go__          : 85398.5
__No__          : 1.84006e+006
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__epsilon__     : 1.72085e-017
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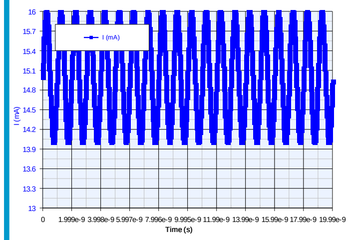
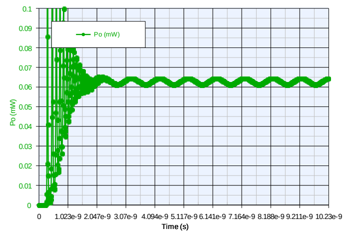
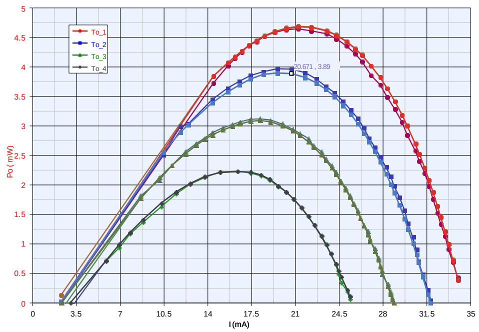
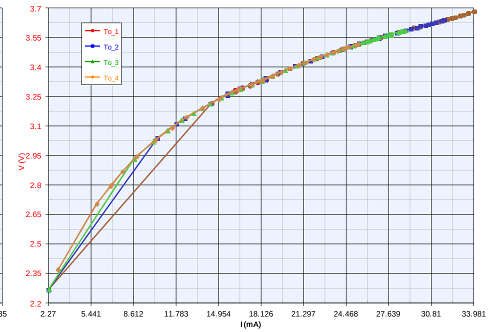


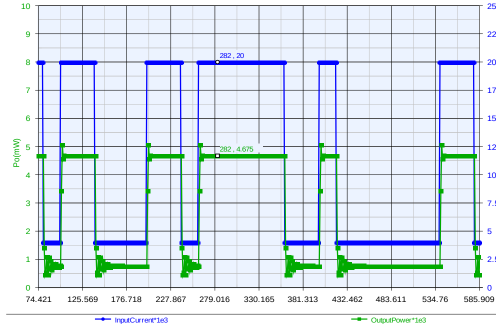


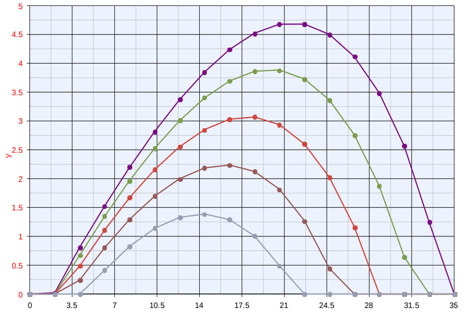
VCSEL Verification

- Case 1 ~ device verification
  - 863-nm bottom-emitting VCSEL, 16-mm diameter
  - Extraction
    - Curves fitting result
      - LI and VI curve
    - Behavior mode is generated with file format
  - Simulation
    - Po(I) under different To
    - Response for large signal









VCSEL Verification

- Case 2 ~ device verification
  - 3.1um diameter thin-oxide-aperture VCSEL
  - Extraction Result
    - Curves fitting result
      - LI(Fig 1)
      - VI(Fig 2)
      - Freq. response(Fig3)
    - Simulation
      - Po(I) simulation (Fig4)
      - Frequency response(Fig5)
      - Response for large signal(Fig6)

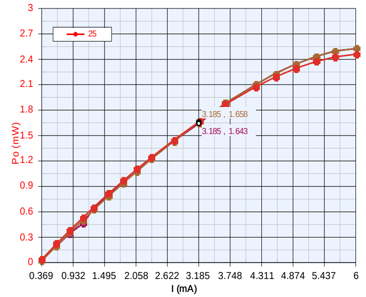


Fig 1

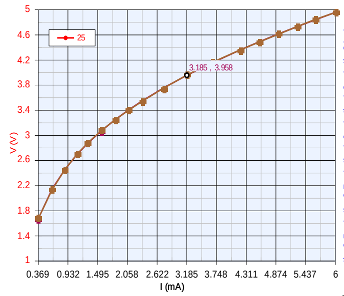


Fig 2

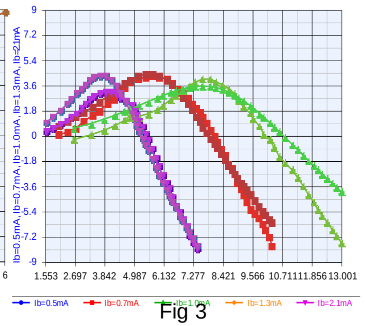


Fig 3

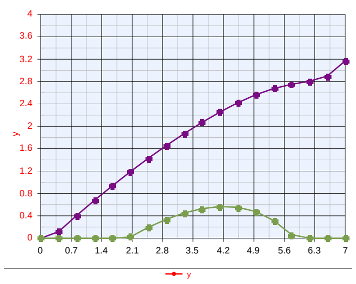


Fig 4

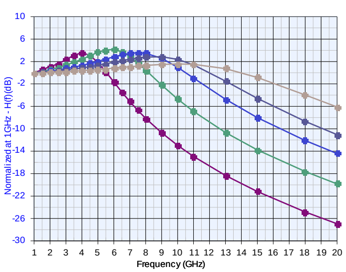


Fig 5

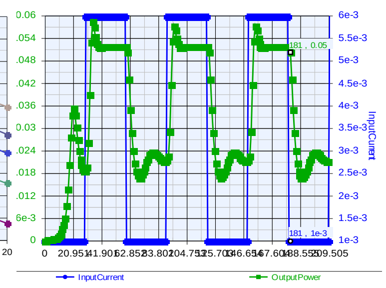
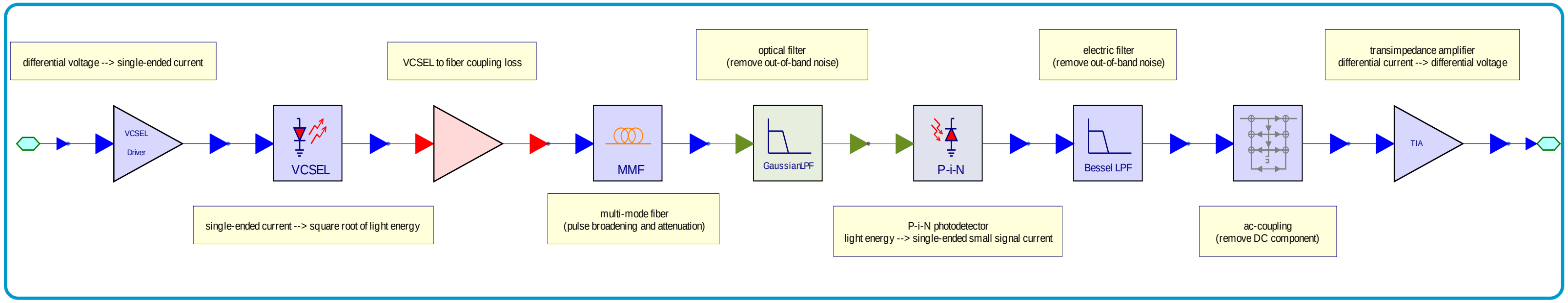
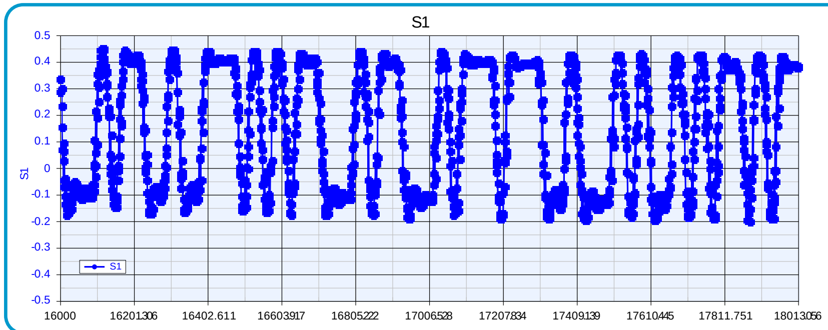


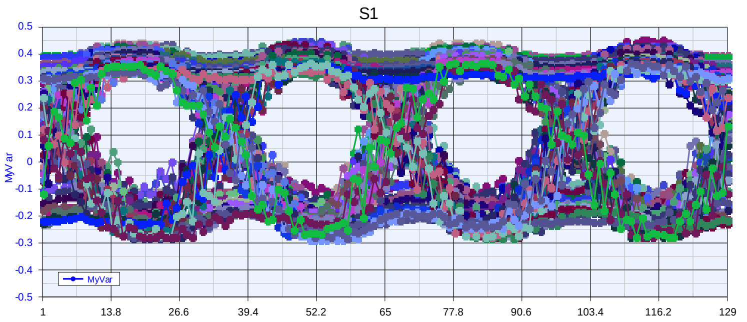
Fig 6

VCSEL Verification

- Case 3 ~ optical link simulation
  - 25GHz signal transmission
  - A whole optical link: current → optical signal → current







Thanks