Efficient End-to-end Simulations of 25G Optical Links

Sanjeev Gupta, Avago Technologies

Fangyi Rao, Agilent Technologies

Jing-tao Liu, Agilent Technologies

Amolak Badesha, Avago Technologies

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Agilent Technologies

Avago Technologies

Outline

- Challenges in end-to-end optical link simulation
- AMI Modeling and Simulation Approach for Optical Channel
- Optical Models
- Simulation Results and Discussion
- Summary

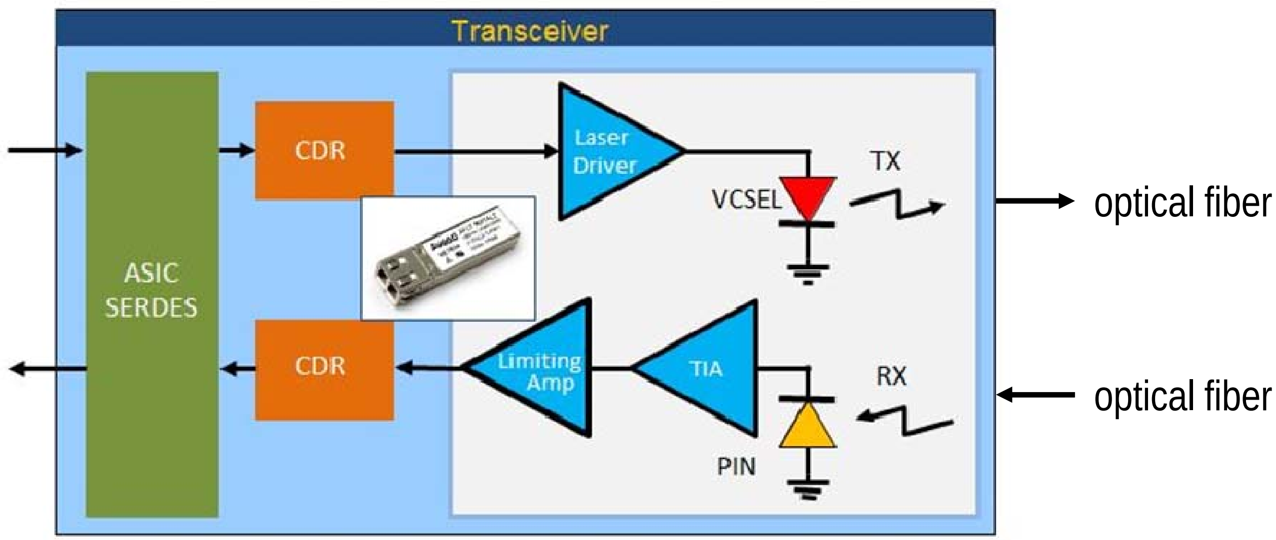
Why Optical?

Bandwidth of traditional electrical link is increasingly limited by channel loss above 25G.

Advantages of optical channels:

- Much smaller loss and superior bandwidth
- Long reach
- Flawless connectivity between digital boards and backplanes
- Small footprint
- Reduced EMI
- Promising candidate to replace electrical links

Optical Link System



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

Challenges in Full Channel Simulation

- Need to model both electrical and optical portions of the link
- Take into account SERDES equalizers and CDR
- Capture behaviors of optoelectronic devices
  - Thermal effects
  - Nonlinearity
  - Optical dispersion and loss
  - Device bandwidth
  - Laser and electrical noise
- Implementation details are proprietary for SERDES and optical Vendors
- Information typically not accessible to external simulator

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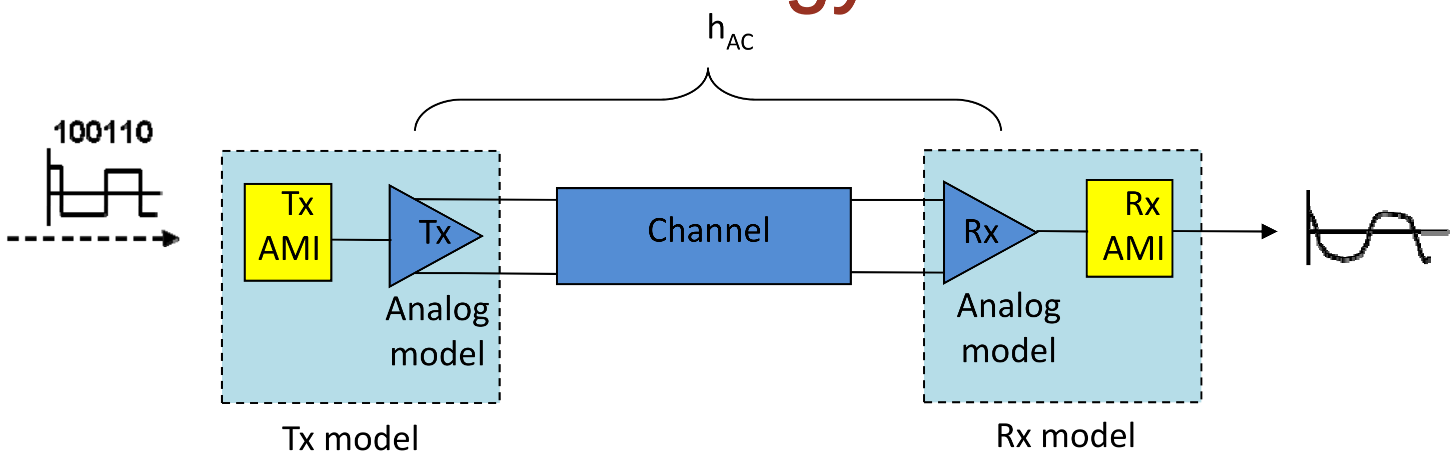
Algorithmic Modeling Interface (AMI) Overview

- AMI is introduced in IBIS 5.0
- Defines SERDES behavioral modeling interface
- An AMI model consists of analog model and algorithmic (AMI) block
- Analog model: regular IBIS model, represents rise/fall edge and impedance/load.
- Algorithmic bock: SW executable, models Tx/Rx logics including gain control, equalizers and CDR
- AMI block implements three standard functions
  - *AMI_Init*: performs model initialization and initial EQ optimization
  - *AMI_GetWave*: takes a waveform as input, and returns a modified waveform
  - *AMI_Close*: release model

AMI Simulation Methodology



- Assume Tx analog model, channel and Rx analog model are linear and can be represented by a combined impulse response, h_{AC}.
- Assume high impedance interface between analog model and algorithmic block so they are electrically decoupled.
- Simulation steps:
  1. Square wave representing bit sequence is sent into Tx AMI
  2. Tx output is convolved with h_{AC}
  3. Resulting waveform is sent into Rx AMI
  4. Rx output is used to calculate eye diagram and BER

AMI Models Advantages and Limitations

Advantage

•Models capture SERDES internal functionalities

•IP protection: models are delivered as DLL or/and shared object, concealing implementation details.

•Interoperability between models from different vendors

•Highly efficient link simulation, capable to process millions of bits in minutes

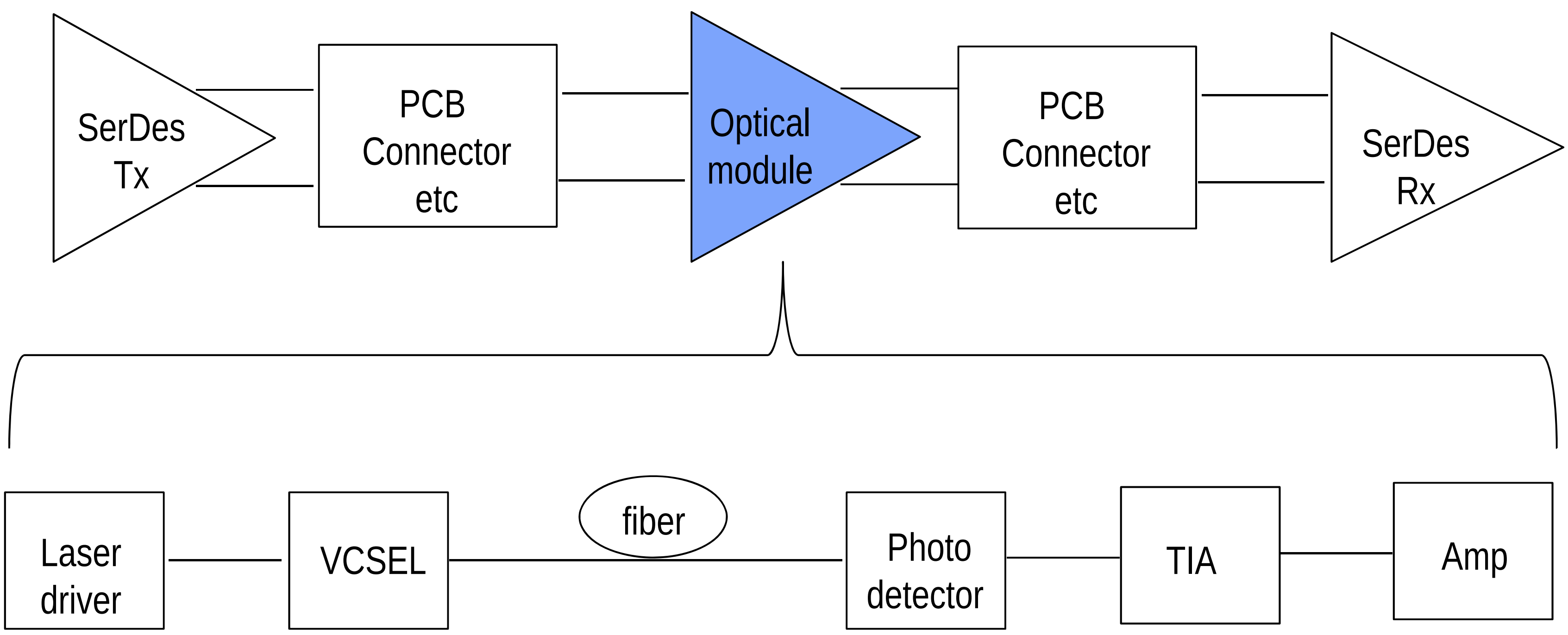
Limitation

•Assumes linear channel

•Optical channel is known to be strongly nonlinear and noisy

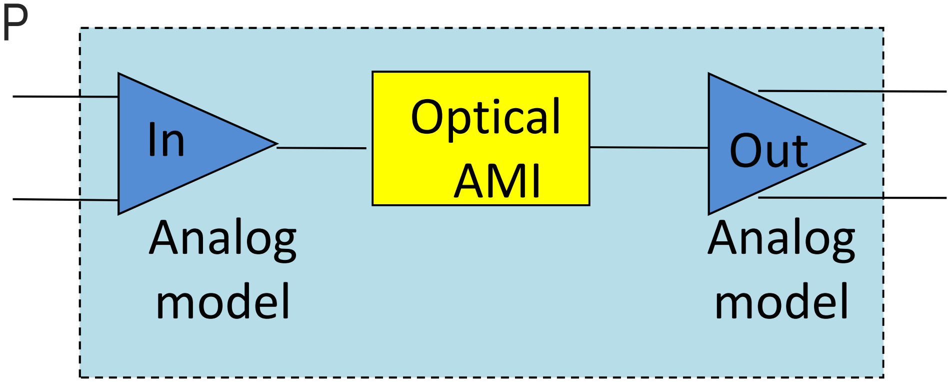
Extending AMI to Optical Channel

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



AMI Modeling for Optical Channel

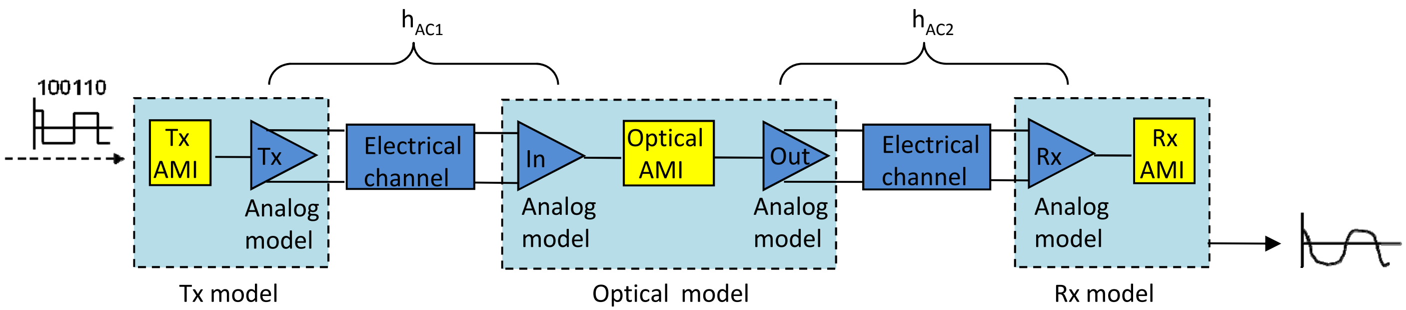
- Model comprises input analog model, optical AMI block and output analog model
- Analog models represent load at input end and impedance at output end
- Optical algorithmic block encapsulates electrical-optical conversion and photon propagation inside the fiber.
- Optical model is defined in electrical domain. AMI_GetWave takes input voltage waveform, and returns output voltage waveform.
- Interoperable with regular SERDES AMI models.
- Protects optical IP



Optical AMI model

Full Channel Optical Link Simulation Flow

- The link includes SERDES Tx and Rx AMI models and optical AMI model.
- SERDES and optical models are connected by two electrical channels (package, PCB, connector, …)
- Tx analog model, 1st electrical channel and optical input analog model are represented by h_{AC1}
- optical input analog model, 2nd electrical channel and Rx analog model are represented by h_{AC2}
- Simulation steps:
  1. Square wave representing bit sequence is sent into Tx AMI
  2. Tx output is convolved with h_{AC1}
  3. Resulting waveform is sent into optical AMI
  4. Optical output is convolved with h_{AC2}
  5. Resulting waveform is sent into Rx AMI
  6. Rx output is used to calculate eye diagram an BER
- Both SERDES and optics are taken into account w/o exposing SERDES or optical implementation details



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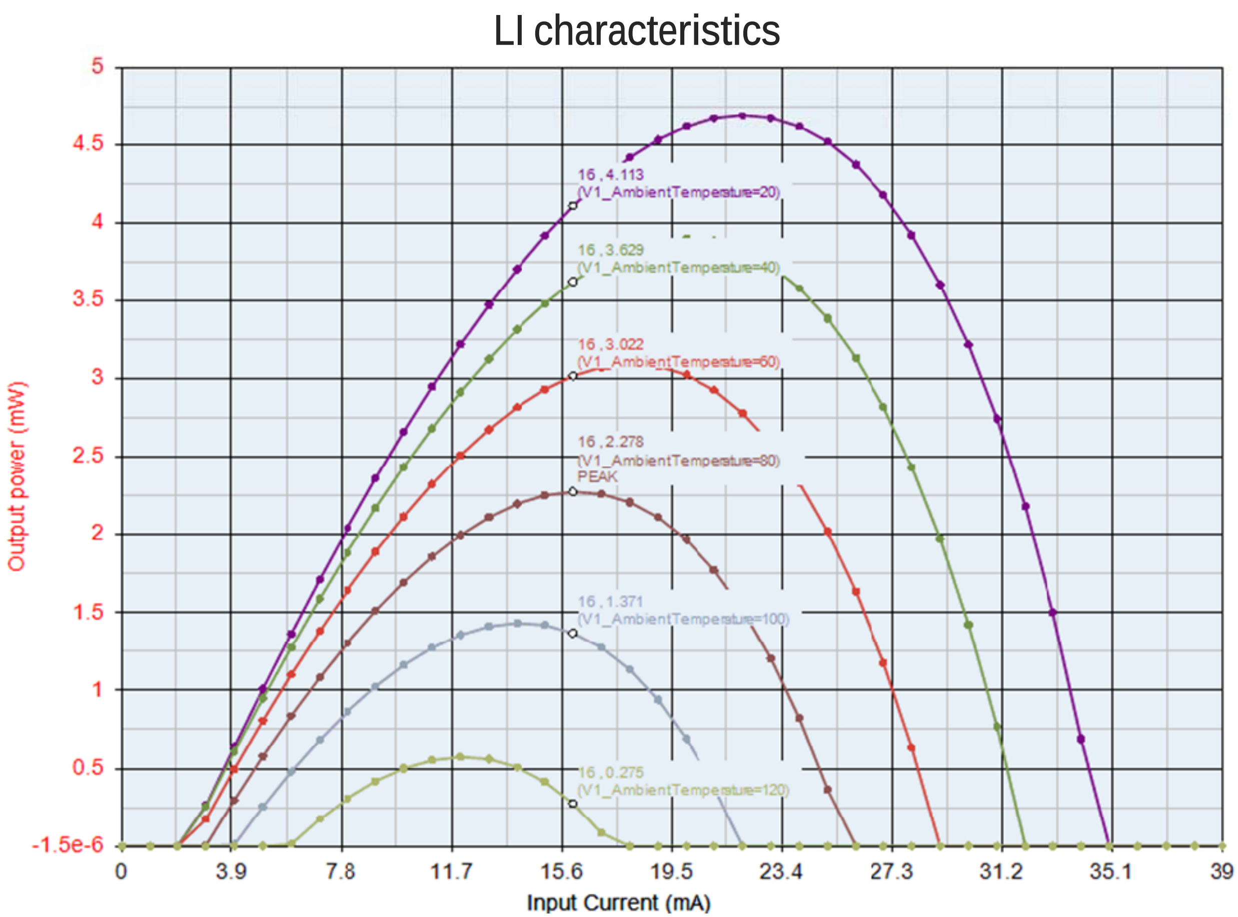
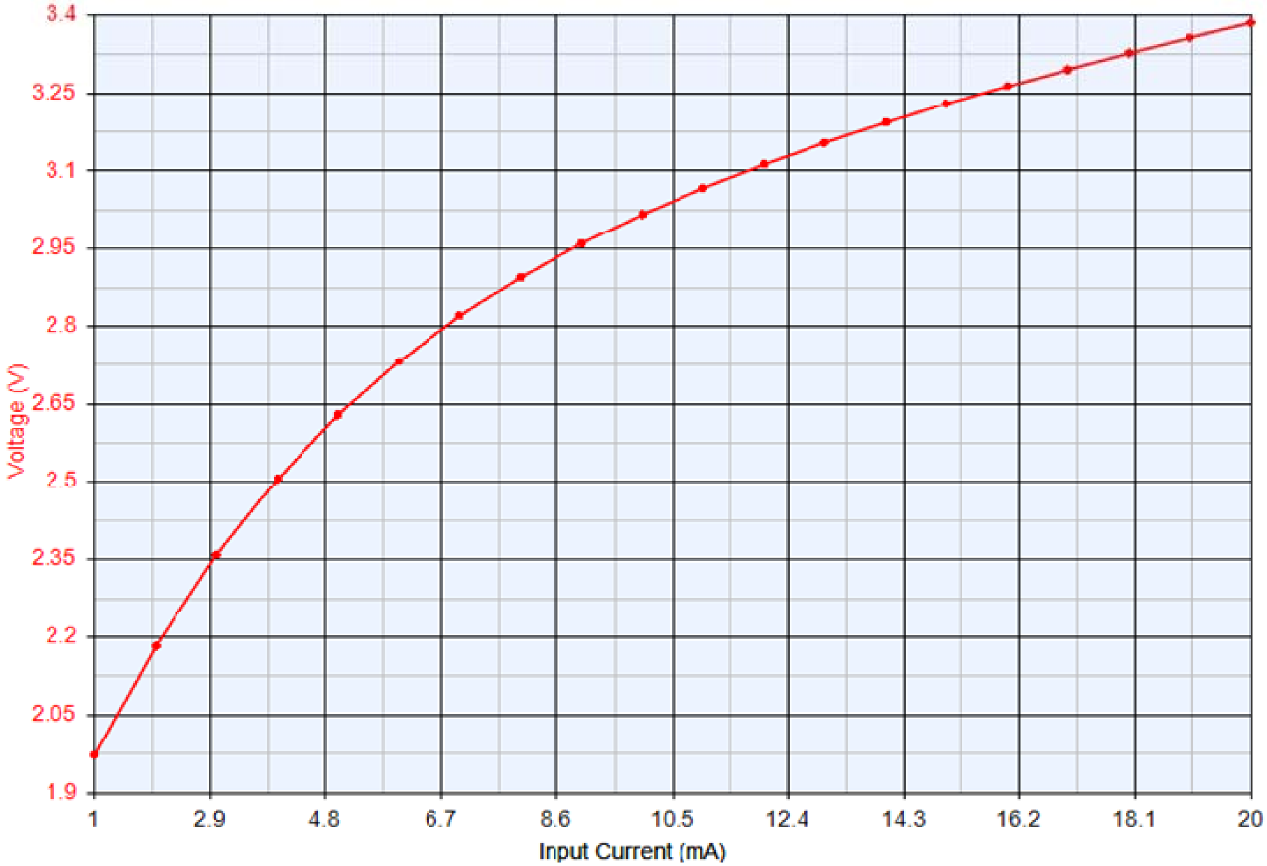
VCSEL Model



- Strong thermal dependency
- Temperature dependent I_{off}
- Output power rollover

VCSEL IV Characteristics



- IV curve is temperature dependent

Laser Rate Equations

$$\frac{dN}{dt} = \frac{\eta(I - I_{off}(T))}{q} - \frac{N}{\tau_n} - \frac{G_0(N - N_0)S}{1+\varepsilon S}$$

$$\frac{dS}{dt} = -\frac{S}{\tau_p} + \frac{\beta N}{\tau_n} + \frac{G_0(N - N_0)S}{1+\varepsilon S}$$

N: carrier number

S: photon number

I: injection current

I_{off}: threshold current

T: temperature

T_0: ambient temperature

P_0: optical power

Thermal Rate Equations

$$T = T_0 + (IV - P_0)R_{th} - \tau_{th}\frac{dT}{dt}$$

$$P_0 = kS$$

IV Characteristics

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

- I_{off}(T) and f(I,T) functions can be fitted from measured LI and IV curves
- Spontaneous emission noise, gain compression and laser driver bandwidth are also included in the VCSEL model.

Fiber Model

Master Equation

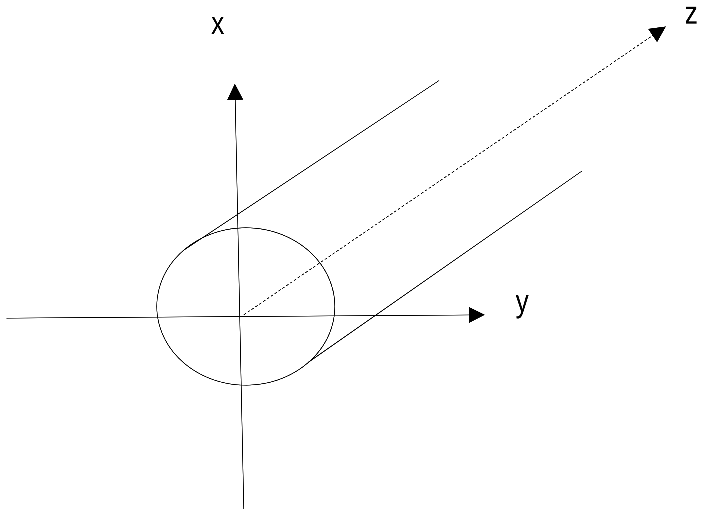
$$\left(\nabla_\perp \frac{1}{\varepsilon(x,y)}\right)\times\left[\left(\nabla_\perp + ik_z\hat{z}\right)\times\vec{H}(x,y)\right]-\frac{1}{\varepsilon(x,y)}\nabla_\perp^2\vec{H}(x,y)+k_z^2\vec{H}(x,y)=\left(\frac{\omega}{c}\right)^2\vec{H}(x,y)$$

Dispersion

$$k_z(\omega_0+\delta\omega)\approx\beta_0+i\alpha+\beta_1\delta\omega+\frac{1}{2}\beta_2\delta\omega^2+\cdots$$

ω_0:center frequency of laser spectrum

$k_z(\omega_0) = \beta_0 + i\alpha$



- Waveguide dispersion: photon confinement in fiber
- Material dispersion: frequency dependent $\varepsilon(\omega)$

Nonlinear Schrodinger Equation of SM fiber

$$\frac{\partial A}{\partial z}+\alpha A+\beta_1\frac{\partial A}{\partial t}+\frac{i}{2}\beta_2\frac{\partial^2 A}{\partial t^2}=i\gamma\left|A^2\right|A$$

PIN Diode and TIA Models

Photon absorption in PIN creates electron-hole pairs and photocurrent

$$I_{ph} = \frac{\eta q}{\hbar \omega} \Phi$$

η:quantum efficiency

Φ: laser power

Other factors included in the models

- Optical and electrical bandwidth
- Nonlinear transimpedance
- Thermal noise and shot noise

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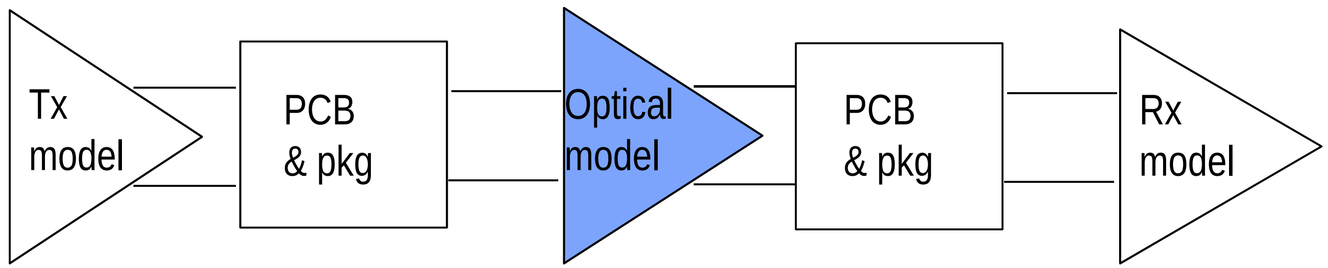
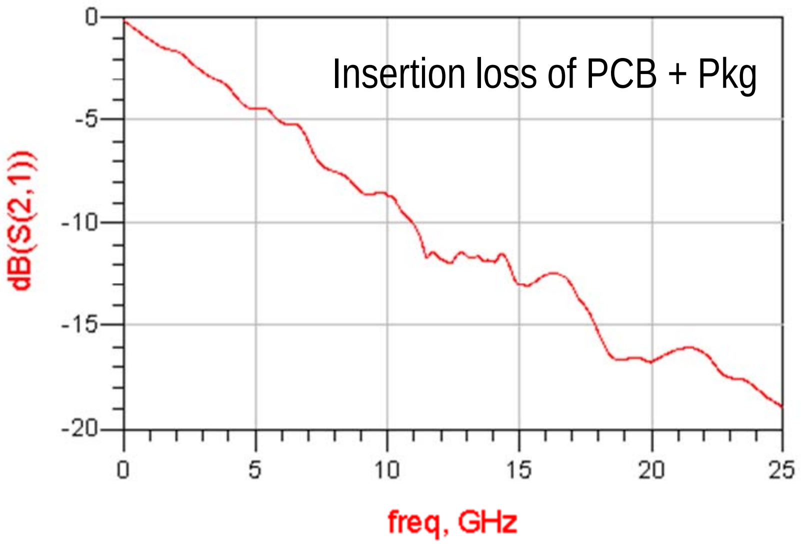
25G Optical Channel

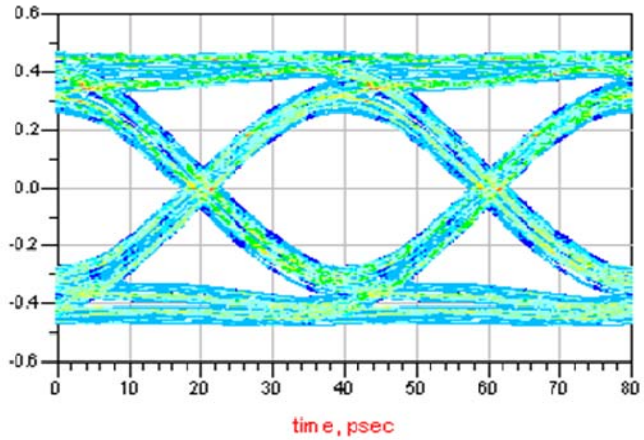


- Tx is a pass-through
- Rx implements voltage-gain control, CTLE, 5-tap DFE and CDR
- SERDES and optical module are connected by Tx/Rx package, PCB and optical package

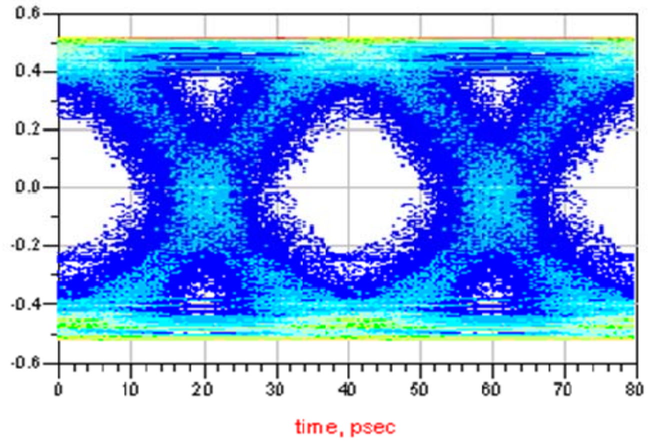


Eye Diagrams at Room Temperature

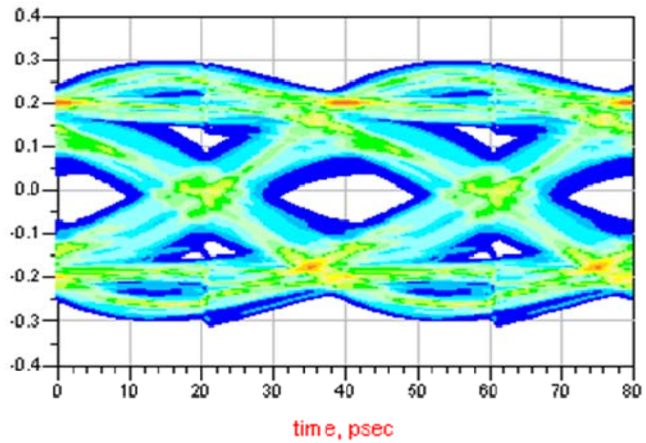
Optical module input



Optical module output



Rx output



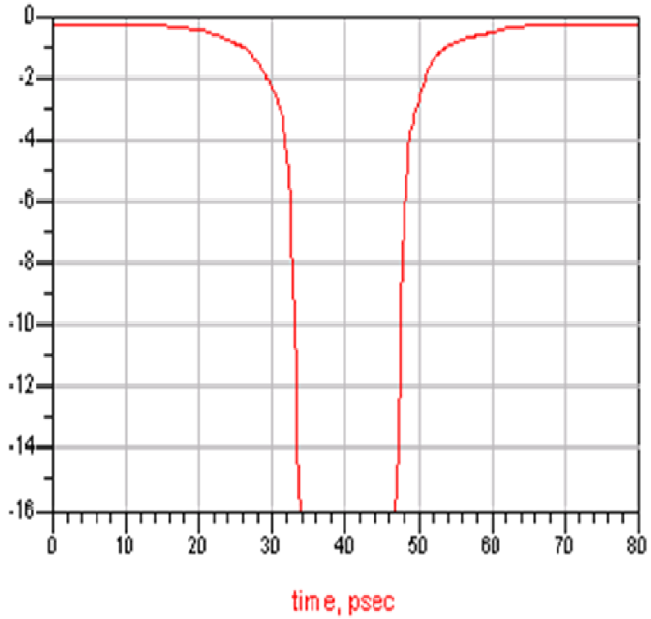
T = 27^{o}C

Fiber length = 50m

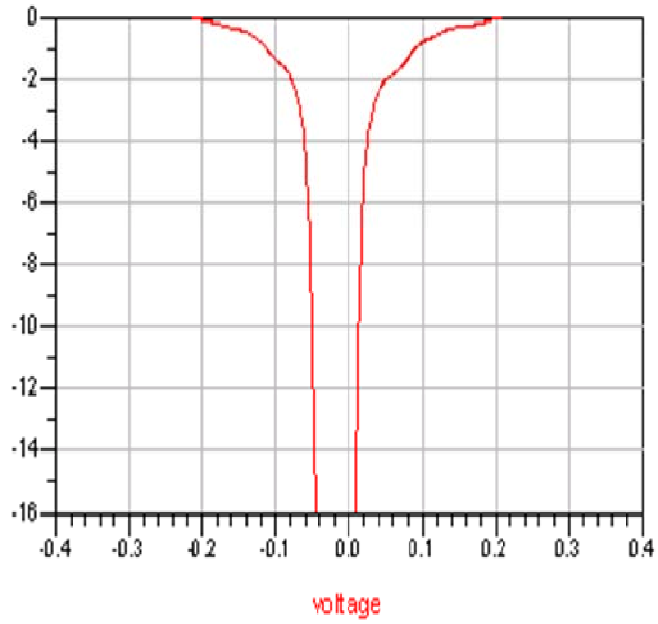
Bathtub Curves

Rx output

Timing bathtub

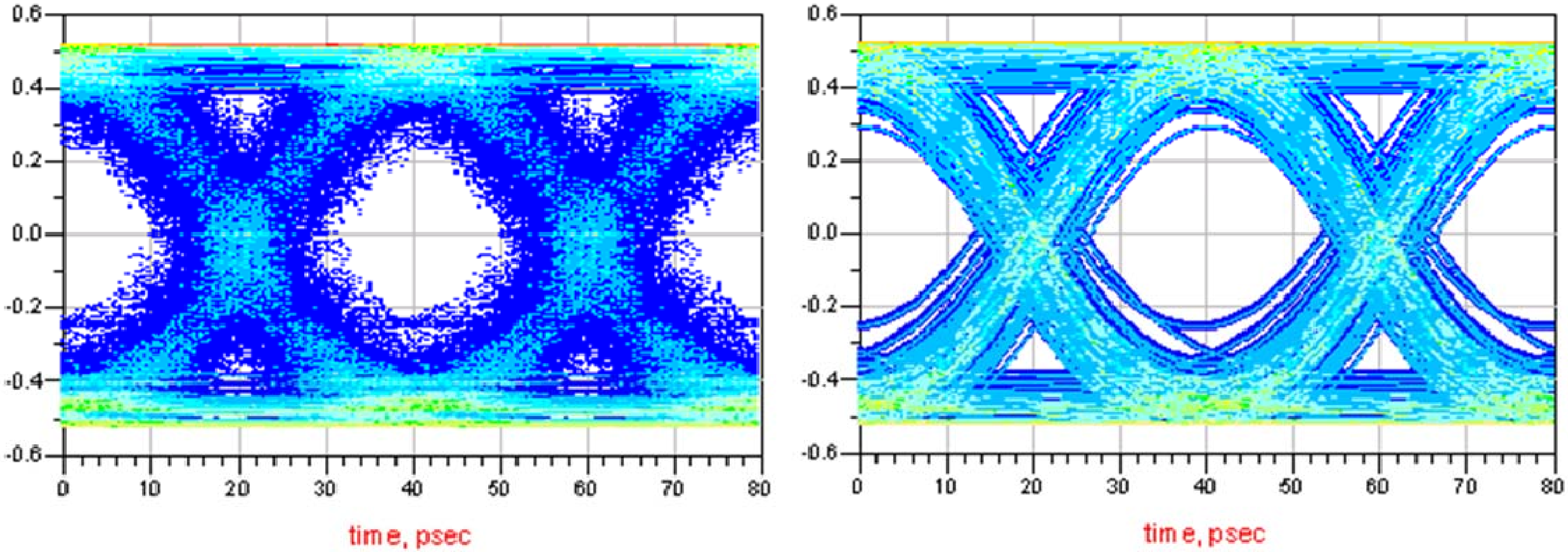


Voltage bathtub



Optical Noise Effects

Eye at optical output



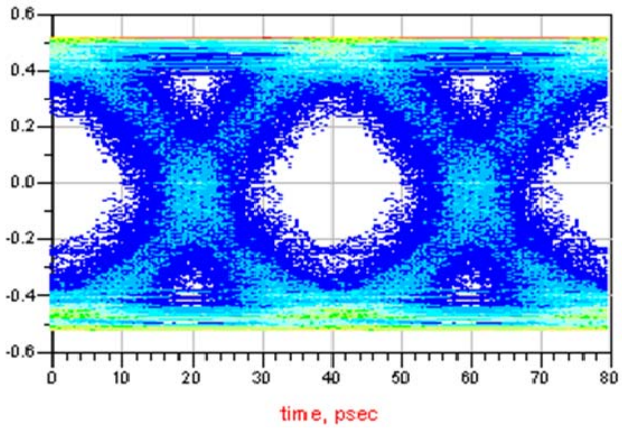
with optical noise

optical noise turned off

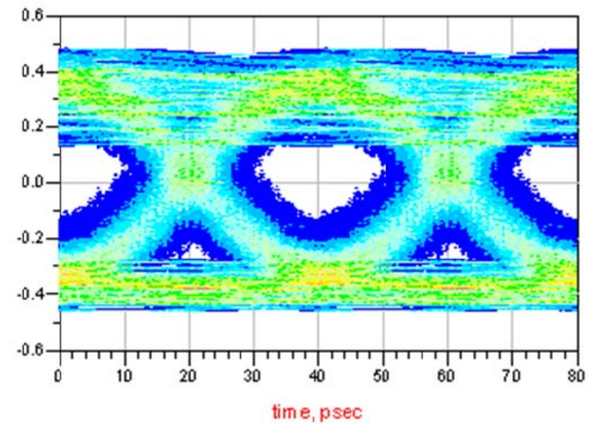
Temperature Effects

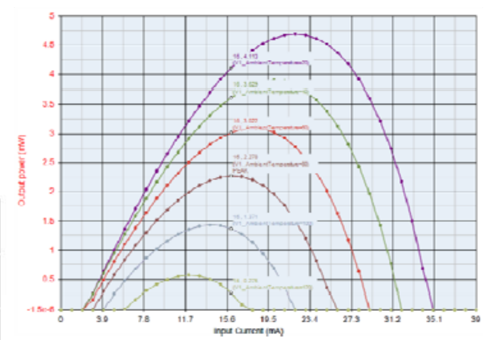
Eye at optical output

27°C



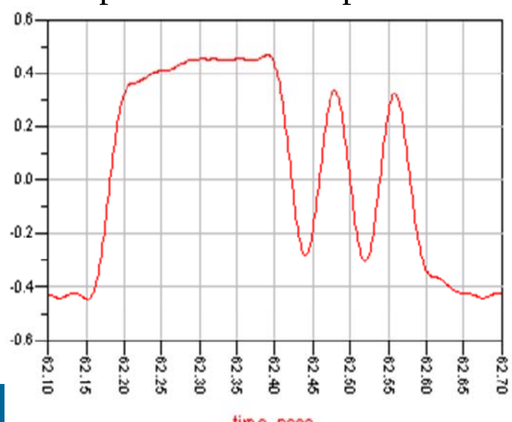
65°C



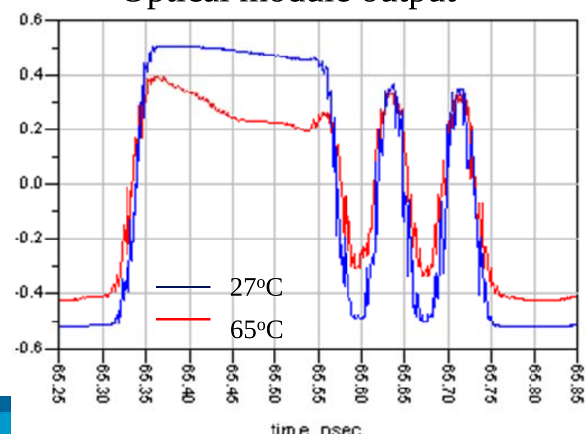


- Output level of long consecutive logic-1 sequence drops as temperature increases
- Caused by VCSEL LI curve rollover

Optical module input

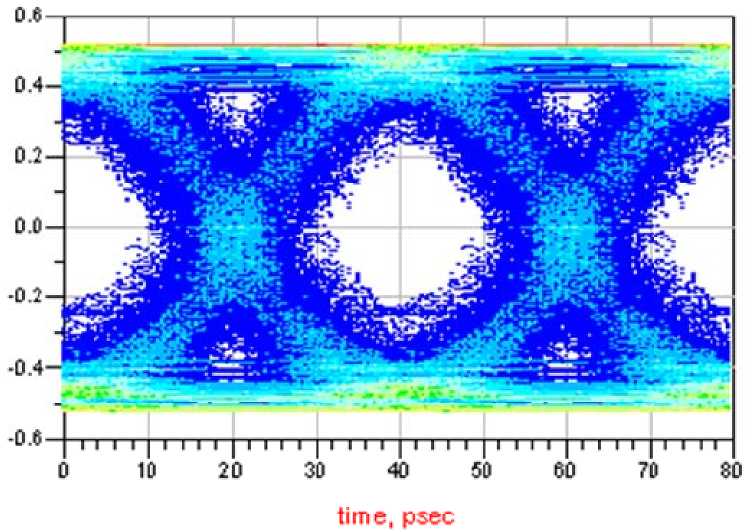


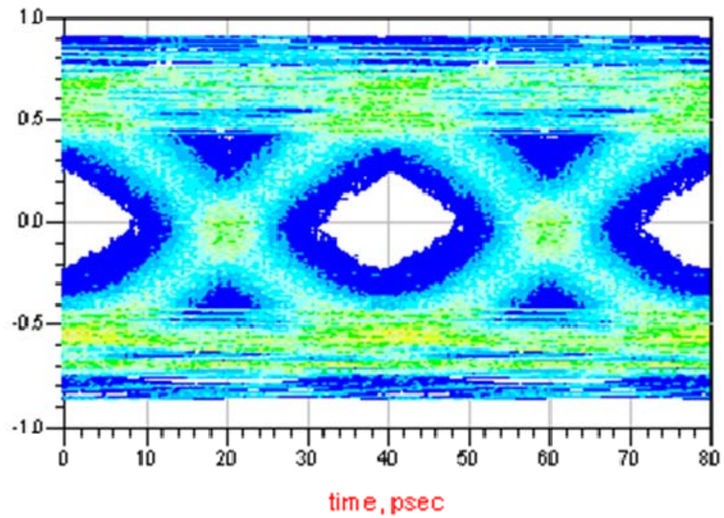
Optical module output



Nonlinear Effects

Eye at optical output





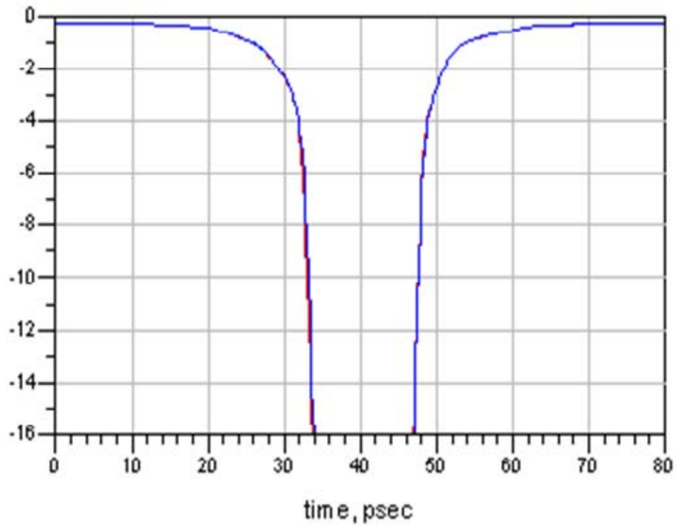
- TIA 1dB compression at 0.4V
- Output amplitude: 1V

- TIA 1dB compression at 2V
- Output amplitude: 1.8V

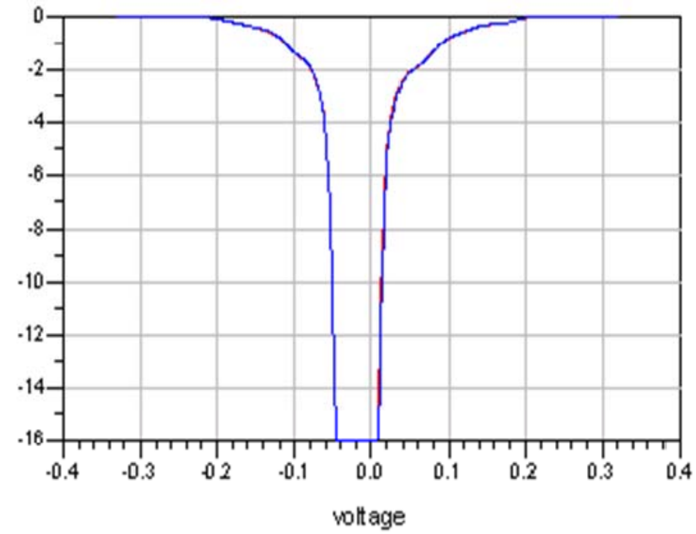
Fiber Length Effect

Bathtubs at Rx output

Timing bathtub



Voltage bathtub



50m   100m

Due to low optical loss length effect is unnoticeable.

Summary

- AMI methodology is applied to model and simulate optical channel
- IP protection to optical vendors
- Interoperable with SERDES models by supporting the same interface
- Enable co-simulation in electrical and optical domains to account for SERDES and optical effects
- Optical models are developed to describe behaviors of laser driver, VCSEL, fiber, PIN and TIA.
- Thermal effects, nonlinearity and optical noise are demonstrated in simulation results
- The approach provides a practical and efficient solution for end-to-end optical link analysis