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

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Outline

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

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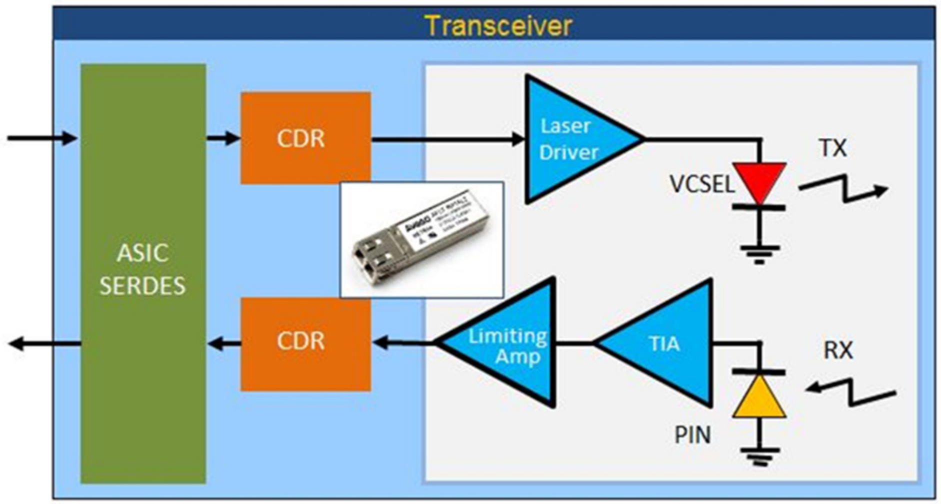
Bandwidth of traditional electrical link is increasingly limited by channel loss above 25G.

Advantages of optical channels:

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

Optical Link System



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

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

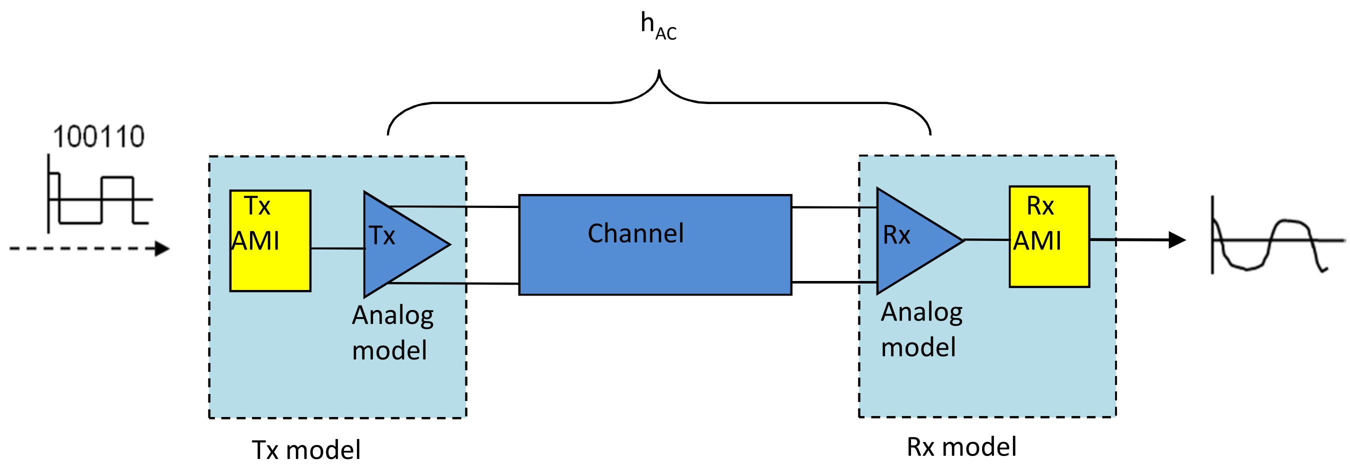
- AMI is introduced in IBIS 5.0
- Defines SERDES behavioral modeling interface
- An AMI model consists of analog model and algorithmic (AMI) block
- Analog model: regular IBIS model, represents rise/fall edge and impedance/load.
- AMI bock: SW executable, models Tx/Rx logics including gain control, equalizers 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 AMI 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

Advantages and Limitation of AMI

Advantages of AMI

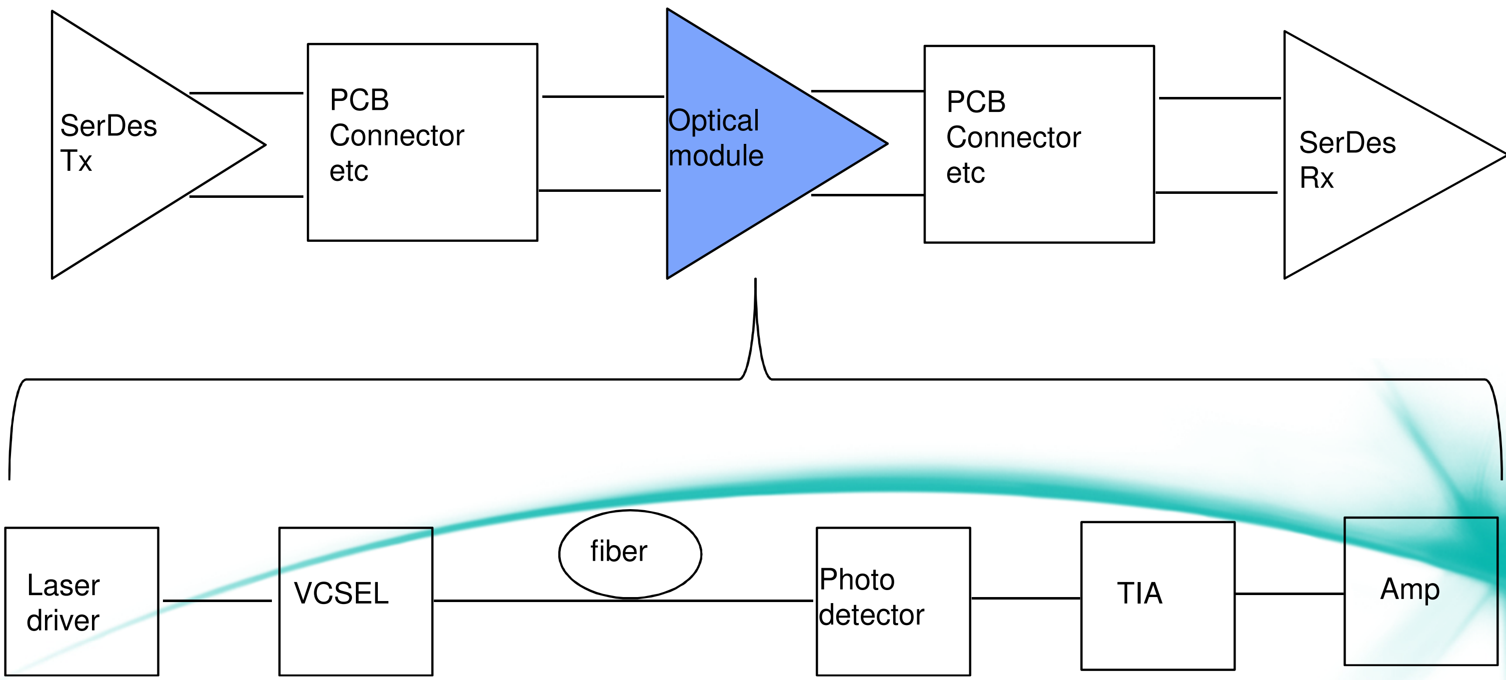
- Models capture SERDES internal functionalities
- IP protection: models are delivered as DLL or/and shared object, concealing implementation details.
- Interoperability between models from different vendors
- Highly efficient link simulation, capable to process millions of bits in minutes

Limitation

- Assumes linear channel
- Optical channel is known to be strongly nonlinear and noisy

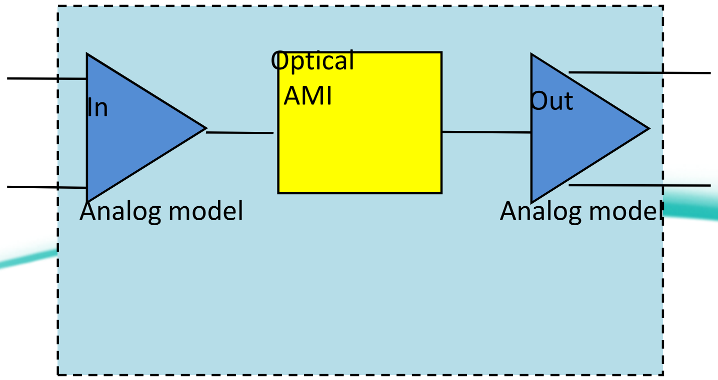
Extending AMI to Optical Channel

- 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

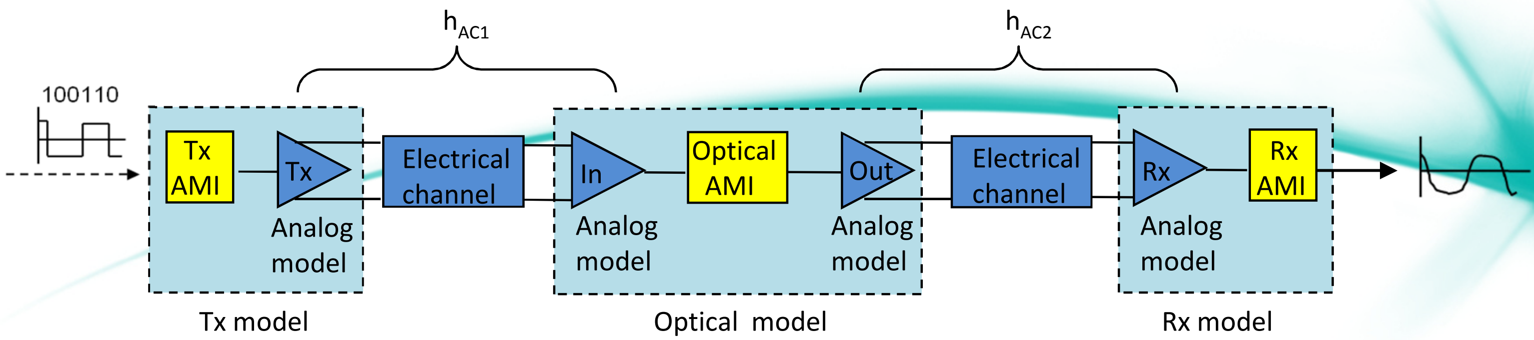
- Model comprises input analog model, optical AMI block and output analog model
- Analog models represent load at input end and impedance at output end
- Optical AMI block encapsulates electrical-optical conversion and photon propagation inside the fiber.
- Optical model is defined in electrical domain. AMI_GetWave takes input voltage waveform, and returns output voltage waveform (same as regular AMI models).
- 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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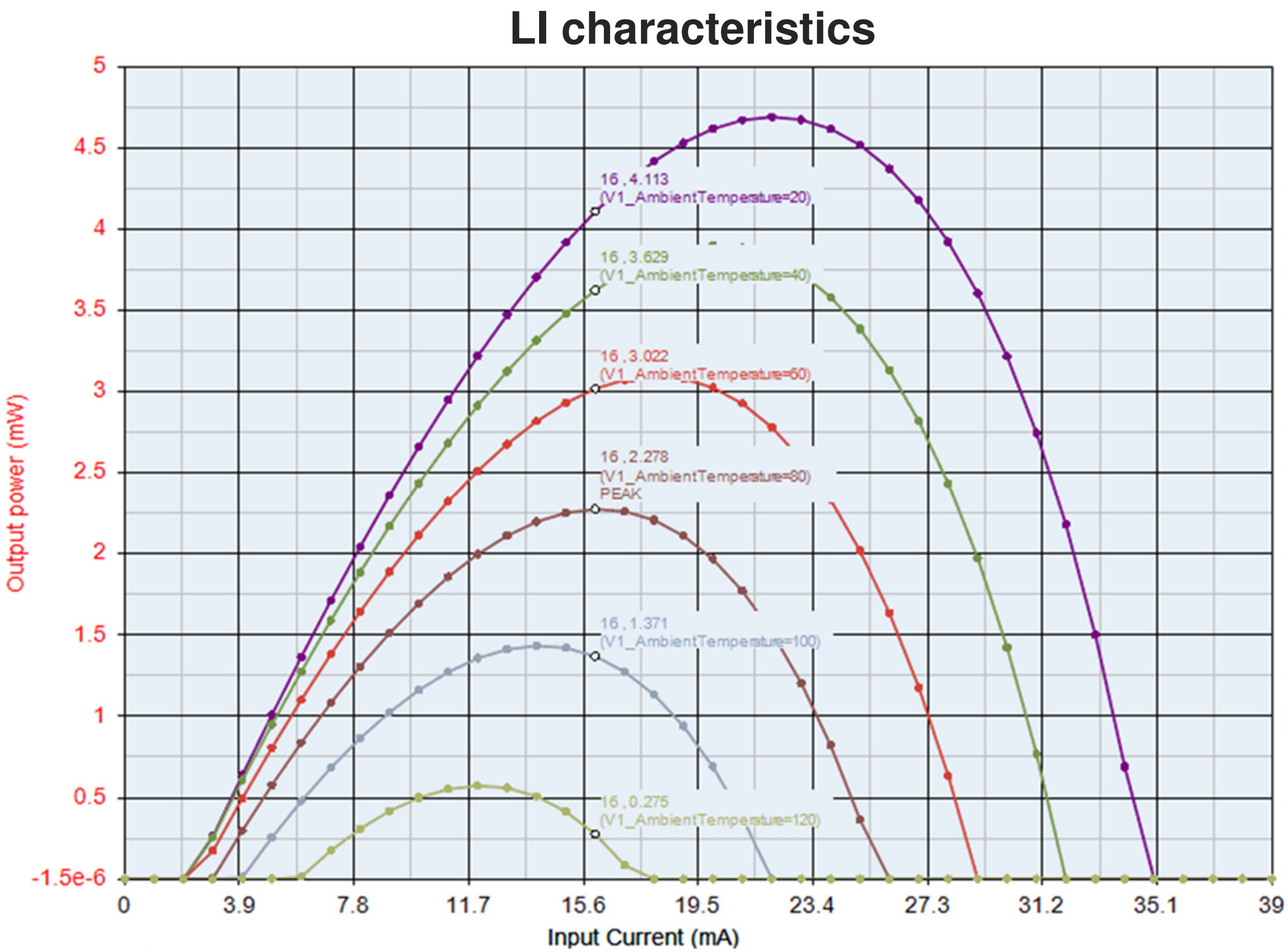
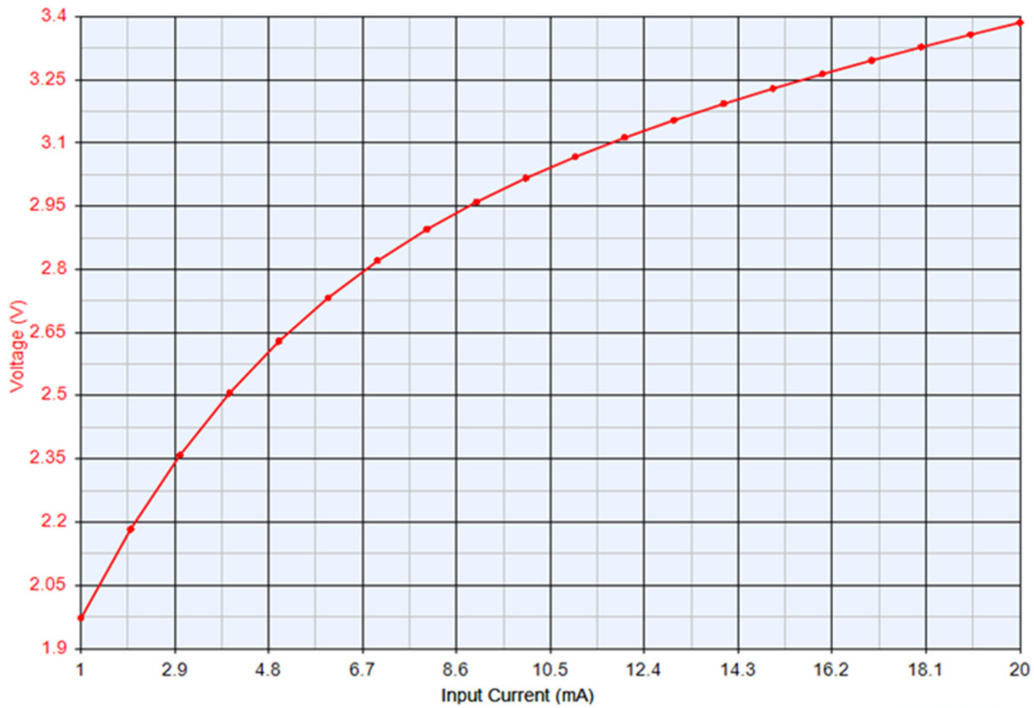
VCSEL Model



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

VCSEL IV Characteristics



- IV curve is temperature dependent

Laser Rate Equations

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

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

Thermal Rate Equation

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

$$P_0 = kS$$

IV Characteristics

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

N: carrier number

S: photon number

I: injection current

I_{off}: threshold current

T: temperature

T_0: ambient temperature

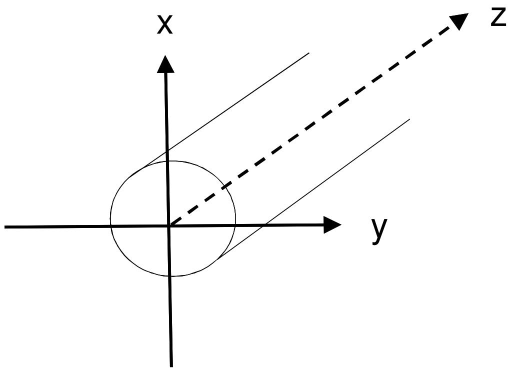
P_0: optical power

- $I_{off}(T)$ and f(I,T) functions can be fitted from measured LI and IV curves
- Equations are simplified to improve simulation throughput while maintaining LI and IV characteristics.
- Spontaneous emission noise, gain compression and laser driver bandwidth are also included in the VCSEL model.

Fiber Model

Master Equation

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



Dispersion

- Determined by eigenvalues of $\omega(k_z)$
- Waveguide dispersion: photon confinement in fiber
- Material dispersion: frequency dependency of $\varepsilon(\omega)$
- Small pulse spectral width expansion

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

ω_0:center frequency of laser spectrum

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

Nonlinear Schrodinger Equation of SM fiber

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

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 considered in the models

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

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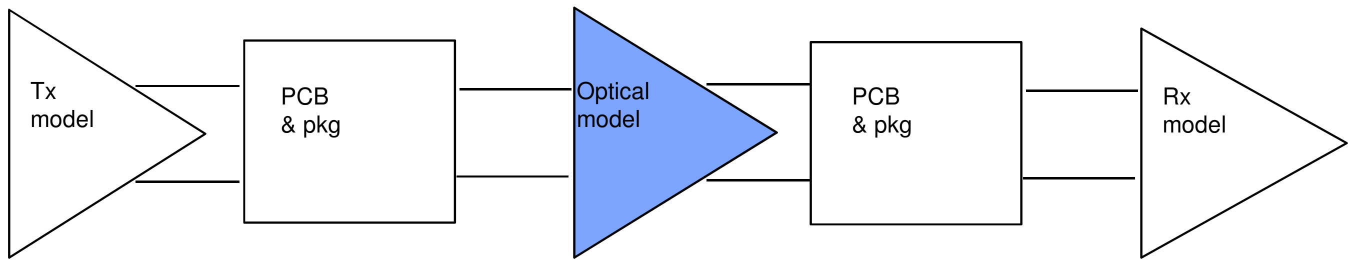
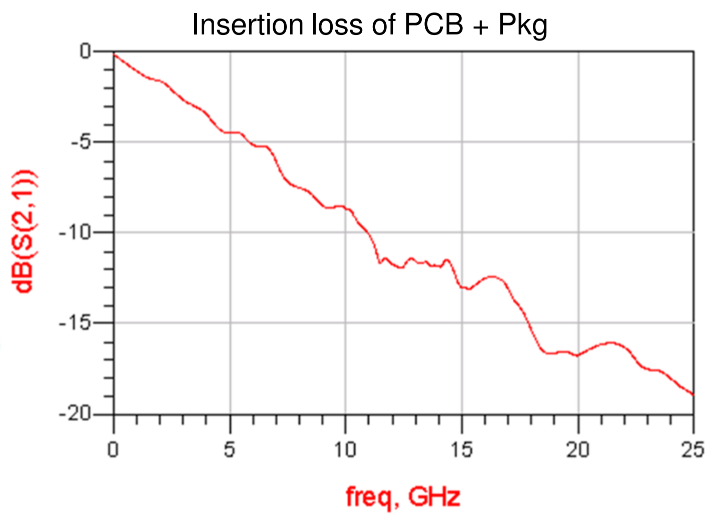
25G Optical Channel

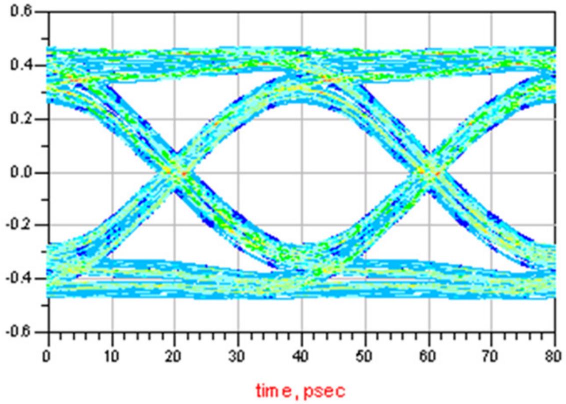


- Tx is a pass-through
- Rx implements voltage-gain control, CTLE, 5-tap DFE and CDR
- SERDES and optical module are connected by Tx/Rx package, PCB and optical package

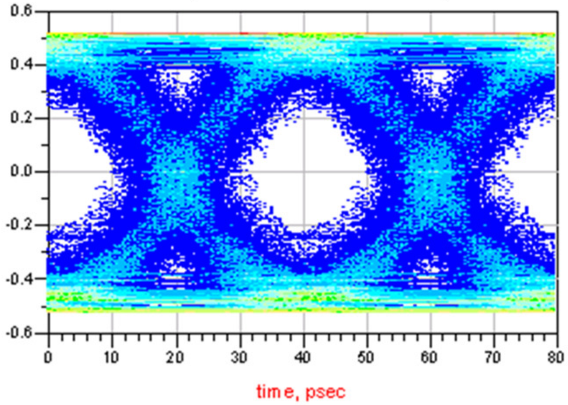


Eye Diagrams at Room Temperature

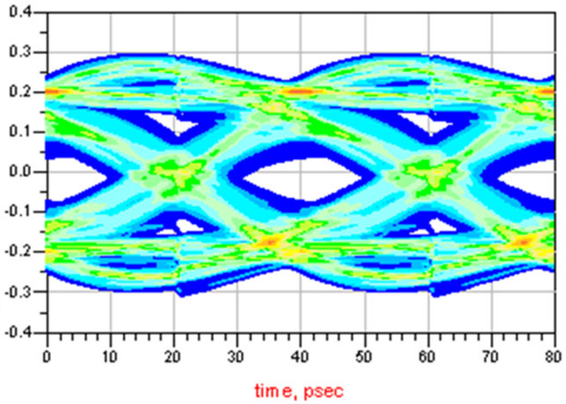
Optical module input



Optical module output



Rx output

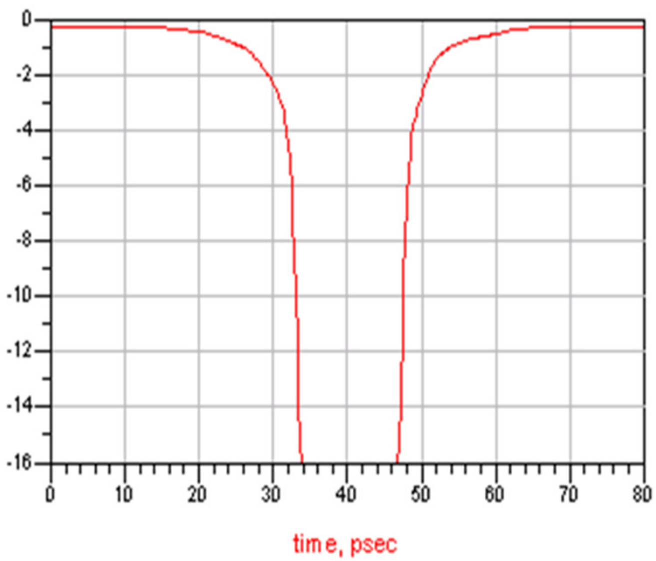


T = 27°C
Fiber length = 50m

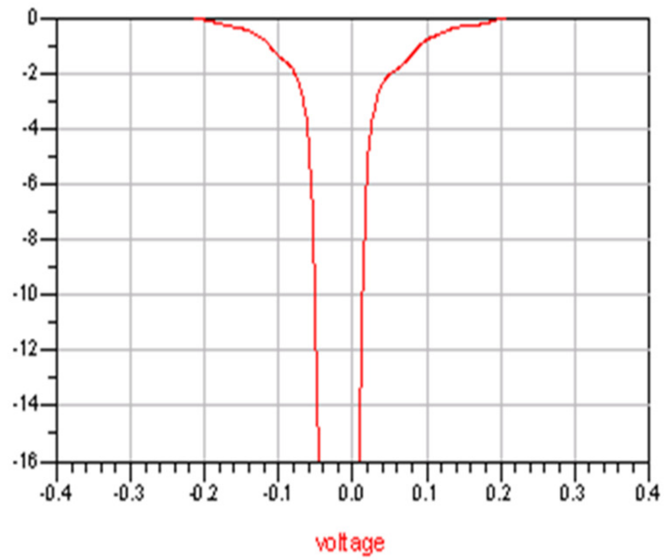
Bathtub Curves

Rx output

Timing bathtub

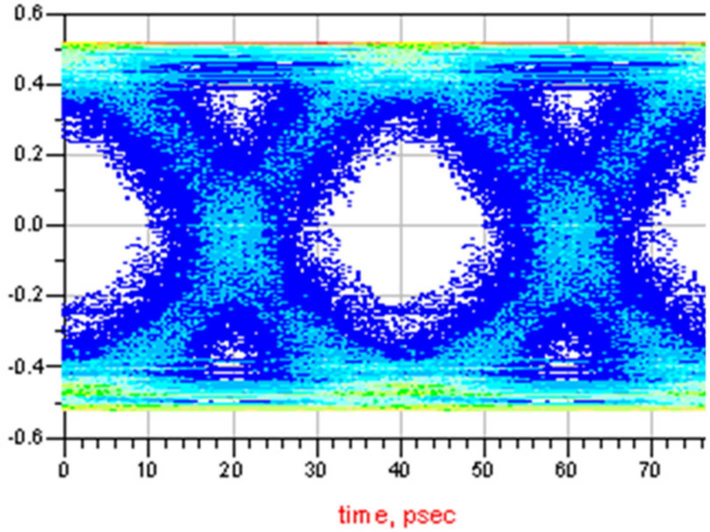


Voltage bathtub

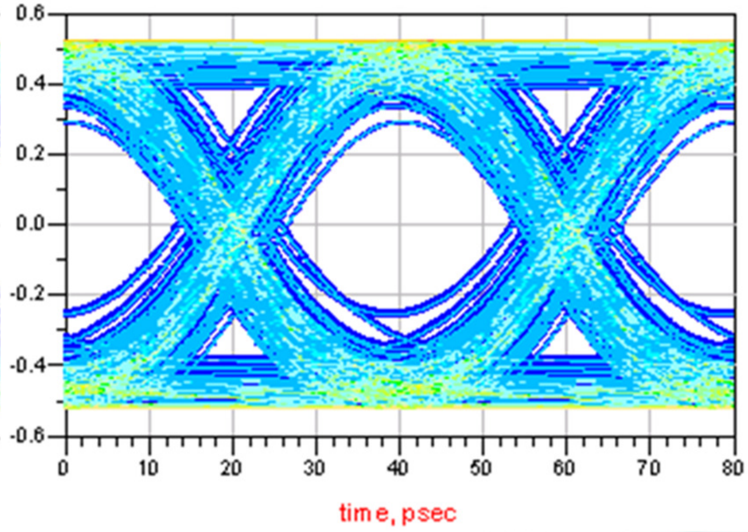


Optical Noise Effects

Eye at optical output



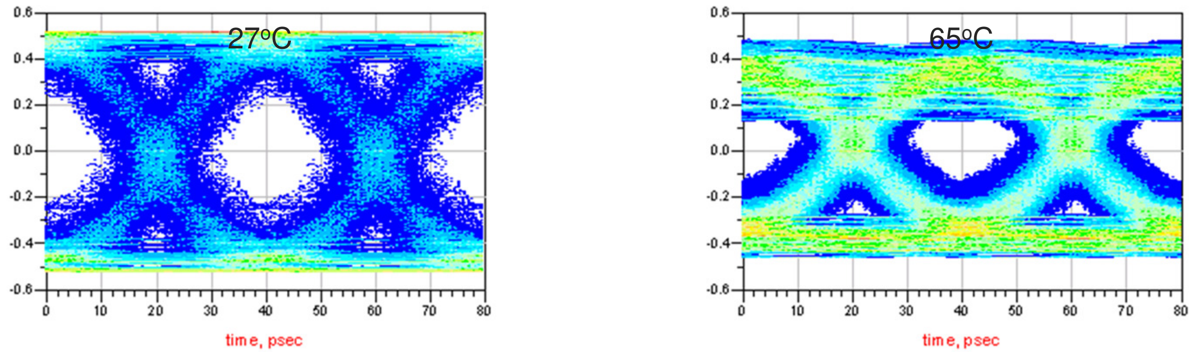
with optical noise



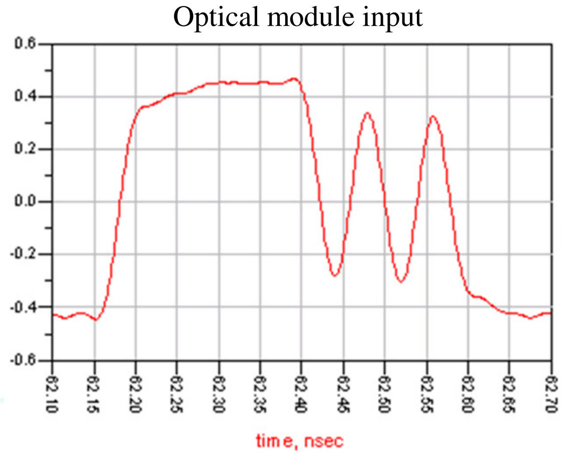
optical noise turned off

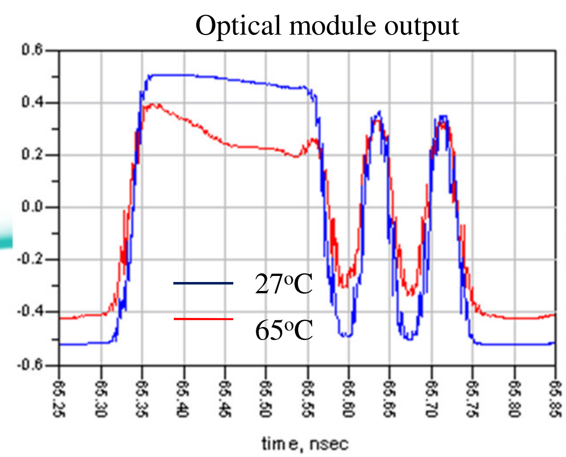
Temperature Effects

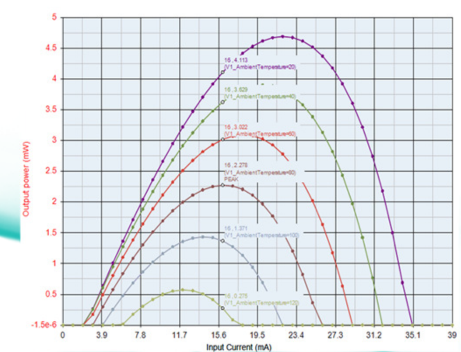
Eye at optical output



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

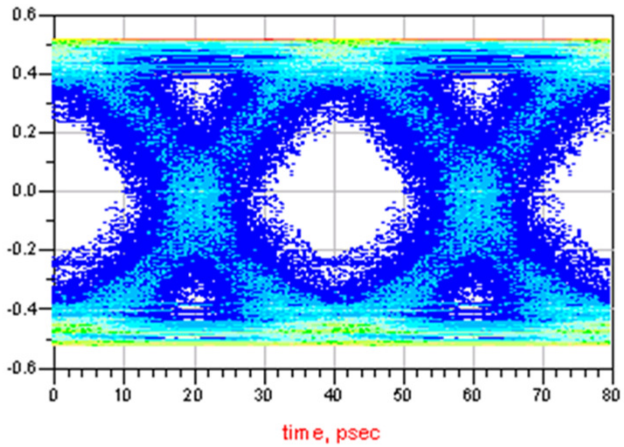




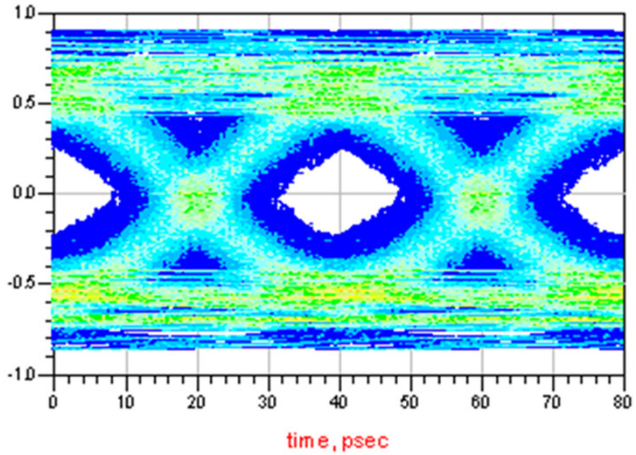


Nonlinear Effects

Eye at optical output



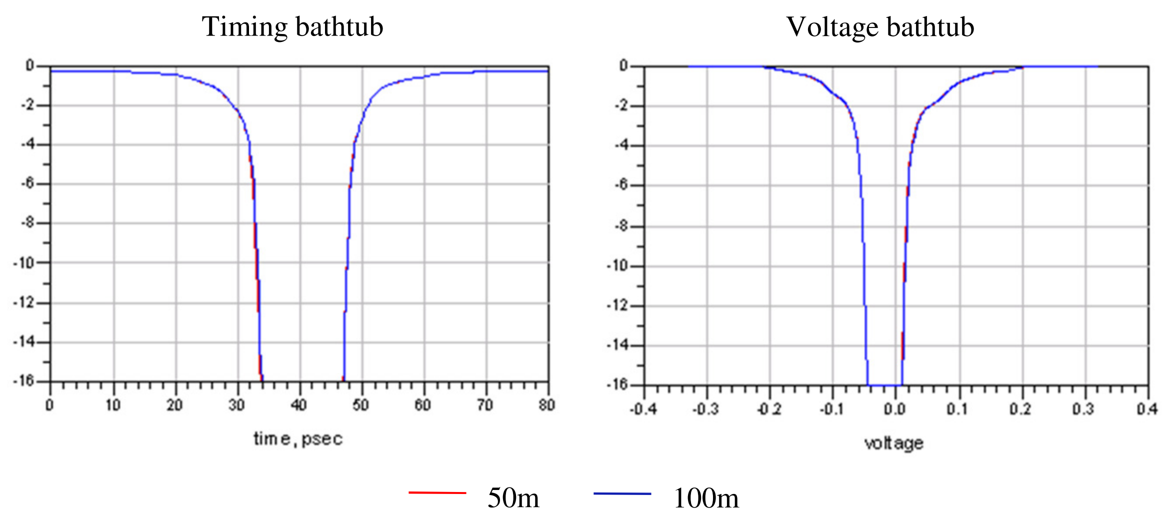
- TIA 1dB compression at 0.4V
- Output amplitude: 1V



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

Fiber Length Effect

Bathtubs at Rx output



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