System-aware PIC Design for FSO, Quantum, and Telecom Applications

EPIC TechWatch @ ECOC 2023

Chris Maloney, Director of Business Development

October 4th 2023

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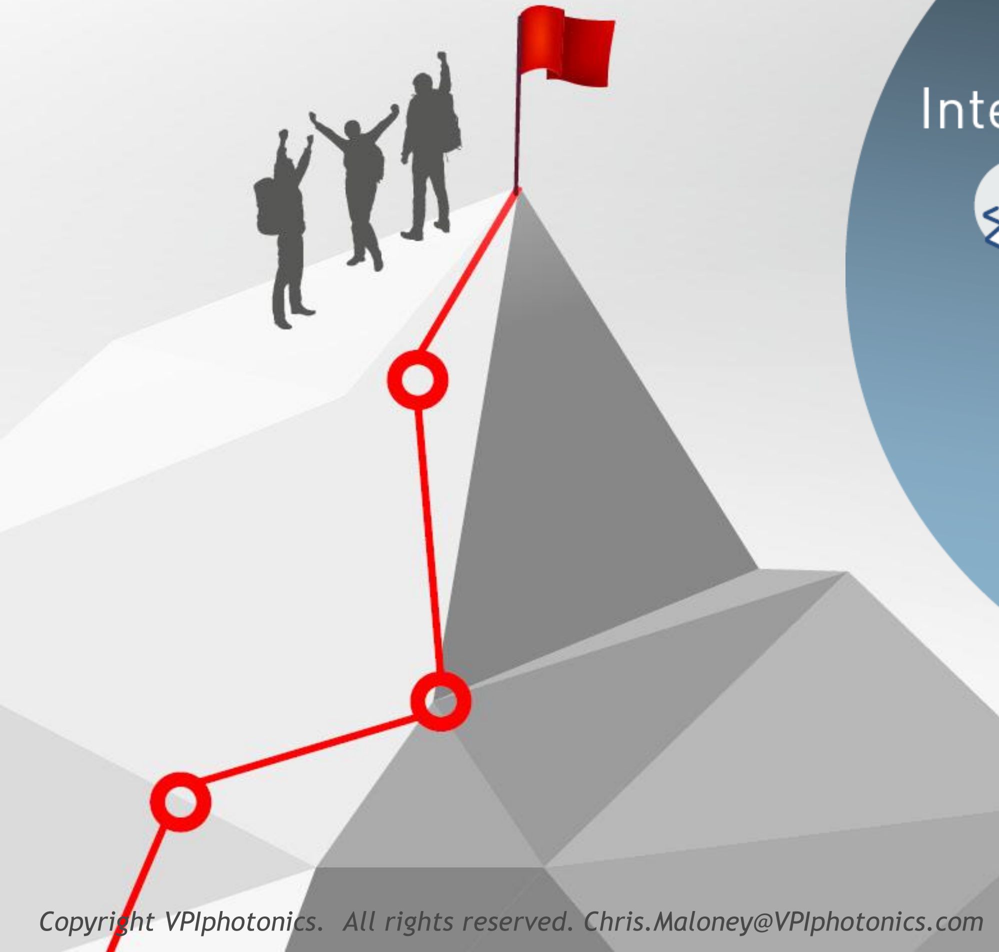

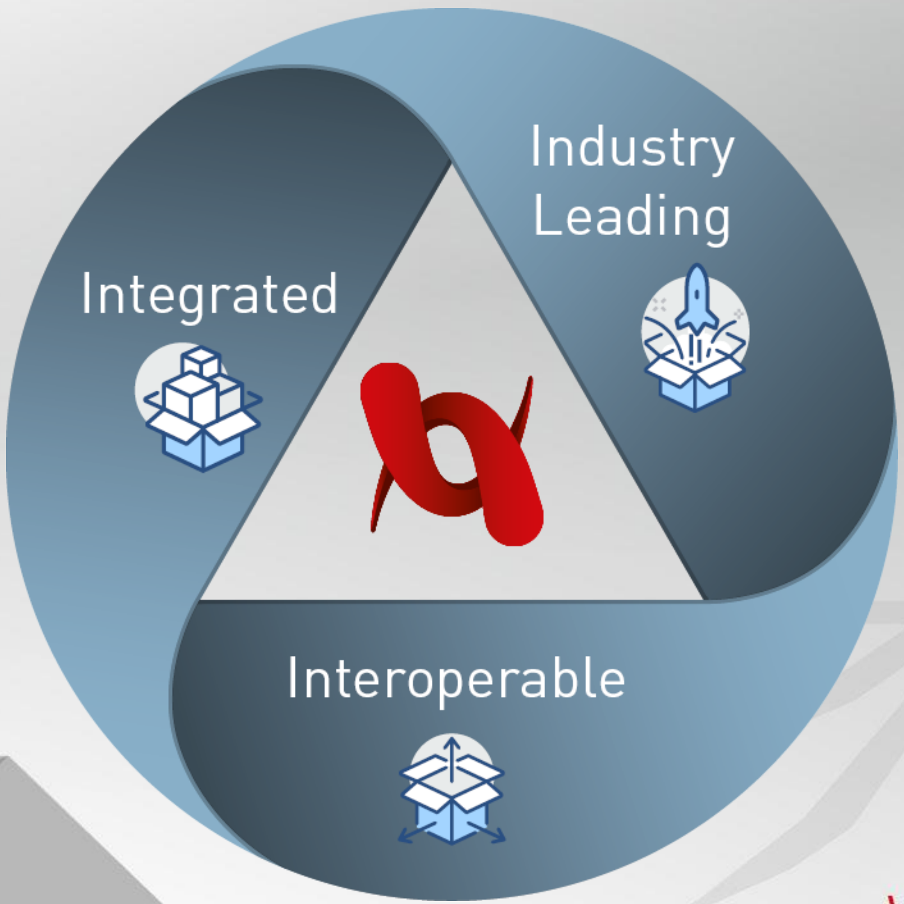

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- VPItransmissionMaker Optical Systems
- VPI Lab Expert
- DSP Library
- QKD

Component Design

- VPIcomponentMaker Fiber Optics
- VPIcomponentMaker Photonic Circuits
- PDK<fab>

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Device Simulation

VPI Device Designer

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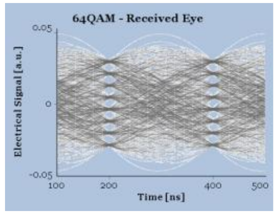
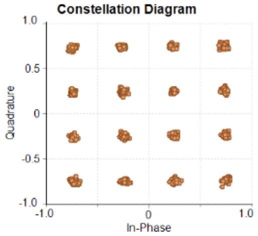
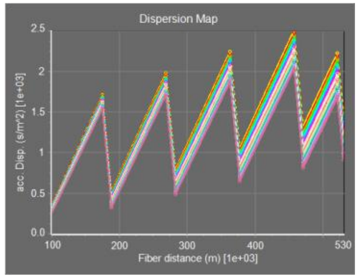
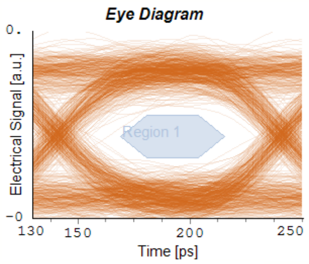
Applications

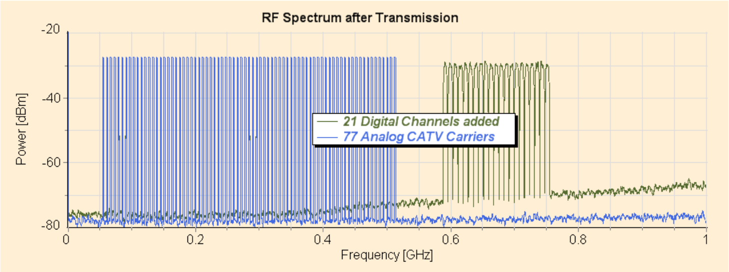
- Short-reach, Optical Interconnects
- Aggregation, metro, core networks
- Ultra-long haul DWDM
- High capacity, high-speed
- Optical networking
- HFC, RoF, Microwave photonics
- LiDAR, Satellite Communications
- Component characterization
- MM/SM transmission, amplification
- Amplification, regeneration
- Coding, modulation, DSP
- Compensation, equalization

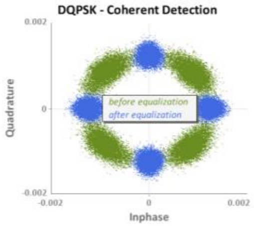




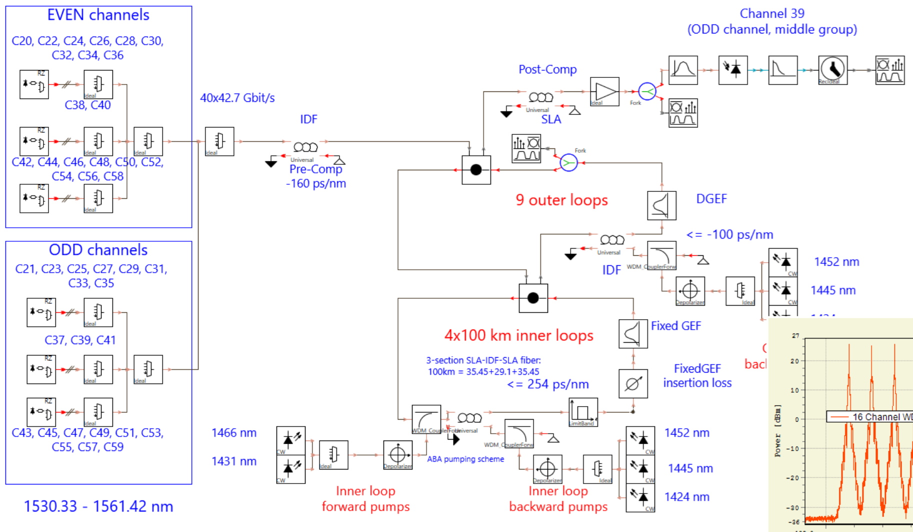


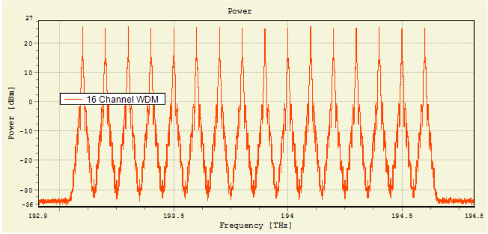






1.6 Tbit/s (40x42.7 Gbit/s) Transmission over 3600 km UltraWave Fiber



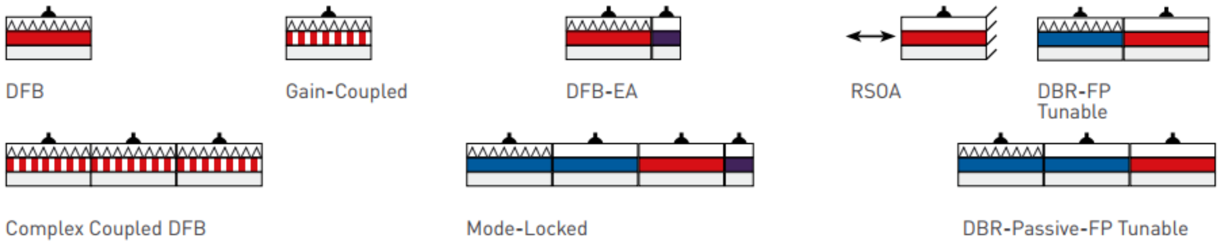


Benefits

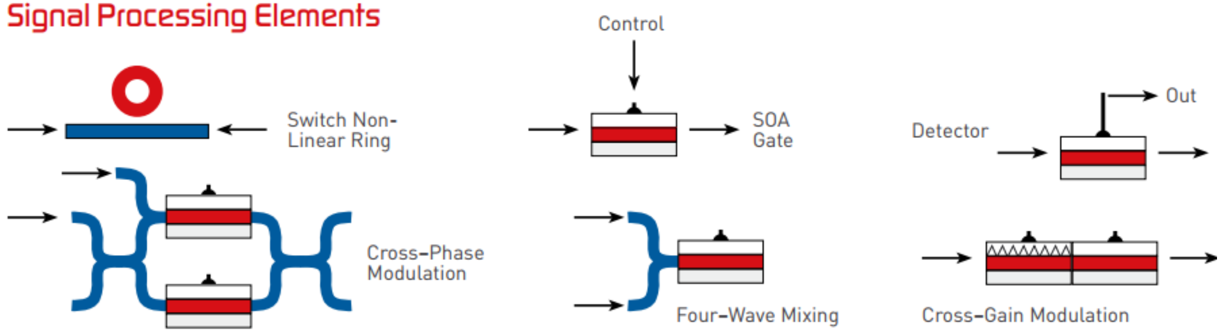
- ✓ Analyze OSNR, Q, BER, TDECQ, ...
- ✓ Evaluate component performance and impairments
- ✓ Compare technology choices and upgrade strategies
- ✓ Optimize equipment placement and mitigation techniques

VPIcomponentMaker Photonic Circuits:
Photonic and Optoelectronic Components

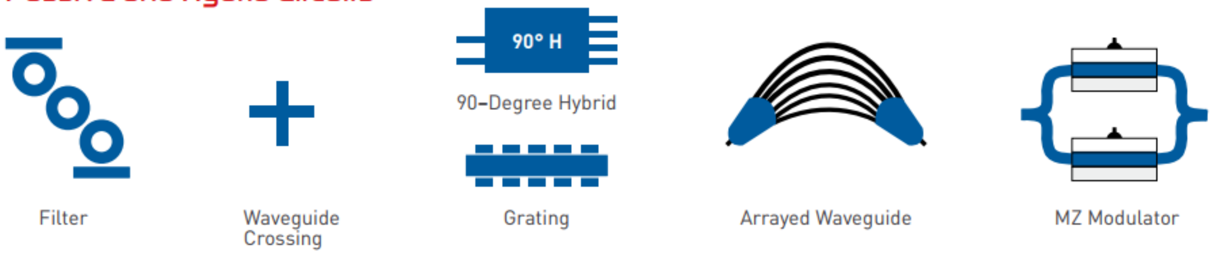
Semiconductor Lasers and Transmitters



Signal Processing Elements

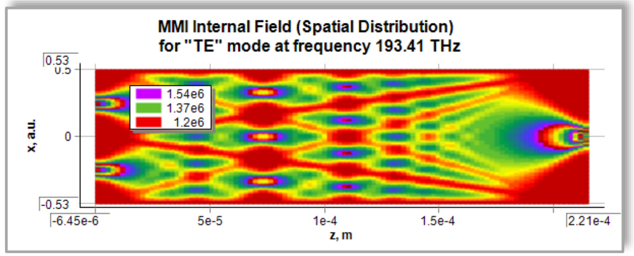


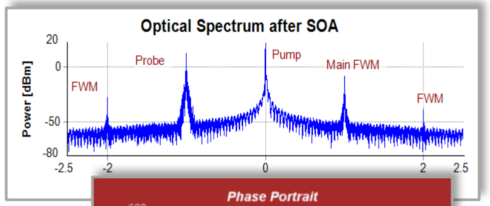
Passive and Hybrid Circuits

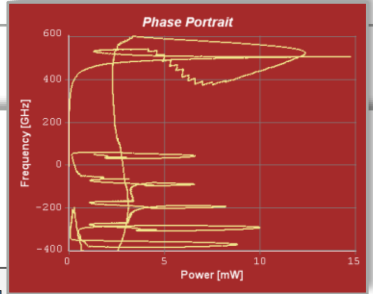


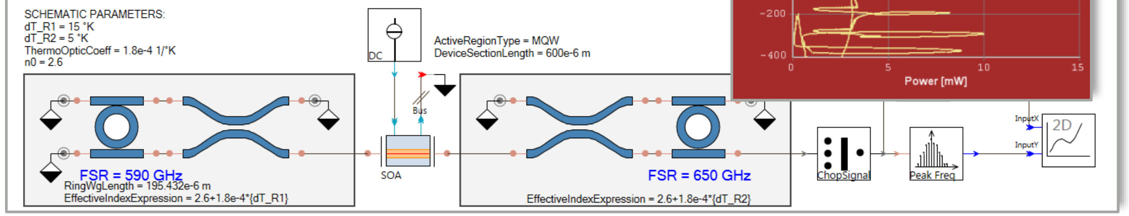
Benefits

- ✓ Fast design & optimization of PICs and multi-section semiconductor devices
- ✓ Study alternative design options
- ✓ Tune and optimize circuit parameters
- ✓ Investigate fabrication tolerances
- ✓ Perform sensitivity analysis





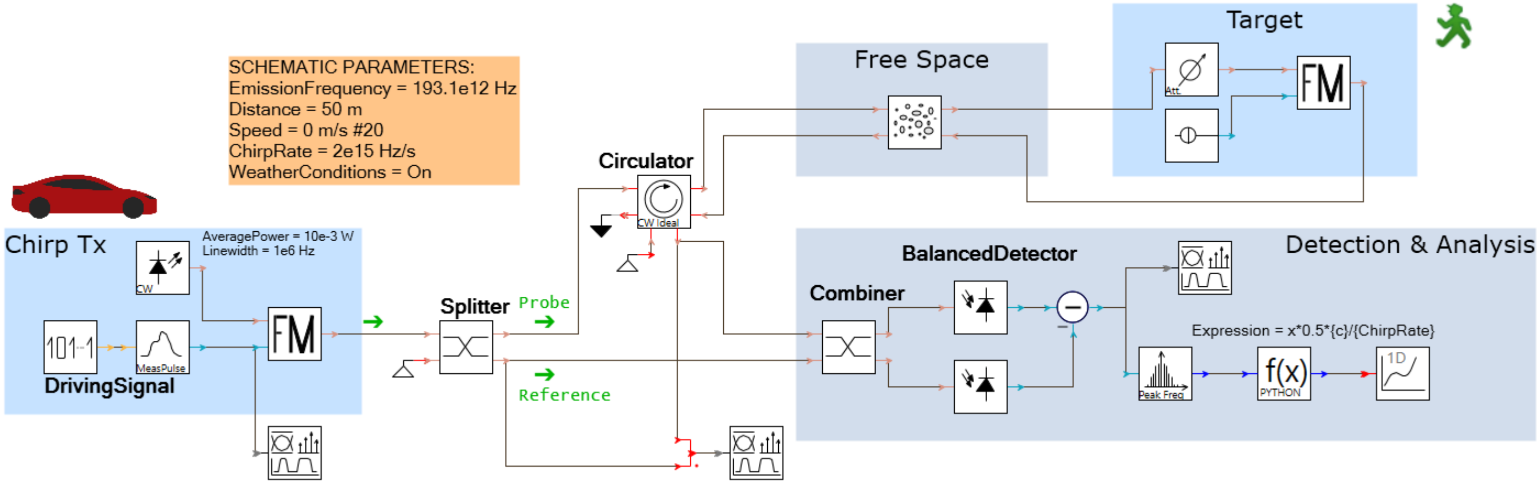




Designing PICs for Free Space Optical Systems

Designing PICs for Free Space Optical Systems

Frequency-Modulated Continuous Wave LiDAR System

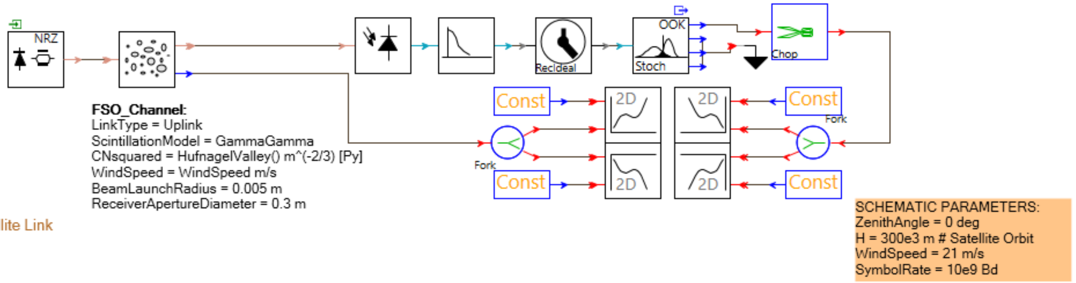


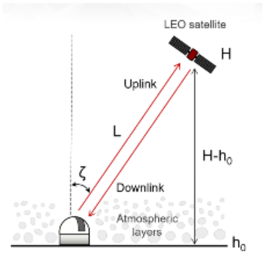
Free-Space Optical Satellite Link

✓ The FSO_Channel module supports atmospheric effects for terrestrial and satellite (up-/down-) link.

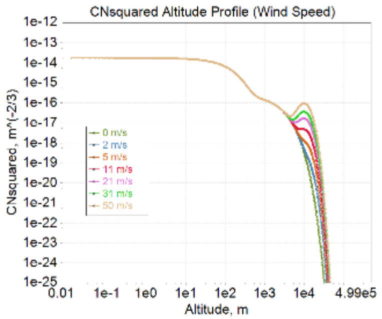
✓ Scintillation model: LogNormal and GammaGamma

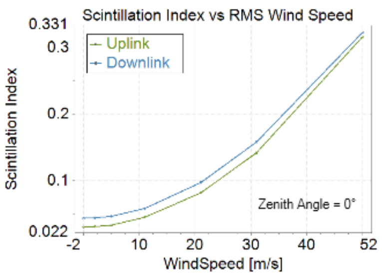
References:
- Application Examples → OS → Short Reach → Scintillation on a FSO Satellite Link

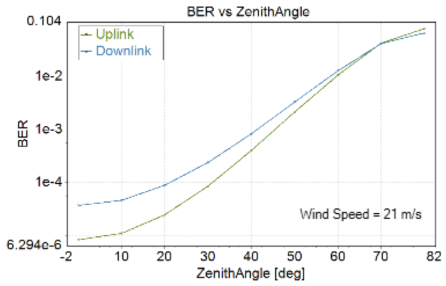




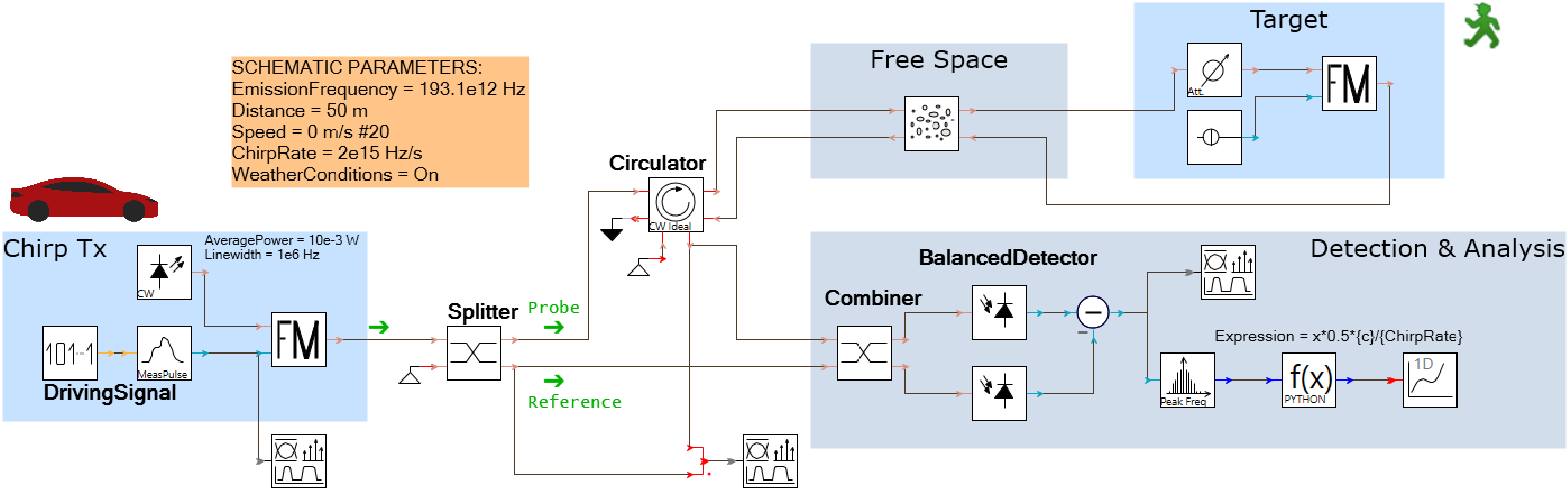
- Zenith angle $\zeta = 90^\circ$-Elevation
- "Flat Earth" approximation: $H = h_0 + L\cos(\zeta)$

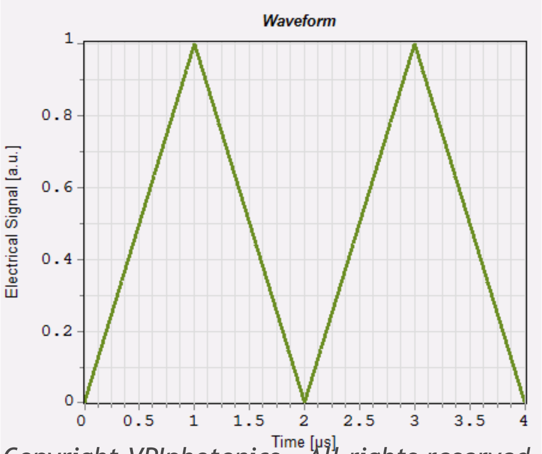


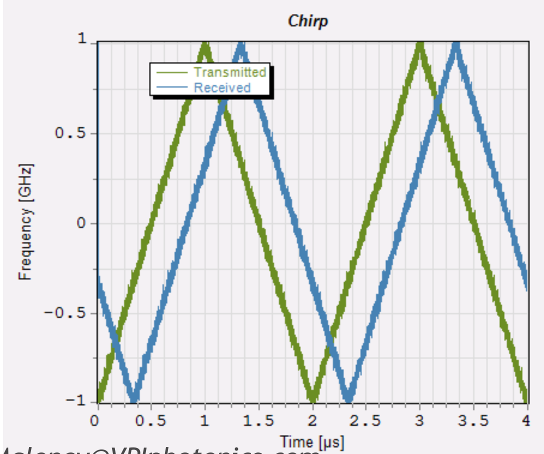


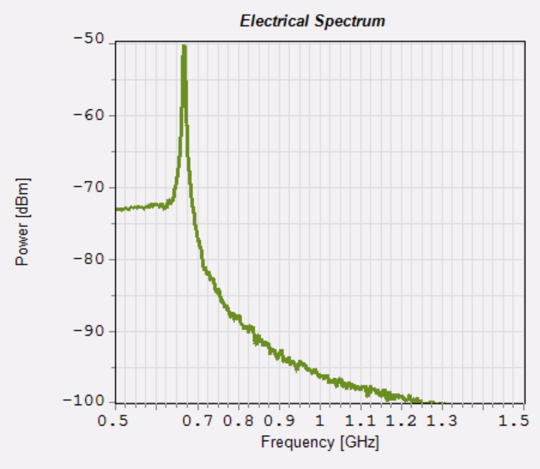


Frequency-Modulated Continuous Wave LiDAR System





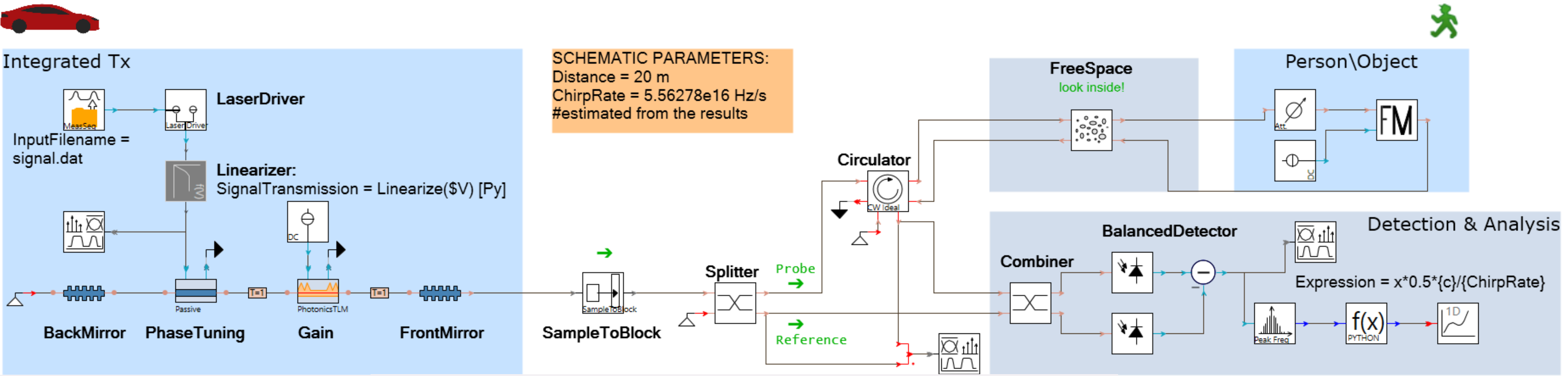


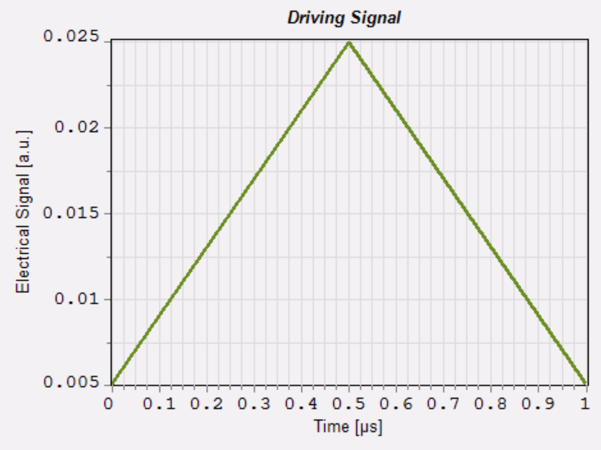


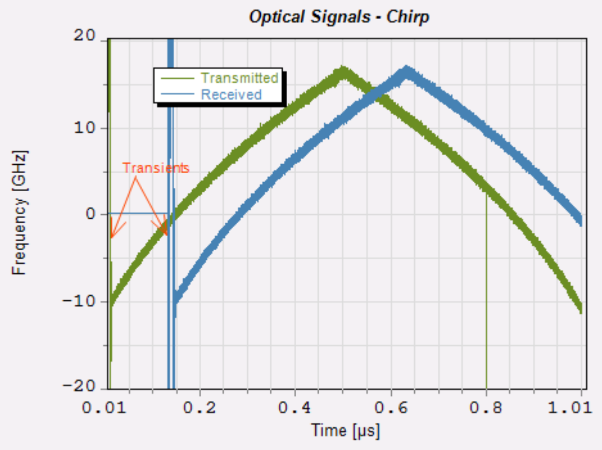
Idealized FMCW System simulation demonstrates ranging and detection operation of the system

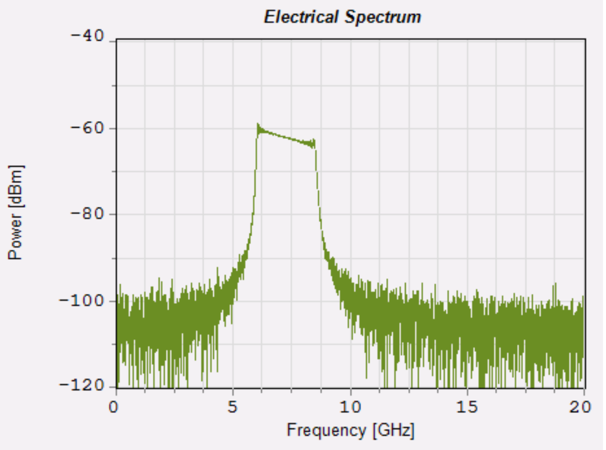
Sampled-Grating Distributed Bragg Reflector Laser for Frequency-Modulated Continuous Wave LiDAR System

This demo shows a sampled-grating distributed Bragg reflector (SG-DBR) laser used for frequency-modulated continuous wave (FMCW) LiDAR systems. It illustrates one of the challenges in developing a functional FMCW LiDAR - the residual nonlinearity of the laser, and demonstrates how digital predistortion can help mitigate this effect. To learn more about FMCW LiDAR, please check the application example [1].





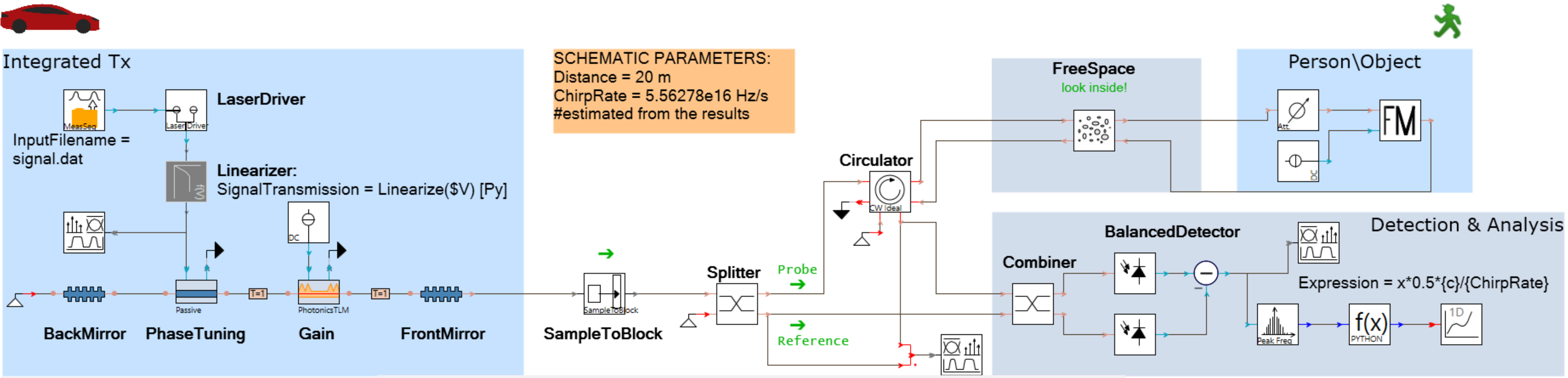


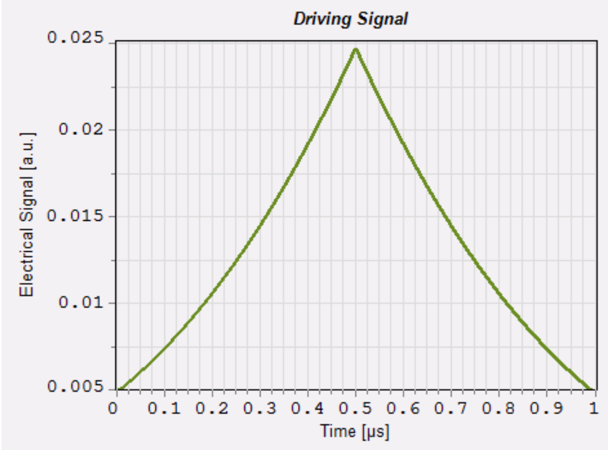


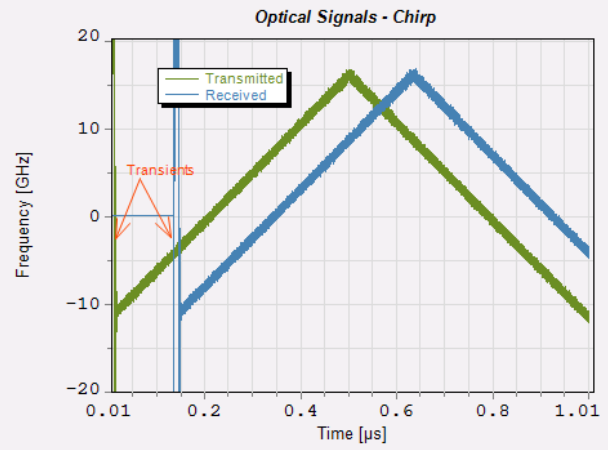
Adding PIC components to the simulation introduces non-linearities and noise impacting ranging performance

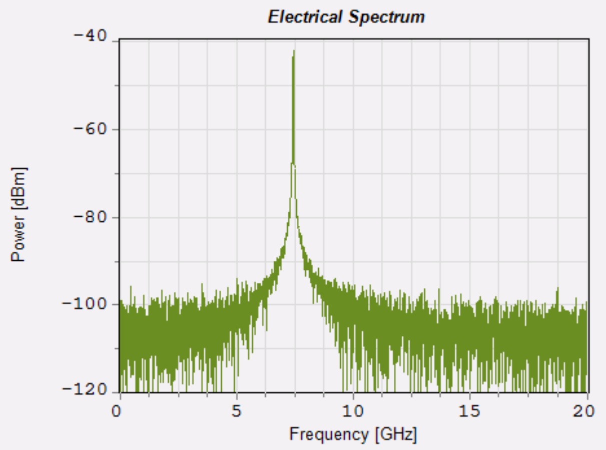
Sampled-Grating Distributed Bragg Reflector Laser for Frequency-Modulated Continuous Wave LiDAR System

This demo shows a sampled-grating distributed Bragg reflector (SG-DBR) laser used for frequency-modulated continuous wave (FMCW) LiDAR systems. It illustrates one of the challenges in developing a functional FMCW LiDAR - the residual nonlinearity of the laser, and demonstrates how digital predistortion can help mitigate this effect. To learn more about FMCW LiDAR, please check the application example [1].









System-level mitigation strategies can be explored to compensate for PIC-based impairments

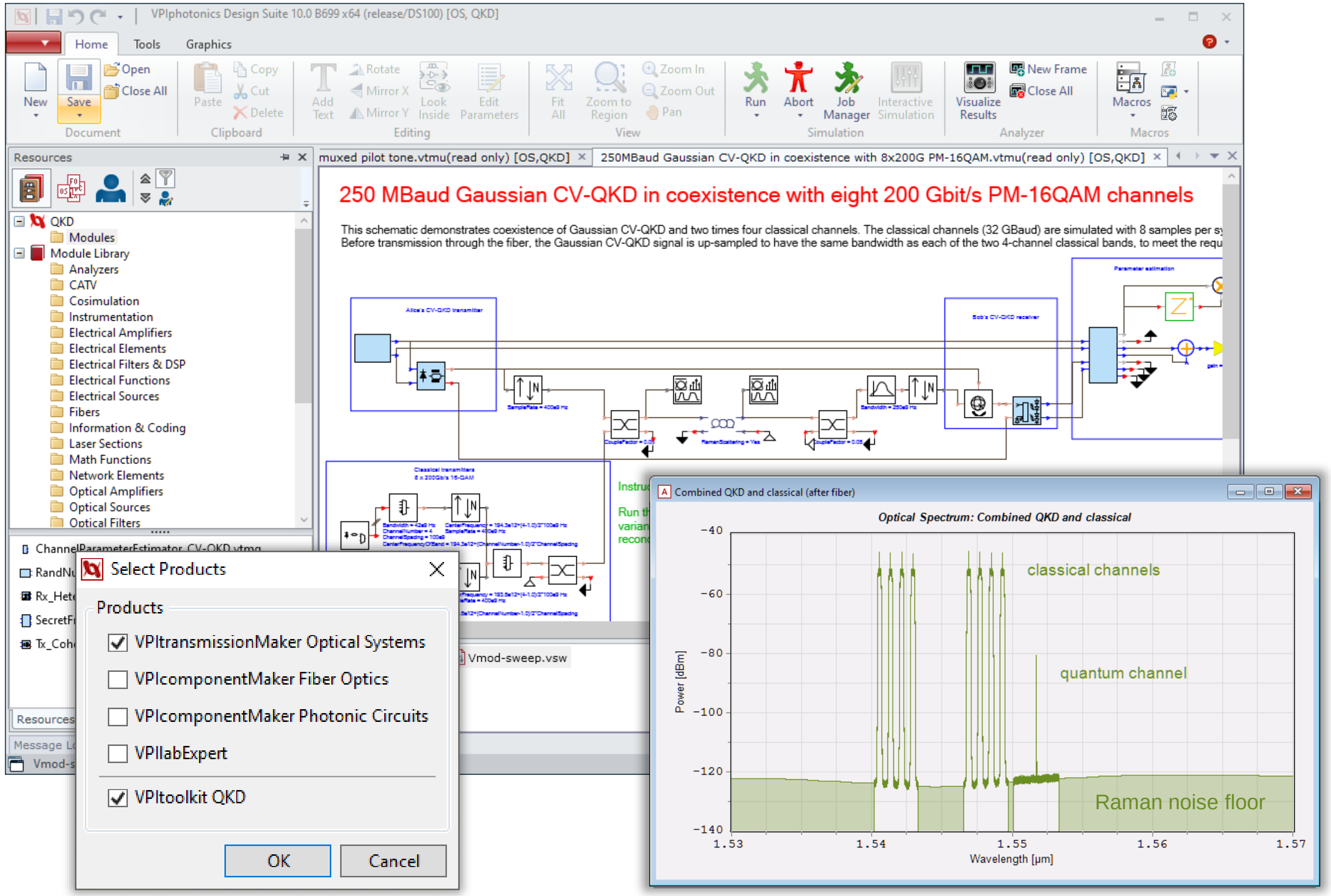
Designing a PIC Transmitter for QKD Systems

Simulation Tool for QKD Applications

VPItransmissionMaker Optical Systems
classical system simulation environment

together with

VPItoolkit QKD
for system-level CV/DV-QKD simulations



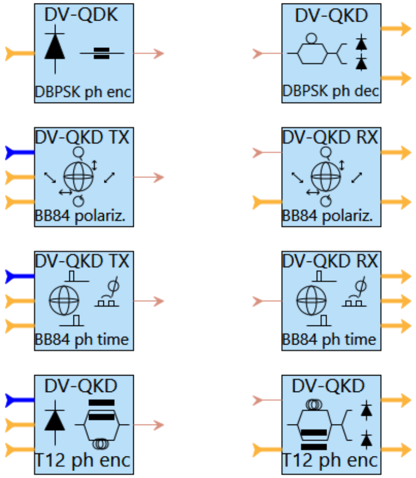
provides models for QKD transmitter/receiver, parameter and secret key rate estimation, and application examples.

- ✓ System design:
  various implementation options for QKD systems and sub-systems
- ✓ Study of co-existence scenarios:
  Raman scattering, cross-talk from classical channels, etc.
- ✓ Account for component imperfections:
  thermal and quantization noise, RIN, phase noise, biased beam splitting ratios, dark count rates, after pulsing, etc.
- ✓ Optimization of system parameters:
  modulation amplitude, photons per pulse, filter bandwidth, BB84 basis probability, symbol rate, etc.
- ✓ Estimation of performance criteria:
  max possible secret key rate, transmission distance, etc.

Example: Critical Building Blocks for DV-QKD

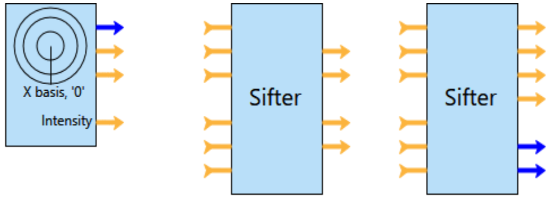
DV-QKD Rx & Tx

- Diff. phase shift (DPS)
- BB84-like with decoy
  - Polarization encoding
  - Phase/time encoding
  - T12
- COW

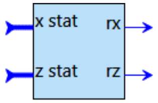


DV-QKD symbol selection & post processing

- Random number generator for (T12-like) BB84 protocols
- Sifters

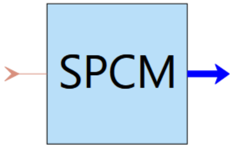


- Secret fraction estimator for T12 DV-QKD



DV-QKD detector: SPAD

Input: Optical signal
Output: Time stamps

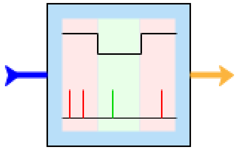


SPAD model includes:

- Dead time
- Gaussian timing jitter
- Exponential timing jitter
- After-pulsing
- Dark counts
- Gating

Analysing time stamps

Input: Time stamps
Output: “click” / ”no click’ for each symbol time bin

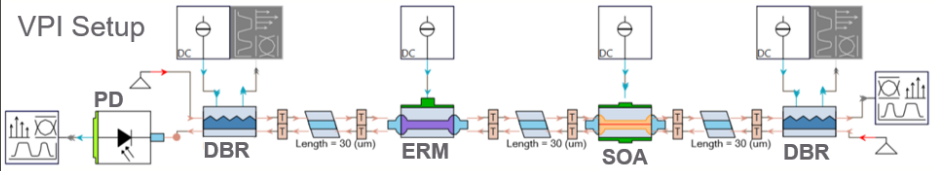


Acceptance window can be reduced for better dark count suppression.

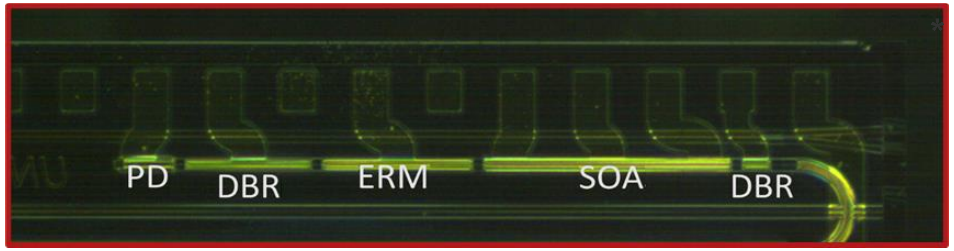
Weak-coherent Source for QKD Systems

Differential Phase Shift Transmitter Structure

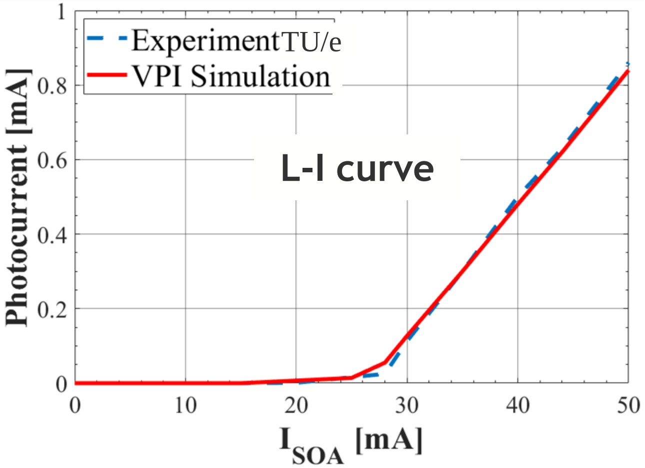
Coh State Source → Phase Modulator → Pulse Carver → Optical Attenuator → Transmitter output



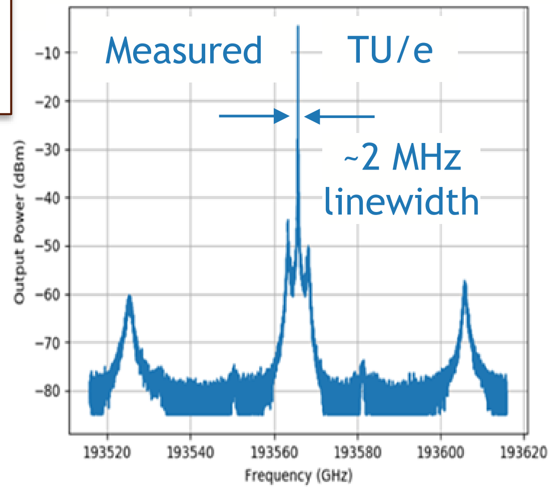
Coherent State Source (Tunable Laser Diode)

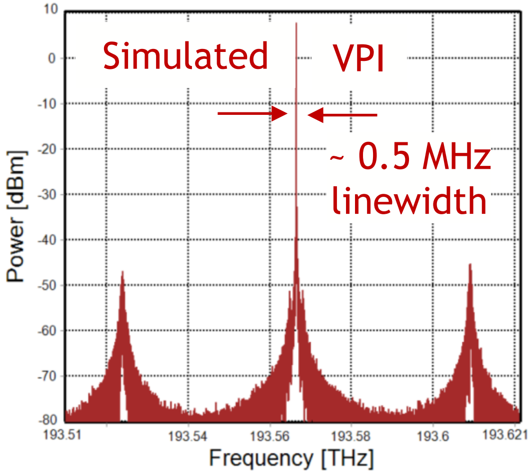


*developed by TU/e for SMART Photonics’ InP-based PIC foundry process



Optical Spectrum





General-purpose circuit simulator, SMART PDK library + custom PDK BBs

⇨ Virtual testbed for laser characterization and design optimization

Weak-coherent Source for QKD Systems

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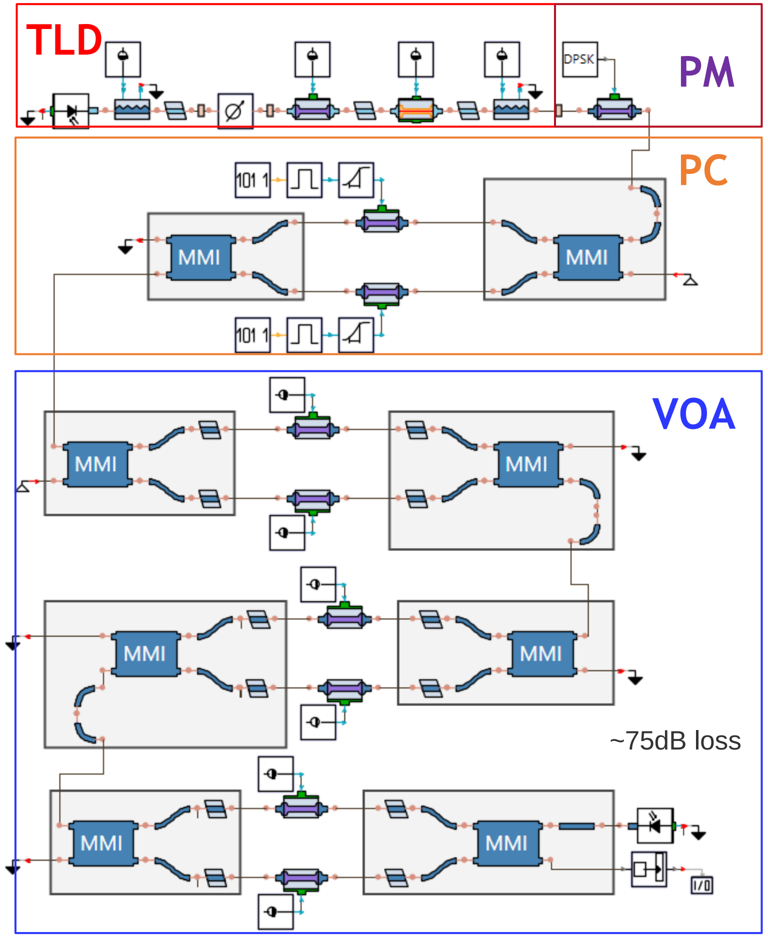
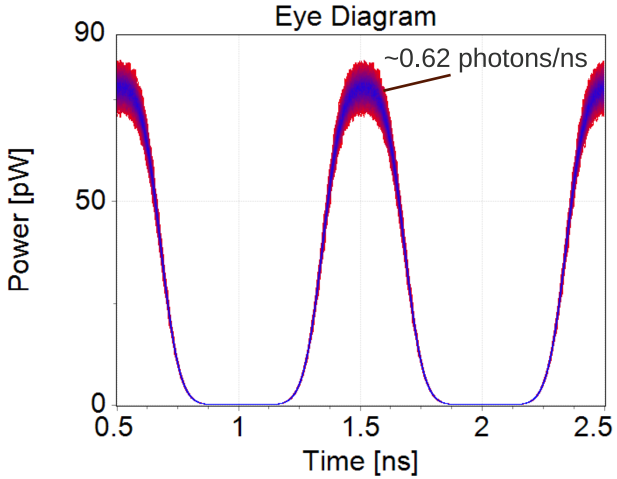


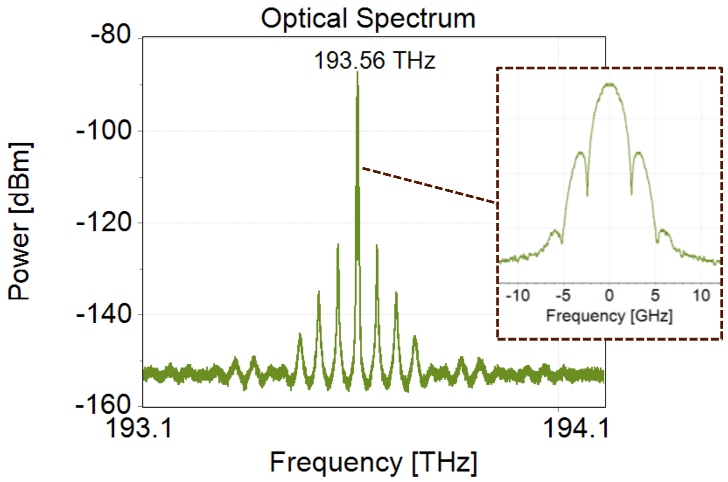
Differential Phase Shift Transmitter Structure

Coh State Source → Phase Modulator → Pulse Carver → Optical Attenuator → Transmitter output

TLD: Tunable Laser Diode
PM: Phase Modulator
PC: Pulse Carver
VOA: Variable Optical Attenuator

Realistic DPS Tx with laser RIN & phase noise





General-purpose circuit simulator, SMART PDK library + custom PDK BBs

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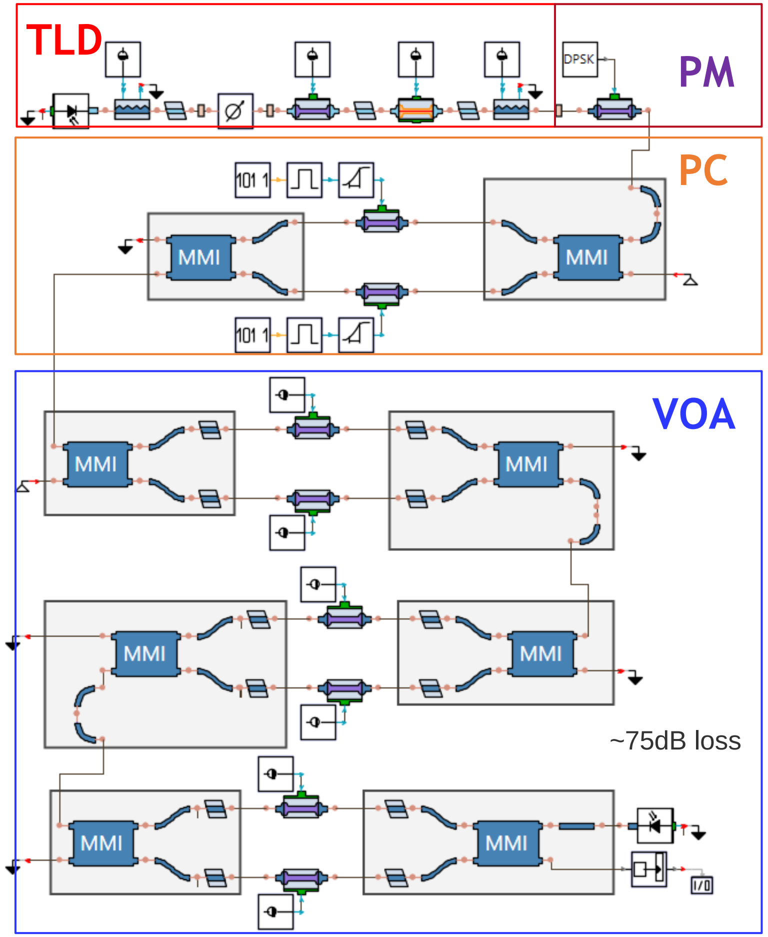

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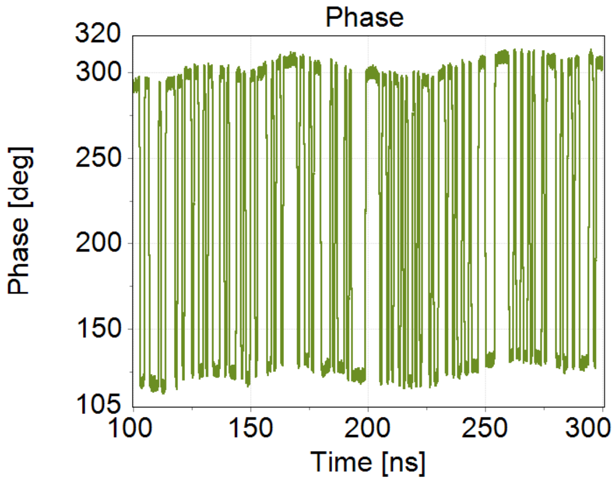

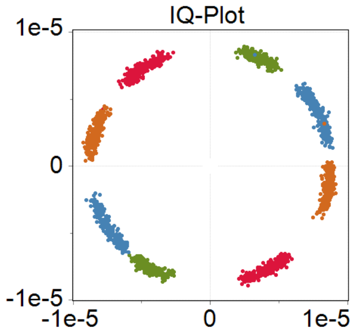

- Case A: PM with 180⁰ phase shift
- Case B: PM with 175⁰ phase shift

General-purpose circuit simulator, SMART PDK library + custom PDK BBs
⇨ Virtual testbed for PIC characterization and design optimization

Discrete Variable QKD System Scenario

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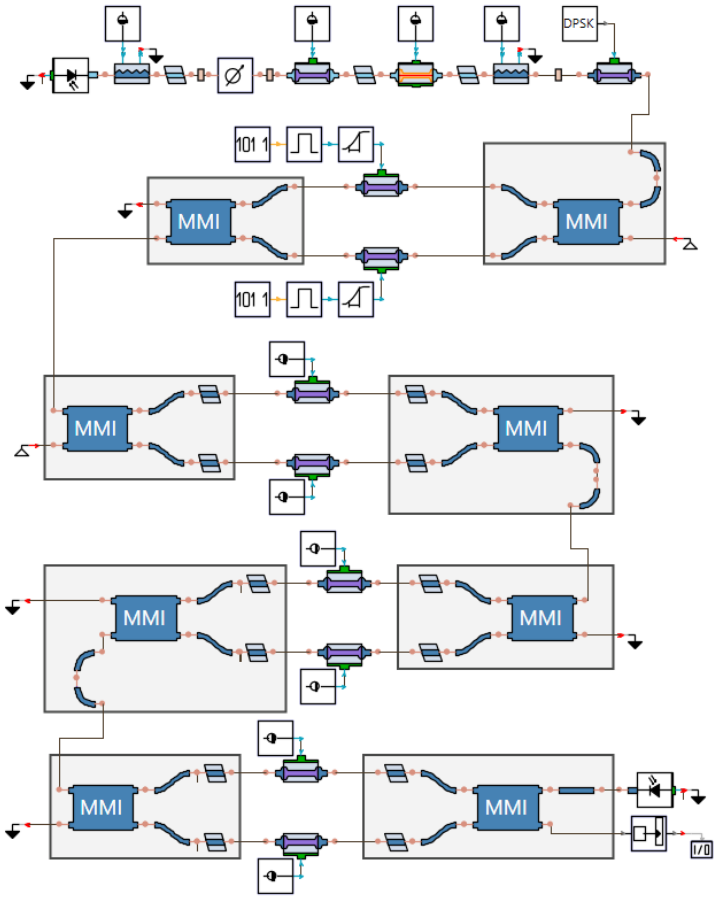
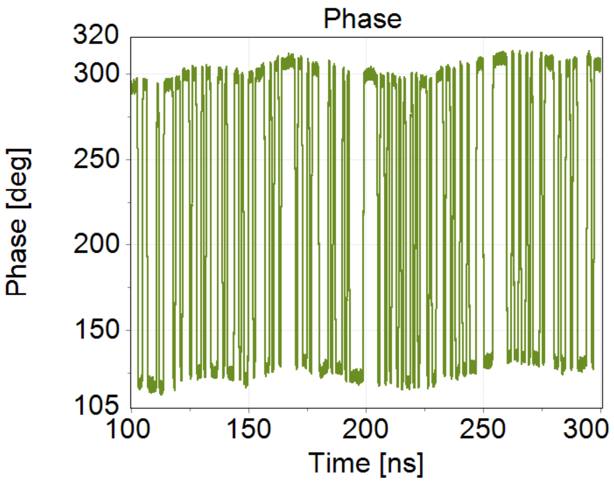
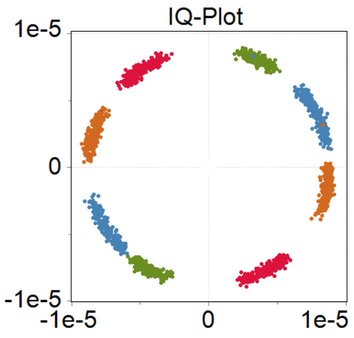
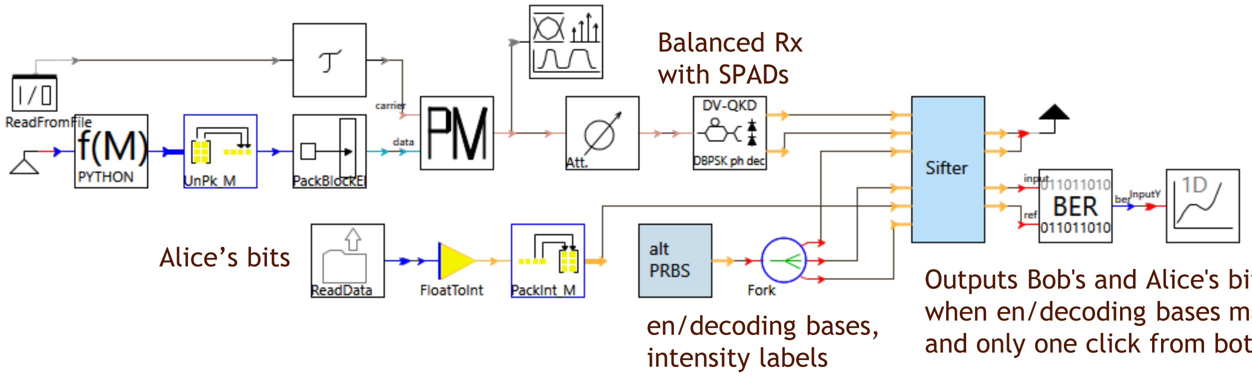
Output of DPS-Tx *circuit-level simulation* applied in DV-QKD ***system-level evaluation***



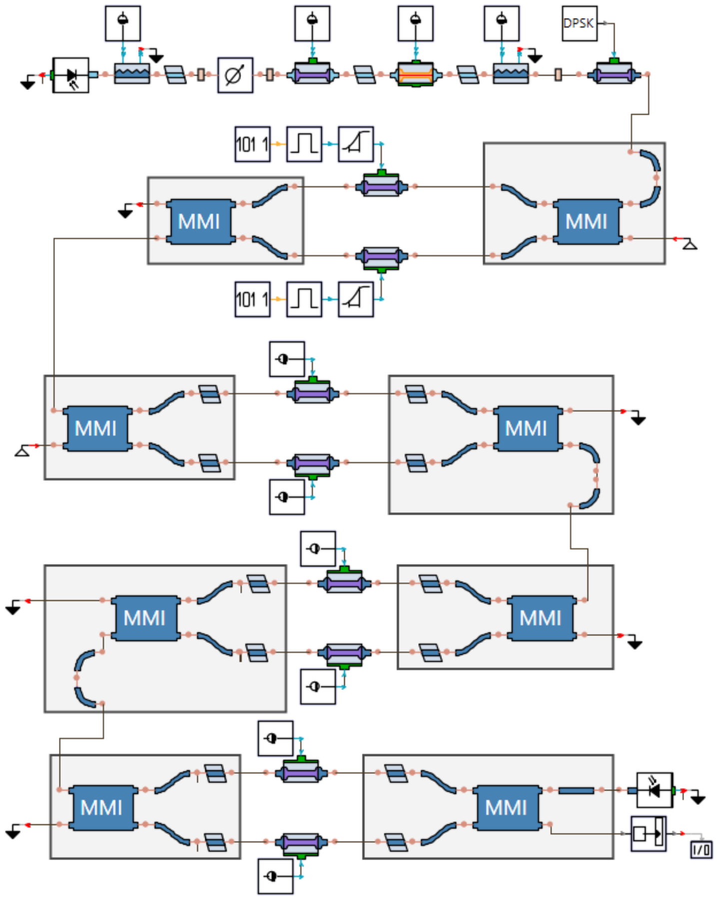






Discrete Variable QKD System Scenario

Output of DPS-Tx ***circuit-level simulation***
applied in DV-QKD ***system-level evaluation***



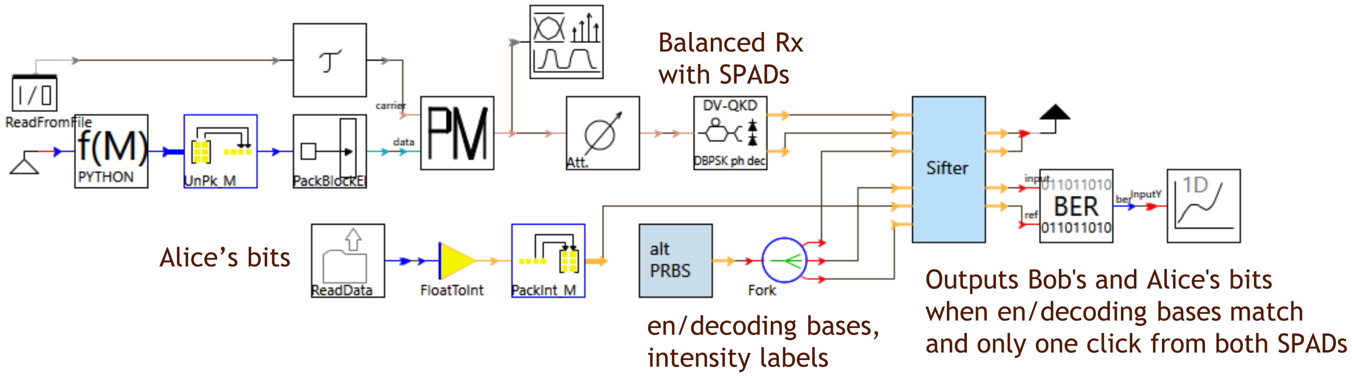
- Realistic DPS Tx
  - laser RIN & phase noise
  - tuned PM with 180⁰ or detuned PM with 175⁰
- Ideal DPS Tx
  - no laser RIN or phase noise
  - tuned PM with 180⁰

System-level simulation results

(for Link loss of 4dB)

DPS Tx modeling	QBER [%] (DCR=0 Hz)	QBER [%] (DCR=100 kHz)
Ideal	0	0.12
Tuned Realistic	0.09	0.20
Detuned Realistic	0.17	0.35

DCR – dark count rate



Designing PICs for Datacom/Telecom

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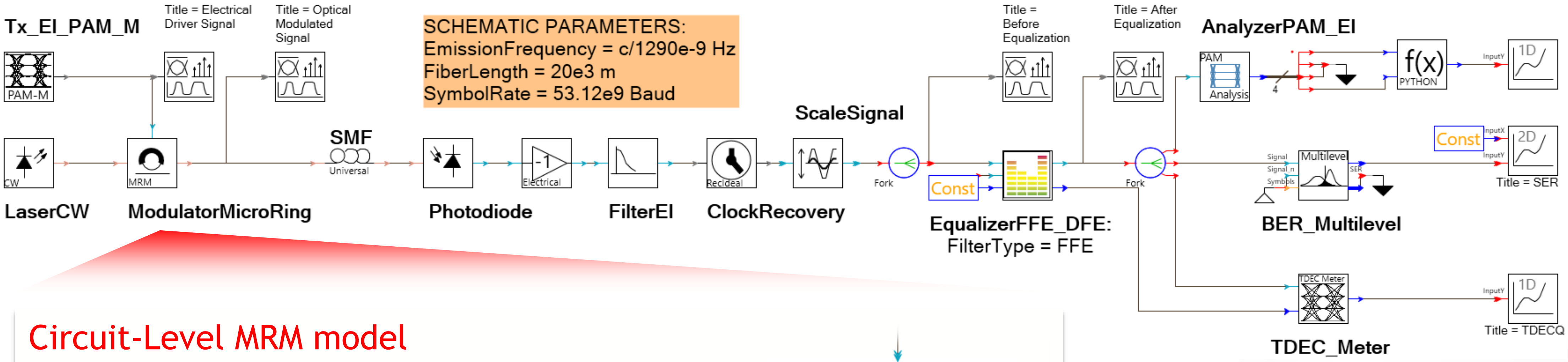
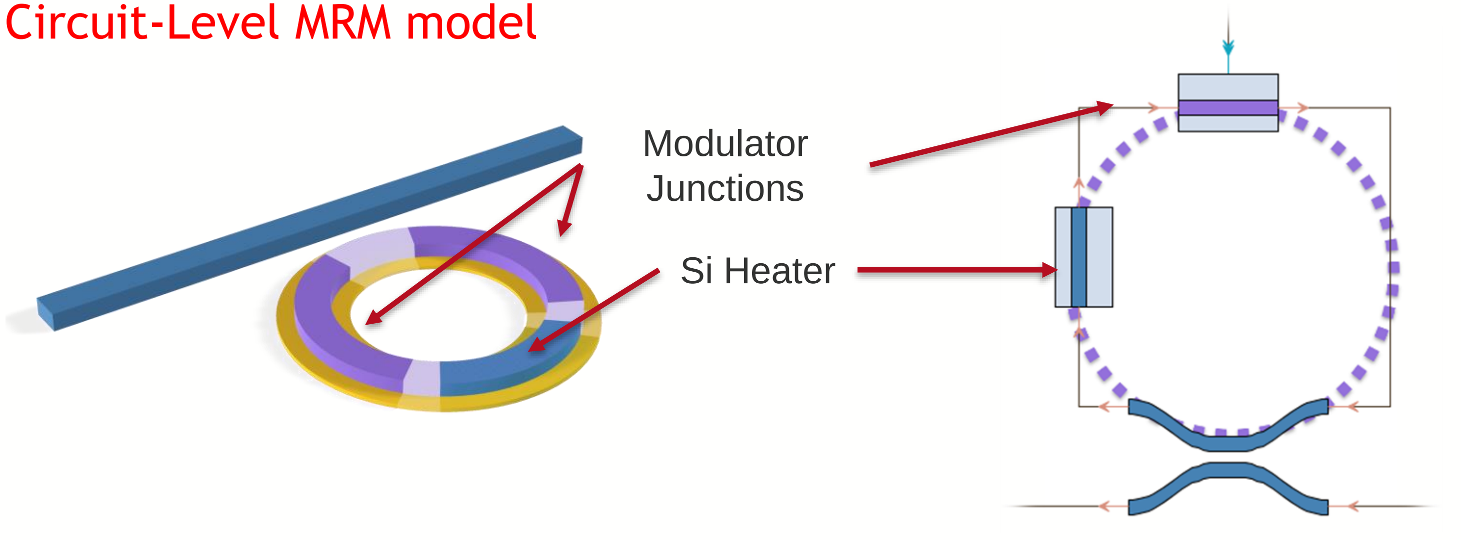
100 Gb/s PAM-4 Link with Silicon Photonics Microring Modulator



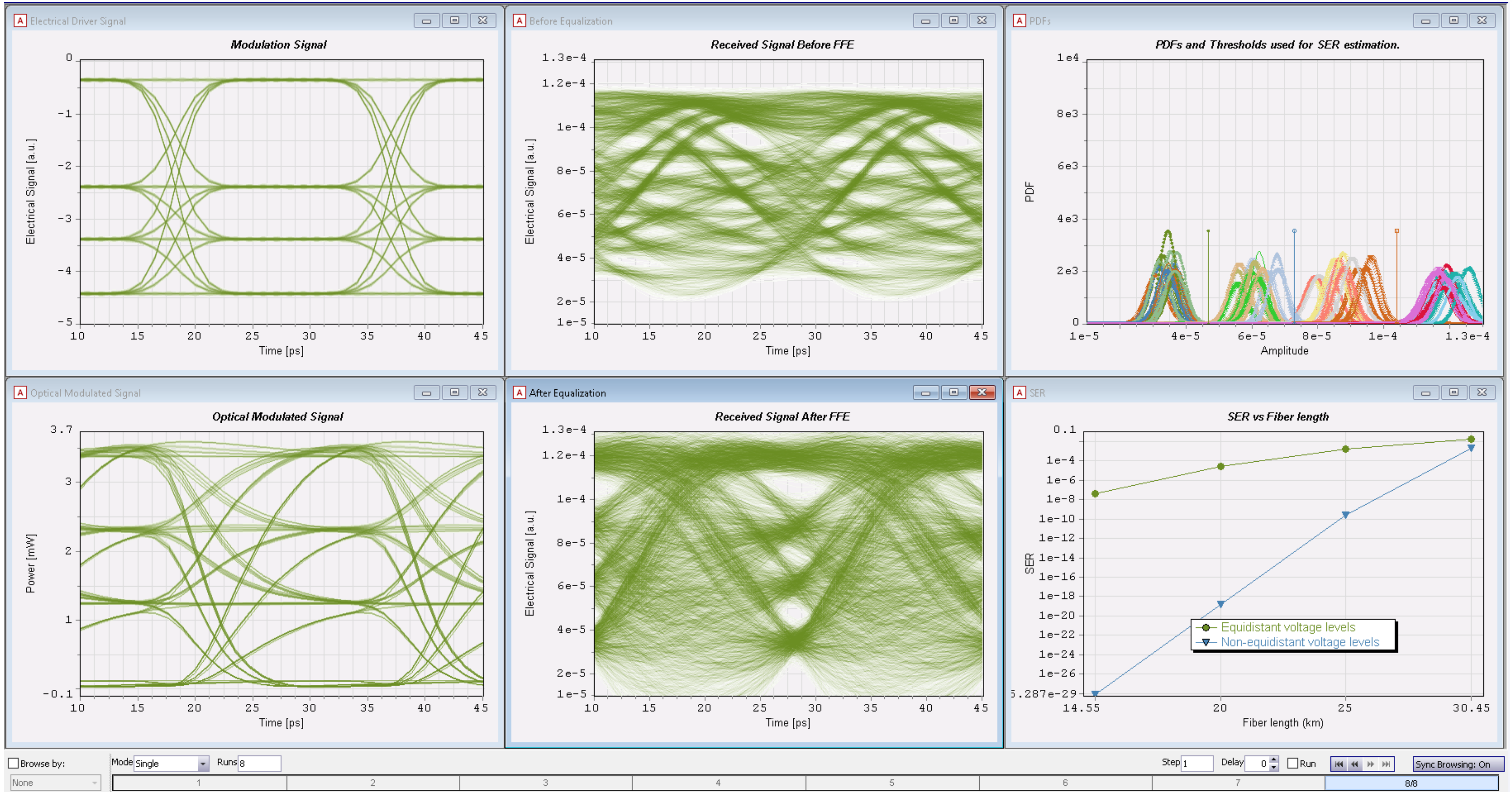
Circuit-Level MRM model



Hierarchical design workflow hides complexity and allows for physical modeling of PIC components

100G MRM-Based PAM4 Link

Simulation Results for Variable Fiber Lengths and Amplitude Levels



Equidist. 15 km	Equidist. 20 km	Equidist. 25 km	Equidist. 30 km	Non-Equidist. 15 km	Non-Equidist. 20 km	Non-Equidist. 25 km	Non-Equidist. 30 km

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