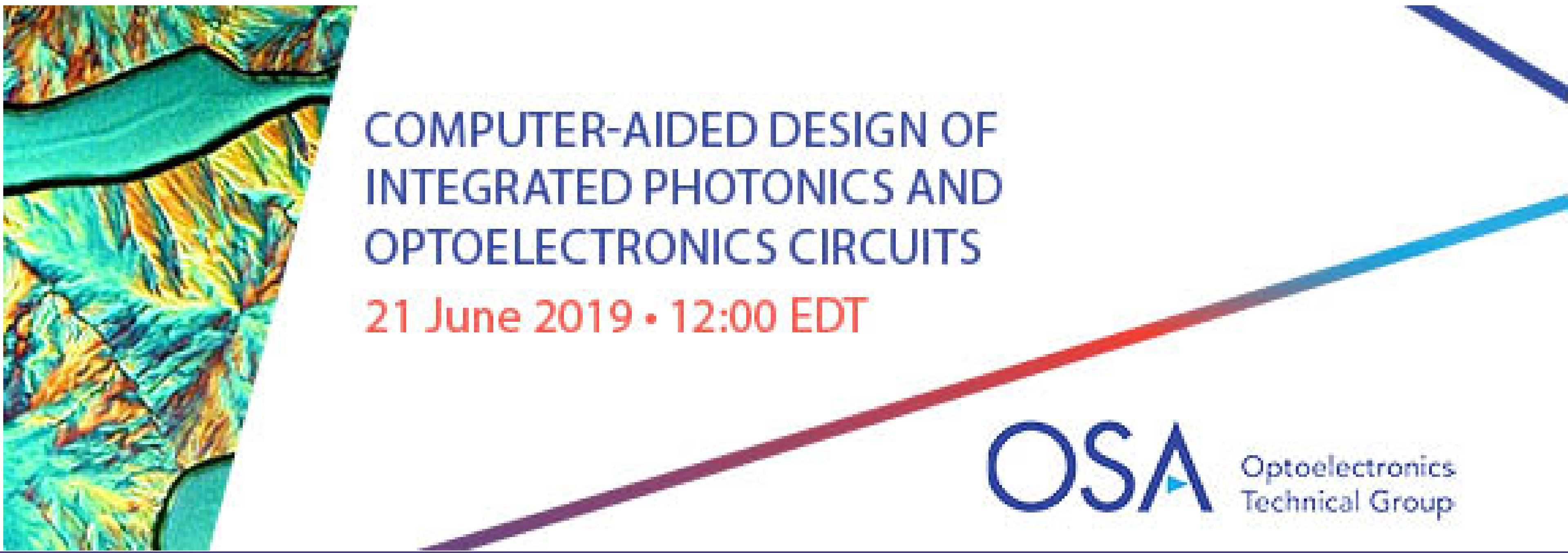
The OSA Optoelectronics (PO) Technical Group Welcomes You!



OSA Optoelectronics Technical Group

Technical Group Leadership 2019

Chair
Winnie Ye
Carleton University, Canada

Vice Chair
Daniele Melati
National Research Council Canada, Canada

Webinar Organizing Volunteer
Jens H. Schmid
National Research Council Canada, Canada

OSA Optoelectronics Technical Group

Technical Group at a Glance

- Focus
  - This group's interests are in the field of semiconductor lasers, amplifiers, LEDs and super luminescent diodes.
  - Over 4,500 members within OSA
- Mission
  - To benefit *YOU*
  - Webinars, e-Presence, publications, technical events, business events, outreach
  - Interested in presenting your research? Have ideas for TG events? Contact winnie.ye@carleton.ca
- Find us here
  - Website: www.osa.org/OptoelectronicsTG
  - LinkedIn: www.linkedin.com/groups/8297718/

OSA Optoelectronics Technical Group

Today's Webinar

Computer-Aided Design of Integrated Photonics and Optoelectronics Circuits

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Photonics Application Engineer
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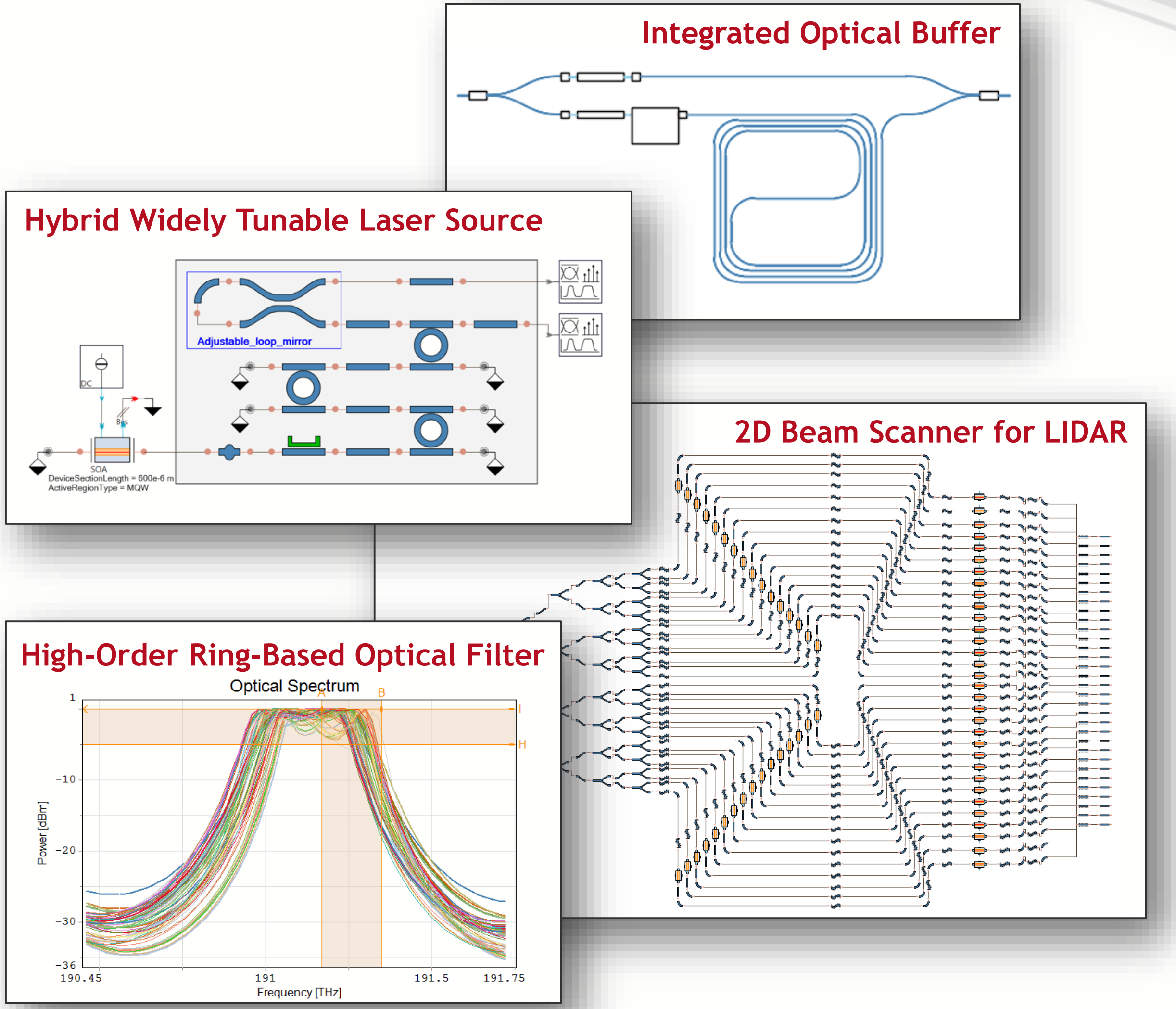
Computer-Aided Design of Integrated Photonics and Optoelectronics Circuits

Presenter: Eugene Sokolov

OSA Optoelectronics Technical Group
21 June 2019

Outline

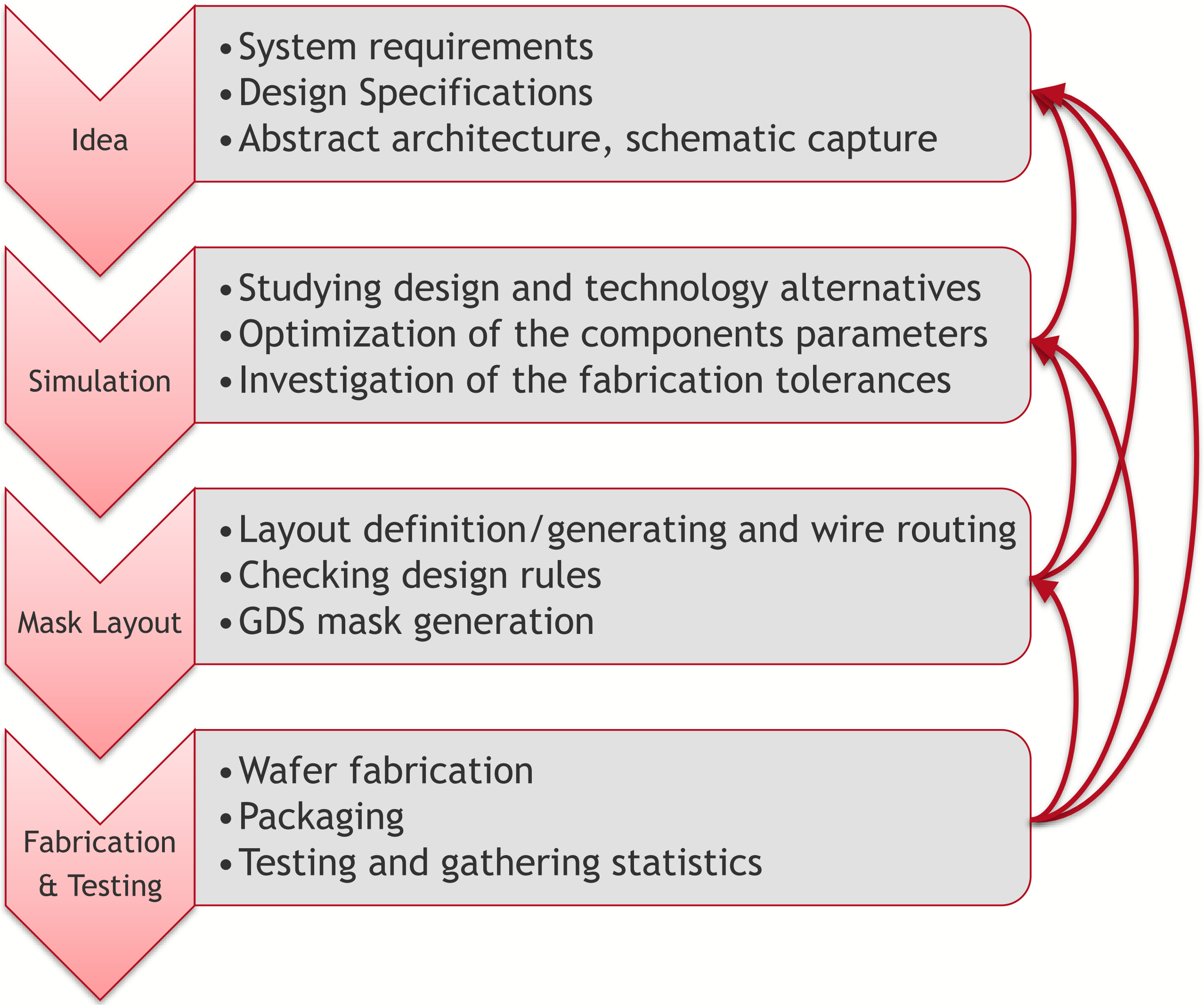
- Introduction
  - What is PIC Design
  - PIC Design Workflow 1997 vs. 2019
- The basics of circuit-level simulation
  - Passive and active components
  - Frequency-, Time- and Hybrid Domains
- Layout-aware design approach and PDKs
  - Introduction to Process Design Kits (PDKs)
  - Layout-aware simulations
- Design automation techniques
  - Simulating arrays and chains of modules
  - Scripting for schematic capture
  - Optimization and automated parameters settings
  - Design robustness & sensitivity analysis
- System-level performance verification



Introduction

- What is PIC Design
- PIC Design Workflow 1997 vs. 2019

Photonic Circuits Design Flow



meet the specifications

choose the technology

choose the components and set the parameters

With CAD SW Help!

agree the layout and the schematic

check that actual layout operates as expected

perform post-validation

compensate fabrication imperfections

PIC Design Workflow 1997 vs. 2019

The state of the art of CAD-tools in 1997*:

- Design architecture is mainly based on the designer's experience. It is first defined symbolically by text or by graphics.
- CAD tools mainly focus on the analysis of waveguide devices and utilizes mode solvers and BPM methods.
- Setting of the components parameters is iterative and is frequently gambling. Parameter scans and the use of optimization algorithms are not common.
- There are accuracy problems at various levels in the design process, which results in multiple trials and errors in fabrication loop.
- As CAD-methods move to 3D and/or vectorial problems, the calculation time increases.
- When active devices are involved, the optical field modelling needs to be combined with electrical and/or thermal modelling.

*R. Baets and D. Van Thourhout, "Computer aided design for integrated optical circuits: task flow and tools," *Conference Proceedings. LEOS '97. 10th Annual Meeting IEEE Lasers and Electro-Optics Society 1997 Annual Meeting*, San Francisco, CA, USA, 1997, pp. 397-398 vol.1.

The state of the art of CAD-tools in 1997*

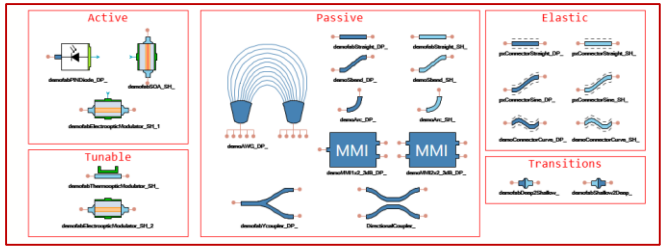
Solution Proposed *:

- Creation of expert system tools which store information about basic elements, validated by numerical simulations or experiments. Emphasis not on field calculation but rather on combining and manipulating previously obtained information.
- Employing an S-matrix approach for more complex circuits
- Interfaces to mode solvers, BPMs, etc. with easy transformation of the results into the tables or formulas for future use
- Standardization of the data formats for exchange between the tools
- Automated mask layout generation

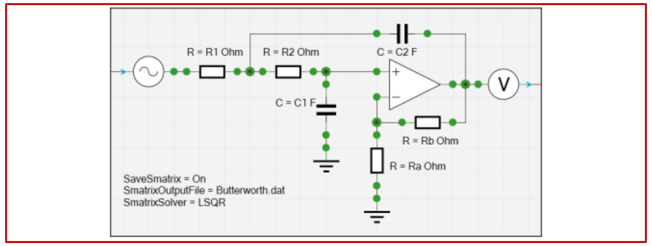
*R. Baets and D. Van Thourhout, "Computer aided design for integrated optical circuits: task flow and tools," *Conference Proceedings. LEOS '97. 10th Annual Meeting IEEE Lasers and Electro-Optics Society 1997 Annual Meeting*, San Francisco, CA, USA, 1997, pp. 397-398 vol.1.

Photonic Circuit Design & Analysis
Schematic-driven & Layout-aware

PDK Building Block Libraries

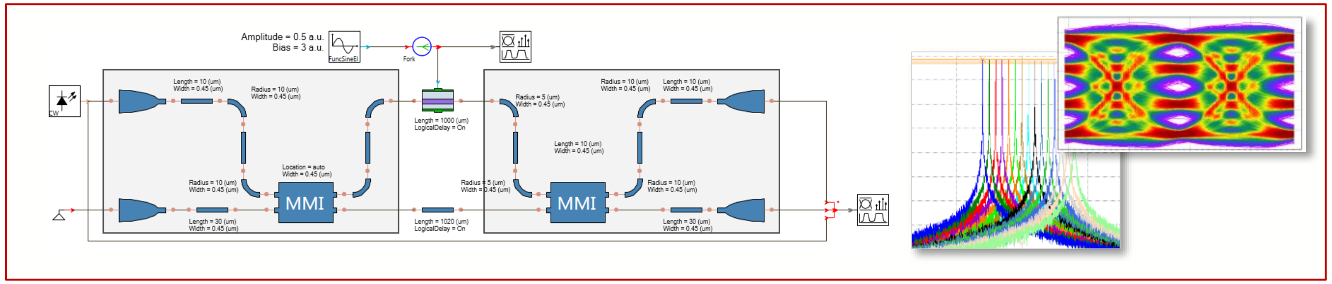


Electronic Design Automation



Foundry-specific models

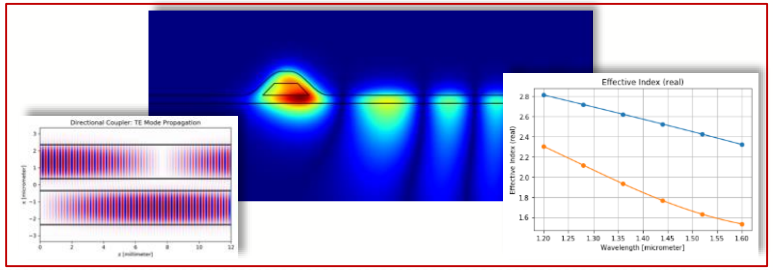
Photonic Circuit Simulation & System Validation



Optoelectronics and electrical simulation

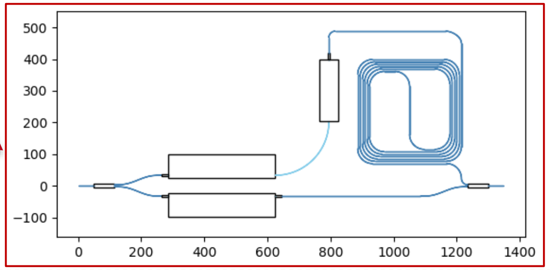
Extract device parameters

Device Modeling



Layout design & DRCs, verification of layout

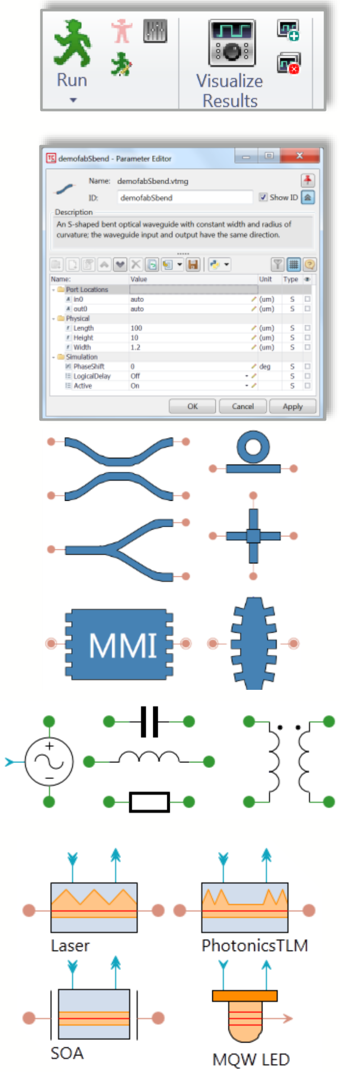
Layout Design



The basics of circuit-level simulation

- Passive and active components
- Frequency-, time- and hybrid time-and-frequency domains
- Design Example: Widely Tunable Laser Source

Photonic Circuit Design & Analysis
Automated Design Environment



Graphical User Interface

- Circuit Topology Graphical Editor
- Parameter Editor
- Topology Scripting

Remote Servers, Resources Management

Compound Hierarchical Models

- Behavioral & Analytical
- Measured
- Custom Programmed

Advanced Parameter Scripting

Device-level Simulators

Layout & Mask Design

Process Design Kits

Simulation Domains

- Opto-electronics — Hybrid-Domain
- Dynamic Tunable Photonics — Time-Domain
- Passive Photonics
- Linear Electronics — Frequency-Domain

TLM, IIR/FIR, S-Matrix assembly, Multi-core CPU parallelization

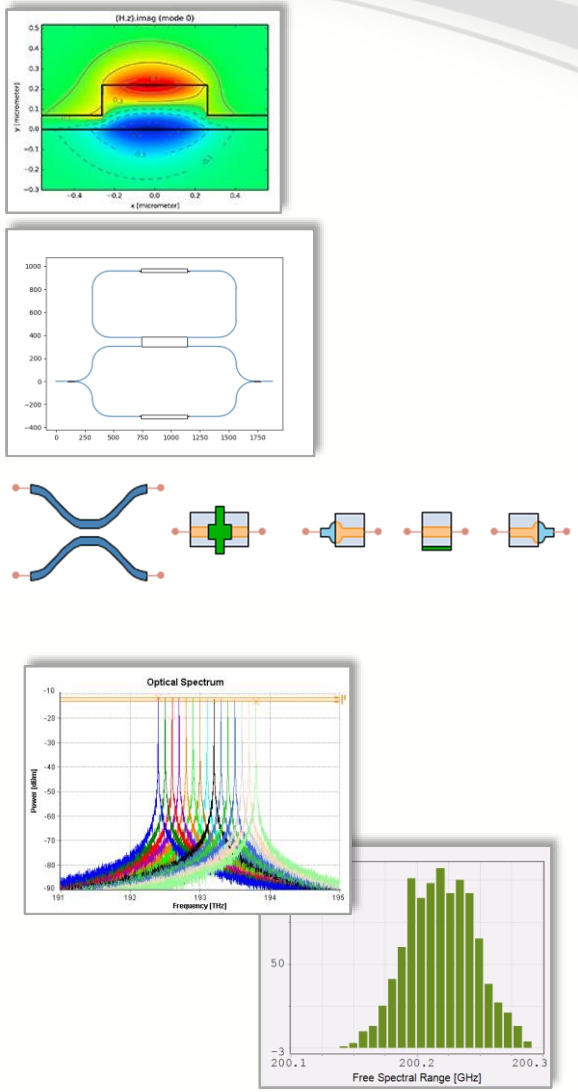
Nonlinear Electronics

EDA Cosimulation

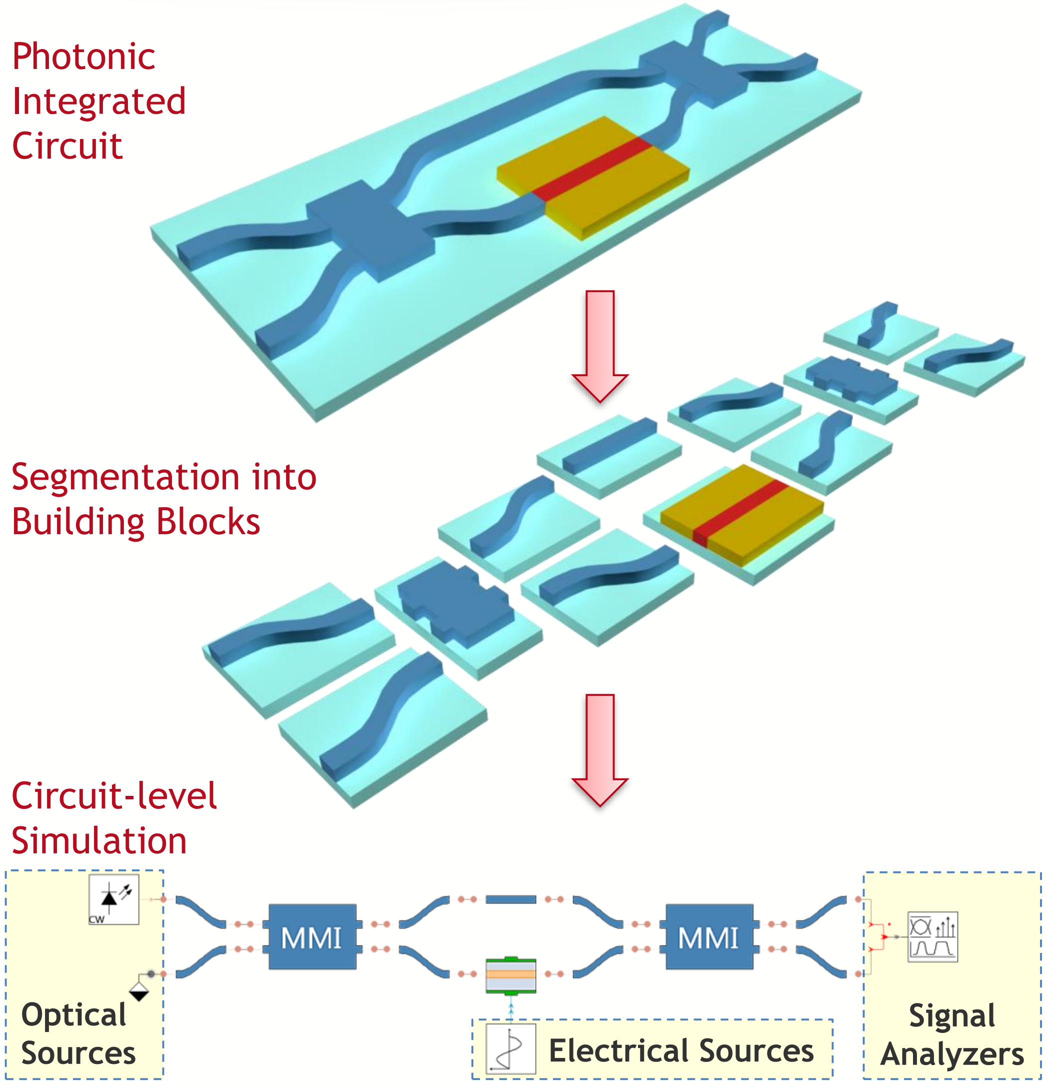
Simulation Control, Optimization & Analysis

- Advanced Visualization
- Instrumentation & Analysis Tools
- Parameter Sweeps
- Simulation Scripting
- Simulation Engine Driver

Sensitivity and Yield Analysis



System-Level Abstraction of Photonic Circuits



- Circuit-level simulation of a PIC is separated from device-level modeling of its BBs
- Individual BBs can be modeled by different methods, providing easy balance between accuracy and speed requirements
- This approach enables efficient design of large-scale PICs, made of many hundreds BBs
- Scalable circuit-level simulation techniques are required

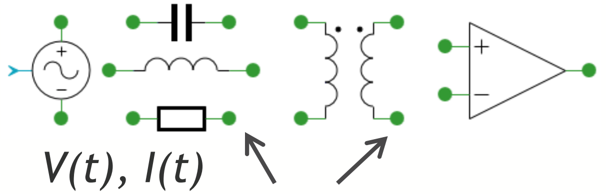
Models & Simulation Parameters

Name	Value	Unit	Type
Physical			
ModelType	EffectiveIndex		S
Length	1000e-6	m	S
ModeCouplingCoefficient	0.0	1/m	S
EffectiveIndexDefinition	Parameters		S
ReferenceFrequency	193.1e12	Hz	S
EffectiveIndex	2.6		S
GroupIndex	4.2		S
Dispersion	0.0	s/m^2	S

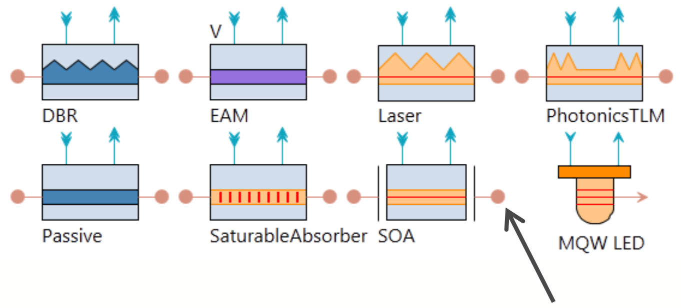
BB – Building Block

Diversity and Complexity of Elements in Photonic Integrated Circuits

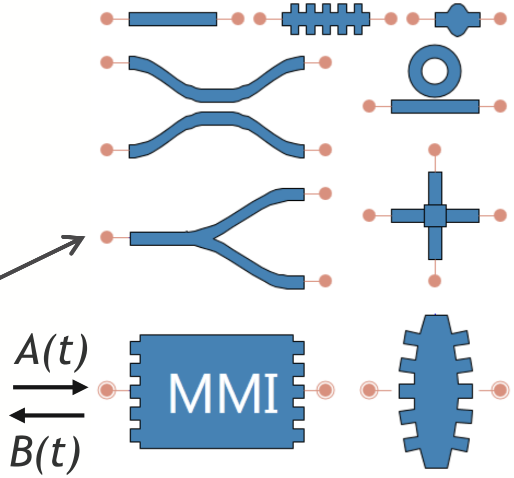
Electronic Elements



Optoelectronic Elements



Photonic Elements



- ⇨ *Large diversity* of basic elements
  many photonic/optoelectronic devices are spatially *distributed*!
- ⇨ Electrical and *optical signals*

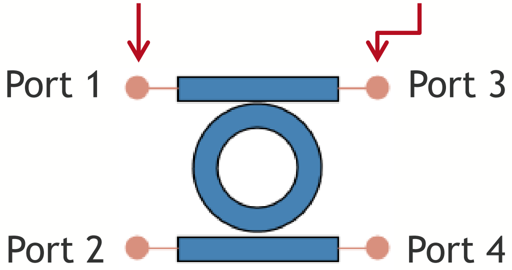
complex-valued amplitudes

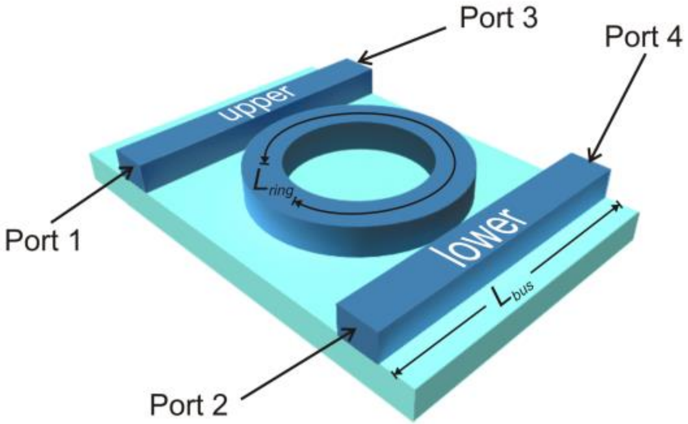
$$\vec{E}(\vec{r}_\perp, t) = \sum_{\nu,\mu} \{A_{\nu,\mu}(t)\vec{F}_\nu(\vec{r}_\perp, \omega_\mu)e^{j\omega_\mu t} + B_{\nu,\mu}(t)\vec{F}_\nu^*(\vec{r}_\perp, \omega_\mu)e^{j\omega_\mu t}\} + c.c.$$

- ⇨ *Complex compact models*
  governed by partial differential and integro-differential equations for time-domain simulations

Physics behind Optical Signals

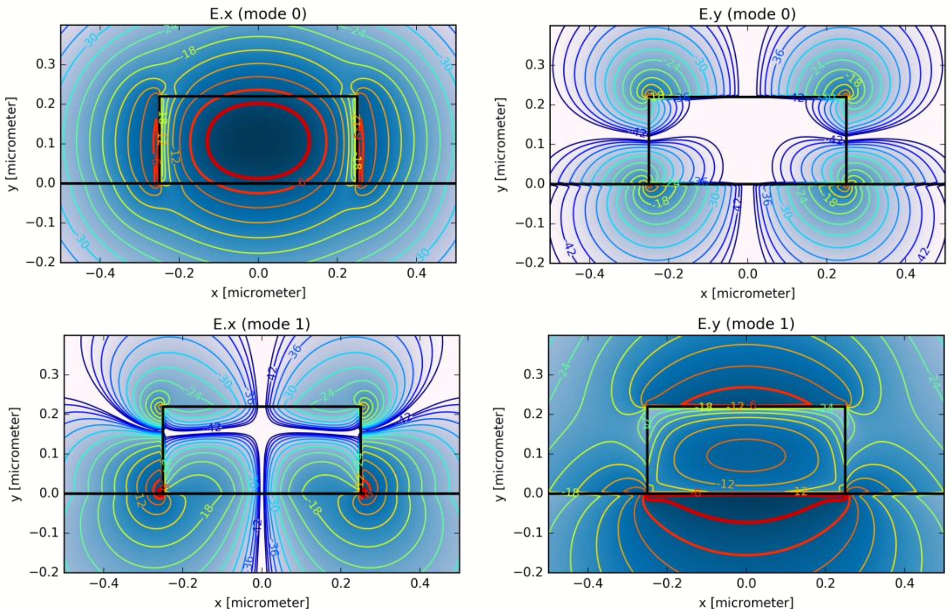
Ports for communication with other modules.
Bidirectional ports may both generate and accept signals





Each optical port is a piece of optical waveguide or fiber:

Waveguide modes:



TE-like mode (X-polarization)

TM-like mode (Y-polarization)

Modulation frequency << Optical carrier frequency ⇒complex-envelope baseband transformation

complex-valued amplitudes

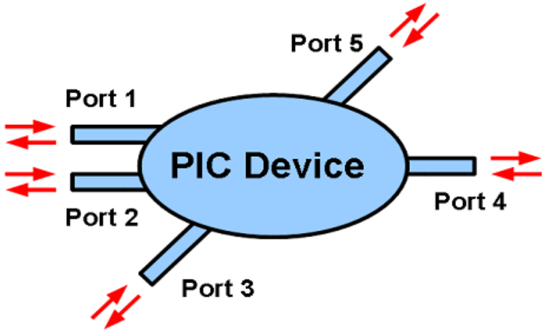
$$\vec{E}(\vec{r}_\perp,t)=\sum_{\nu,\mu}\{A_{\nu,\mu}(t)\vec{F}_\nu(\vec{r}_\perp,\omega_\mu)e^{j\omega_\mu t}+B_{\nu,\mu}(t)\vec{F}^*_\nu(\vec{r}_\perp,\omega_\mu)e^{j\omega_\mu t}\}+c.c.$$

Forward waves — *Backward waves*

$\omega_\mu = 2\pi f_\mu$ *are carrier frequencies (~200 THz)*

S-Matrix Description of Passive PIC Elements

- Passive photonic circuits and devices are considered as black boxes with N ports and are completely characterized by a scattering matrix (S-Matrix)
- S-Matrix of a device with N bidirectional two-mode ports consists of 2Nx2N matrix of complex-valued frequency-dependent transfer functions
- Each transfer function relates complex amplitude of optical signal carried by guided TE/TM modes traveling towards the device port n with the one traveling away from the device port m



$$\begin{pmatrix} \vec{E}_1^{out}(f) \\ \vec{E}_2^{out}(f) \\ \cdots \\ \vec{E}_M^{out}(f) \end{pmatrix} = \hat{S} \begin{pmatrix} \vec{E}_1^{in}(f) \\ \vec{E}_2^{in}(f) \\ \cdots \\ \vec{E}_N^{in}(f) \end{pmatrix}$$

S-Matrix: describes transfer functions between all ports

$$\hat{S}(f) = \begin{pmatrix} \hat{T}_{11}(f) & \cdots & \hat{T}_{1N}(f) \\ \vdots & \hat{T}_{mn}(f) & \vdots \\ \hat{T}_{N1}(f) & \cdots & \hat{T}_{NN}(f) \end{pmatrix}$$

Jones Matrix: connects waves at input port *n* and output port *m*

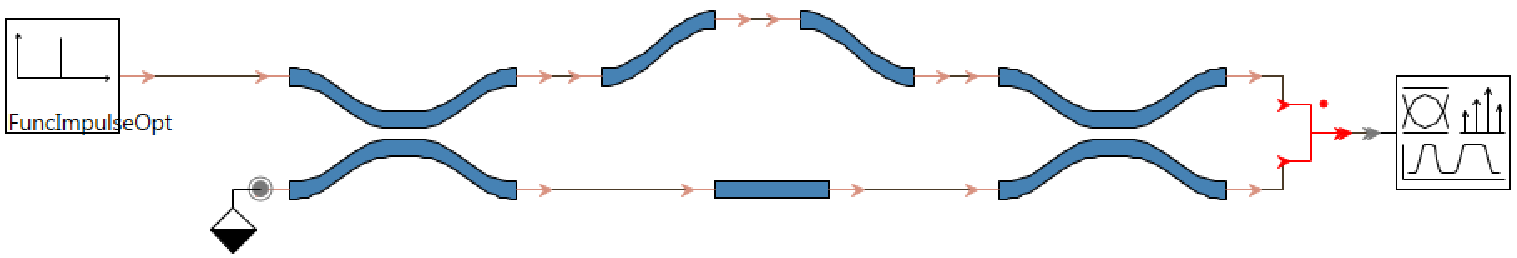
$$\hat{T}_{mn}(f) = \begin{pmatrix} T_{mn}^{TE,TE} & T_{mn}^{TE,TM} \\ T_{mn}^{TM,TE} & T_{mn}^{TM,TM} \end{pmatrix}$$

Transfer Function: connects waves at given input and output ports & modes

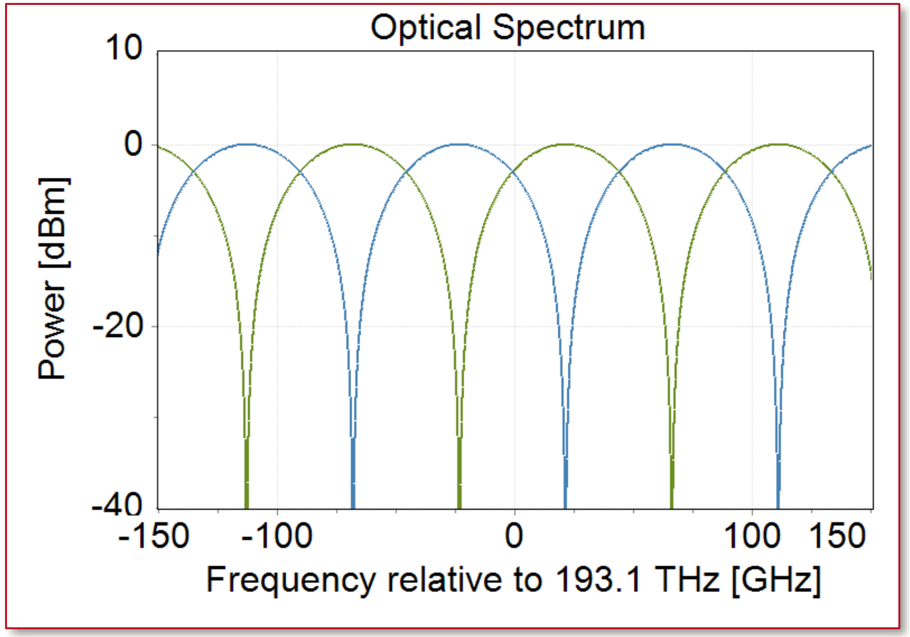
$$T_{mn}^{TE,TM}$$

S-Matrix Description of Passive PIC Elements

Simple Example: Unbalanced MZI

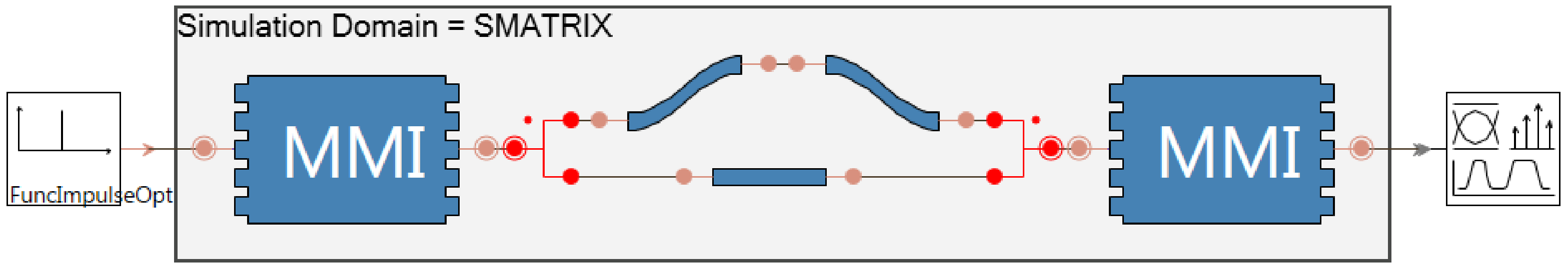


- For unidirectional signal flow signal is filtered in steps by individual S-matrices
- Simulation is performed in the frequency domain



S-Matrix Description of Passive PIC Elements

Simple Example: Unbalanced MZI with Reflections



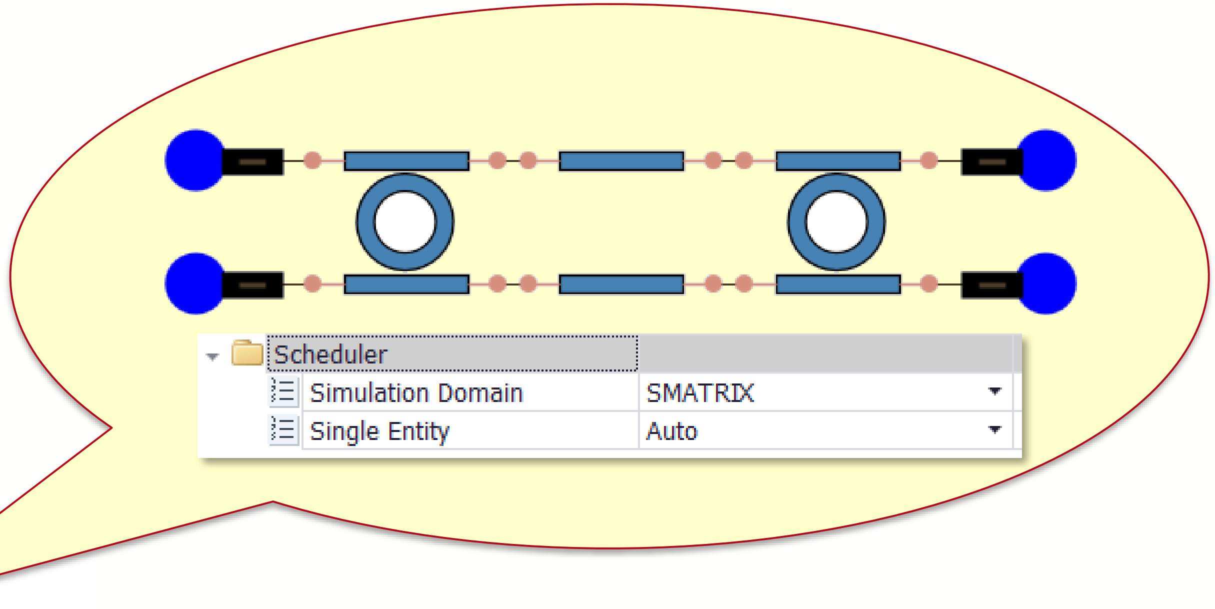
- Multi-mode interference (MMI) devices could partially reflect optical signals
- Bidirectional signal flow is required
- Compound models approach

Compound Models of Passive PIC Elements

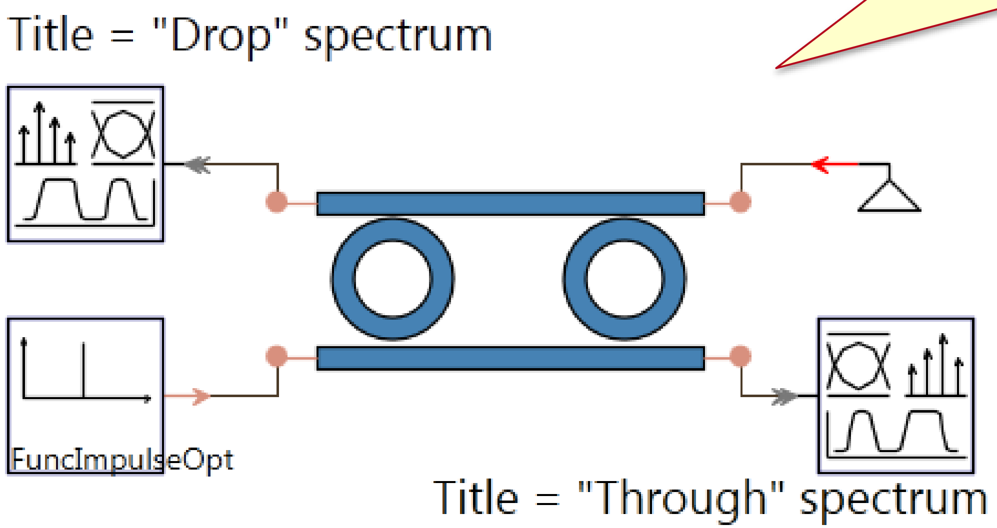
first step to scalability!

SMATRIX-domain galaxy

Assemble S-Matrices of individual sub-elements and operate with the S-Matrix of the whole circuit as a single-entity passive PIC device



Hierarchical design



S-matrix assembly

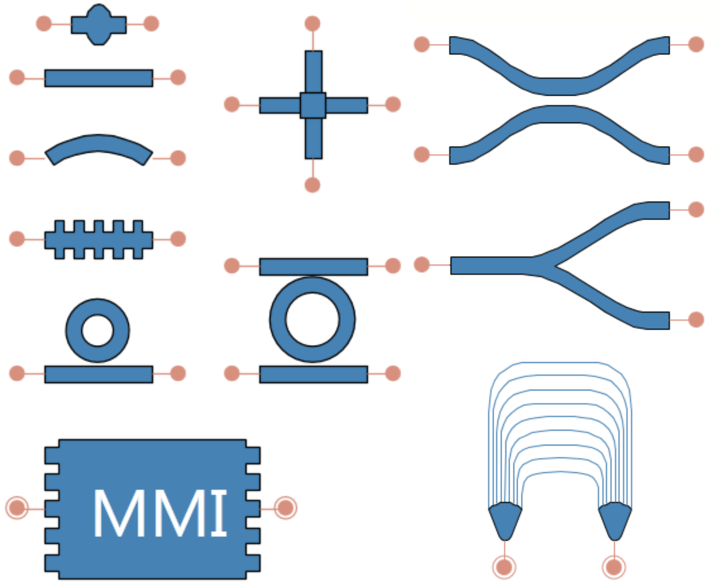
$$\hat{S}_{PIC}(f) = \underbrace{\hat{S}_1(f) \otimes \hat{S}_2(f) \otimes \ldots \otimes \hat{S}_{N-1}(f) \otimes \hat{S}_N(f)}$$

- S-matrix of the whole device is calculated before signal processing involving solving a sparse system of linear equations
- Fastest S-matrix assembly algorithm is automatically chosen

Modeling of Passive PIC Elements

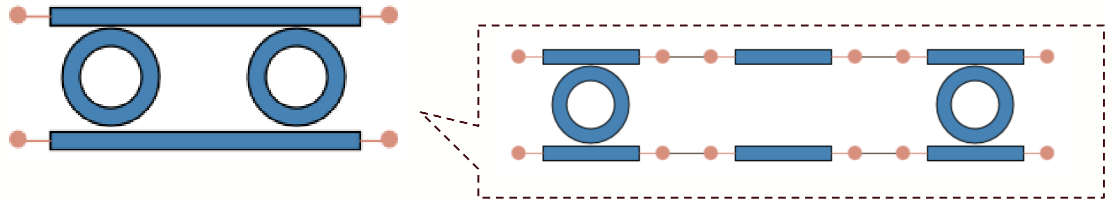
Built-in PIC Elements

S-Matrix from analytical models



Compound PIC Elements

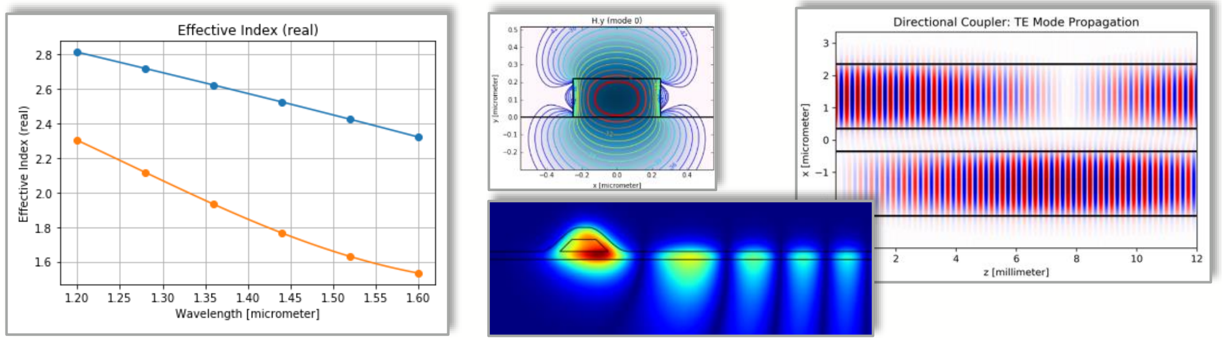
S-Matrix calculated on-the-fly using assembly techniques



Co-simulated PIC Elements

S-Matrix defined in Python or C/C++

Calculated by Device Level Simulators



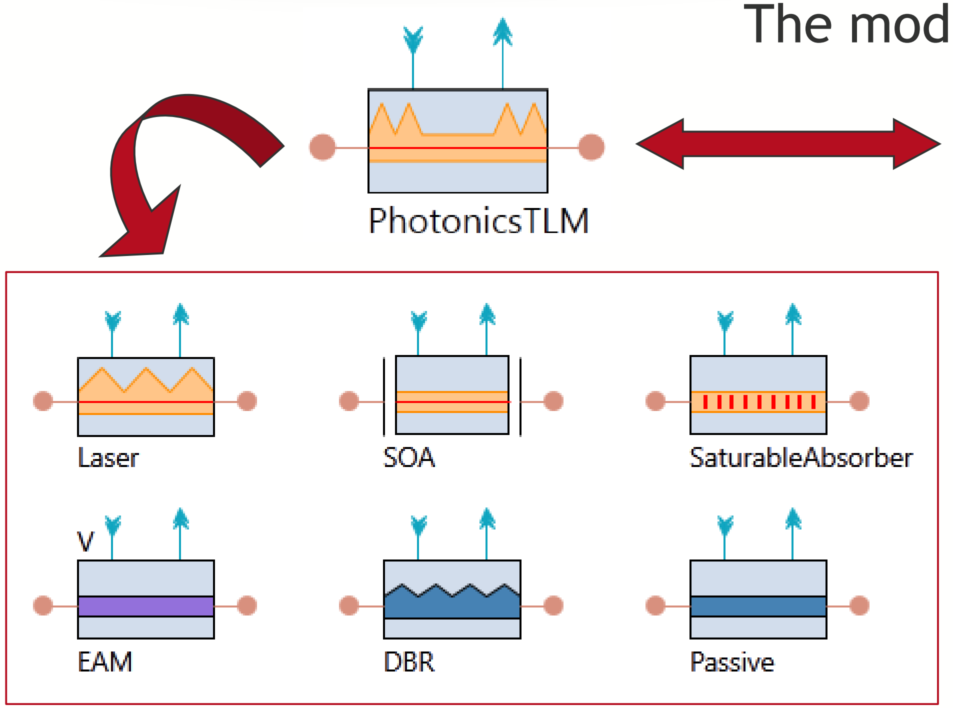
Measured Models

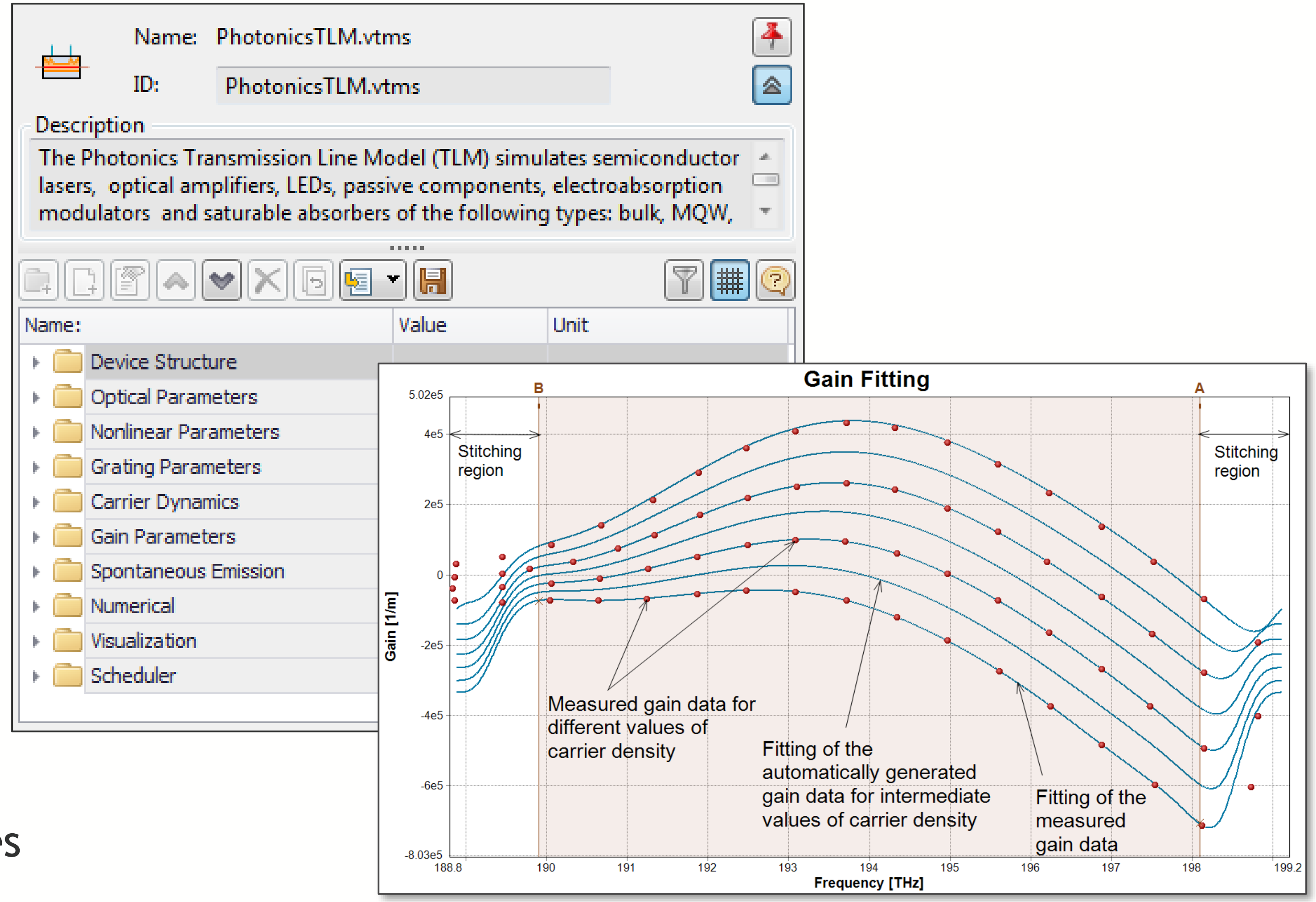
S-Matrix for an element of any type loaded from file

All these elements can be easily combined to form larger structures!

Modeling of Active Components

The models usually are much more complicated and diverse

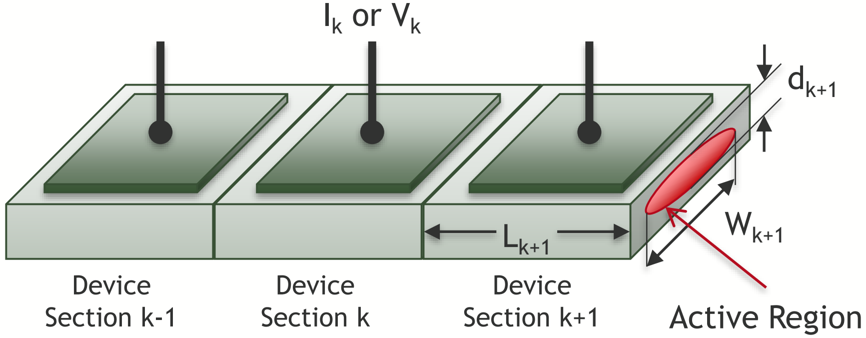




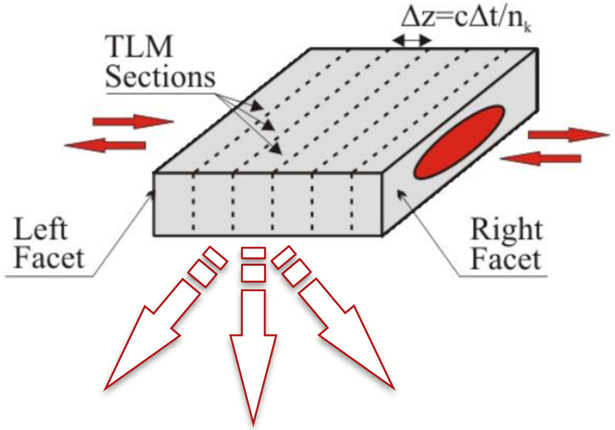
- Bidirectional ports
- Nonlinear effects (Kerr, TPA)
- Index & gain Bragg gratings
- Single-section and multi-section devices

Transmission-Line Model Basics

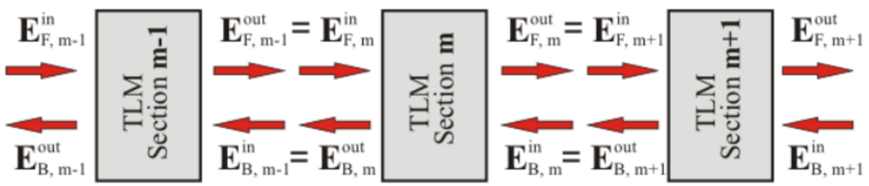
Semiconductor Cavity



Device Section k



Photonics Transmission-Line Model



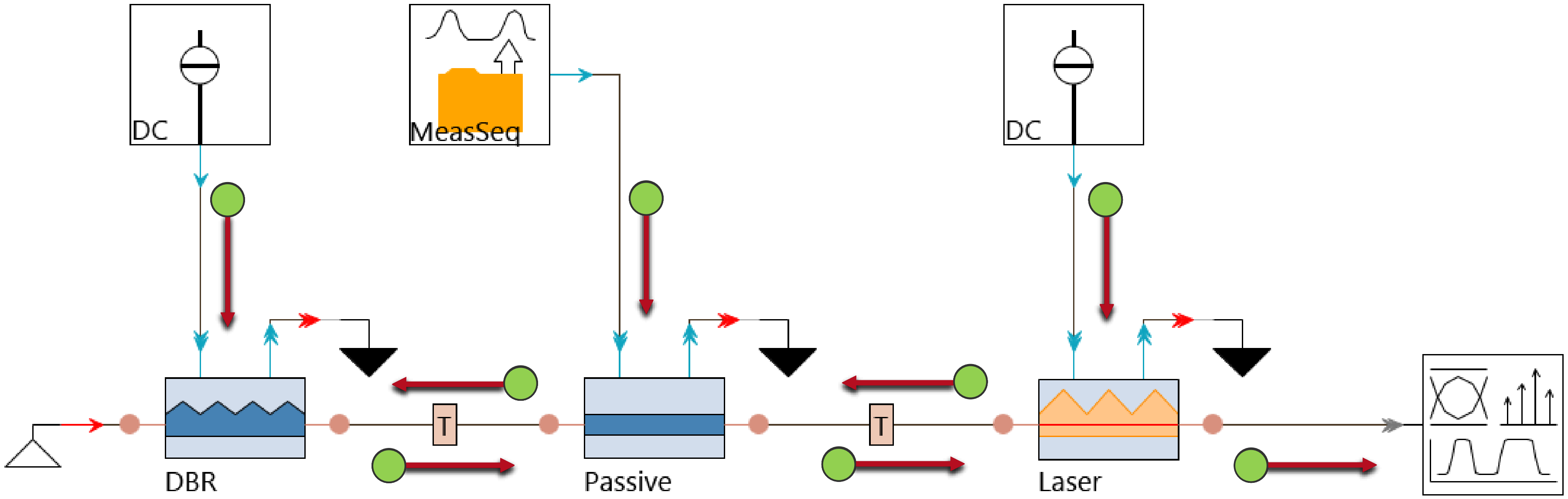
Full dynamics of multisection semiconductor devices:

- nonlinearities during analog modulation
- roles of Kerr and two-photon absorption (TPA) nonlinearities
- evolution of lasing spectra during modulation
- CW spectral performance and purity (multimode, single-mode, noise floors
- spectra during modulation (mode-hopping, dynamic chirp, instabilities)
- optical noise (intensity noise spectra, Amplified Spontaneous Emission)
- RF noise (Relative Intensity Noise, excess noise due to feedback, chaos)
- effects of external optical components, optical injection
- modulation responses (IM,FM, magnitude and phase)
- carriers and photons dynamics in lasers and amplifiers

TLM for semiconductor lasers:

C. Arellano, S. Mingaleev, A. Novitsky, I. Koltchanov, and A. Richter, *Design of complex semiconductor integrated structures*, Proc. SPIE 7631 - Optoelectronic Materials and Devices IV, 76310K - 8 pages (2009).

Time-Domain Modeling of Active Elements

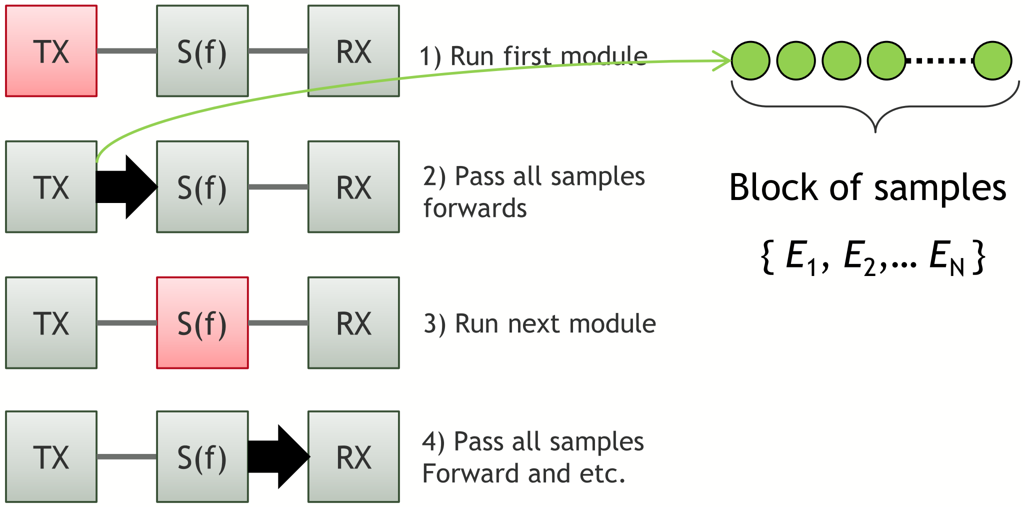


How should interconnected components exchange data?

For active/dynamically tunable devices
time-domain sample-by-sample
data exchange is required!

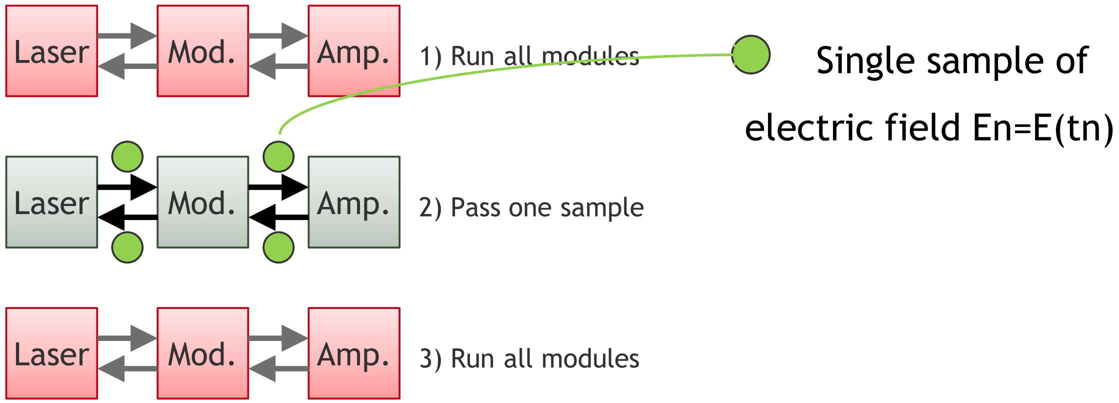
Frequency vs. Time Domain

Block Mode & Frequency Domain



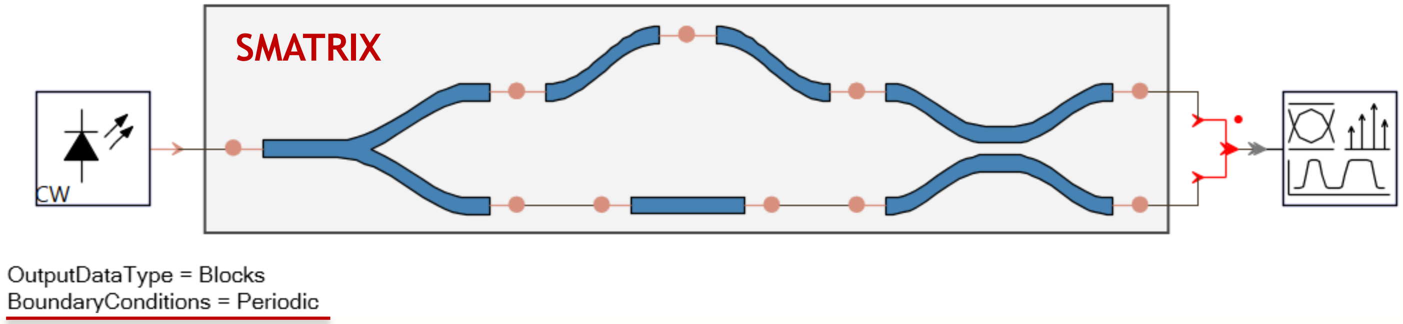
- Fast and efficient for the unidirectionally signal flow and passive, including large-scale, PICs.
- Elements could be described by S-matrices
- No nonlinear effects

Sample Mode & Time Domain

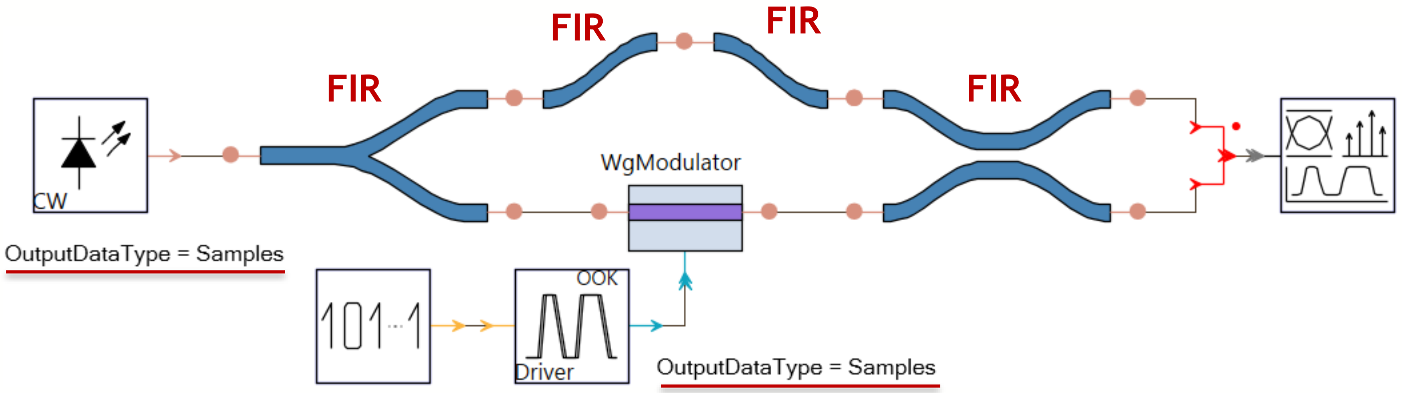


- Multi-section and external-cavity semiconductor lasers
- PICs with embedded active elements and/or dynamically-changing elements
- Time Consuming
- Inherently inaccurate

Circuits with Active Devices require Sample-Mode Simulations



Passive Circuits are best modeled in frequency domain



Active Circuits require switching to time-domain simulations, using Sample-mode signals.

Simple solution: model each passive component in time-domain.

- How good is such an approach?
- How specifically are the passive devices modeled in this case?

Inherent Inaccuracy of Time-Domain Simulations

Time-domain simulations for linear devices are most often based on either finite impulse response (FIR) digital filters:

$$A_{out}(t_i) = \sum_{m=0}^{N} a_m A_{in}(t_{i-m}) \qquad \text{where} \qquad t_i = i \cdot \Delta t$$

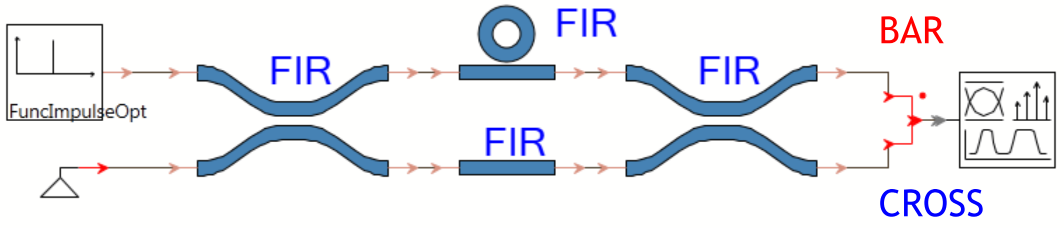
or infinite impulse response (IIR) digital filters:

$$A_{out}(t_i) = \sum_{m=0}^{N} a_m A_{in}(t_{i-m}) + \sum_{m=1}^{M} b_m A_{out}(t_{i-m})$$

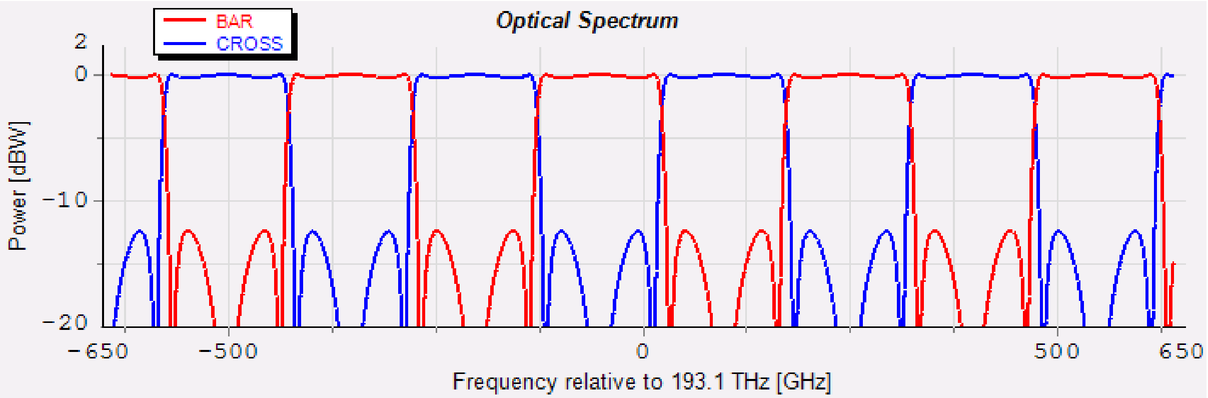
However, even best designed digital filters are not fully accurate in a general case!

Classical problem – fractional delay filter, which delays a signal for a time period τ which is not equal to integer number of time steps Δt.

Time-Domain Approach
for passive PIC sub-circuits

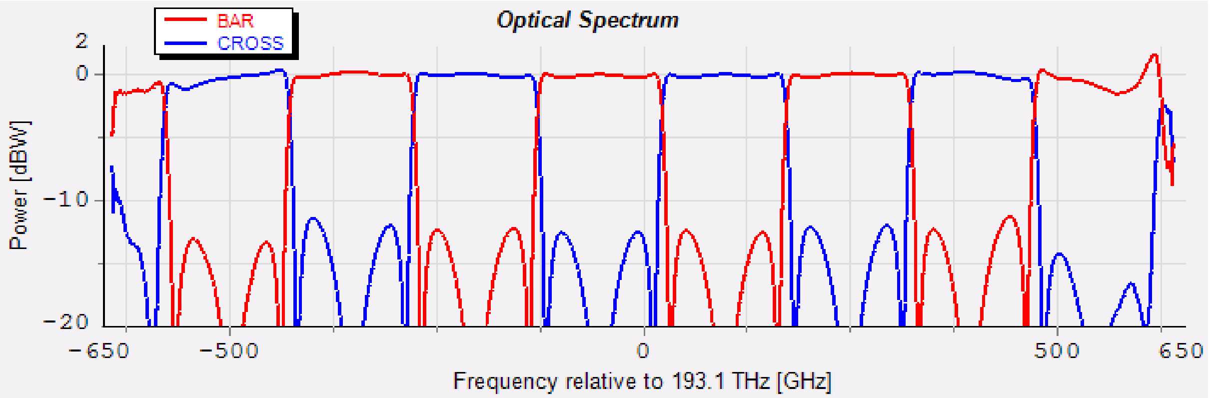


$$\begin{pmatrix} A_1^{out}(f) \\ A_2^{out}(f) \\ \cdots \\ A_M^{out}(f) \end{pmatrix} = \hat{S}(f) \begin{pmatrix} A_1^{in}(f) \\ A_2^{in}(f) \\ \cdots \\ A_N^{in}(f) \end{pmatrix}$$



Frequency-domain results

$$A_m^{out}(t_i) = \sum_{k=0}^{D_{mn}-1} S_{FIR,mn}(\tau_k) A_n^{in}(t_i - \tau_k)$$

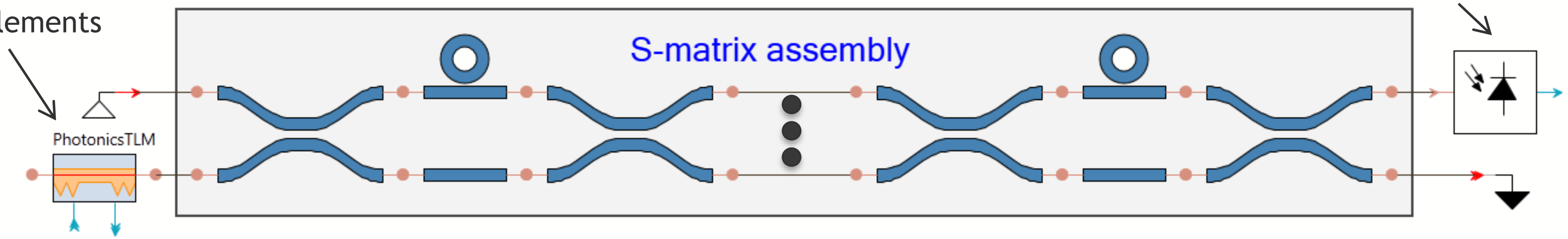


Pure time-domain results

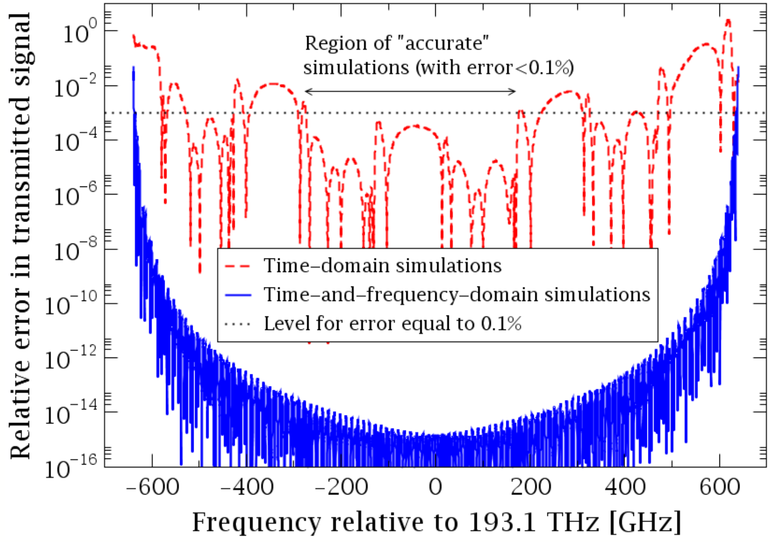
- Time consuming
- The accuracy of FIR solution degrades in the edges of the simulated frequency band
- Errors are significant as the number of elements increases

Hybrid Time-and-Frequency Domain

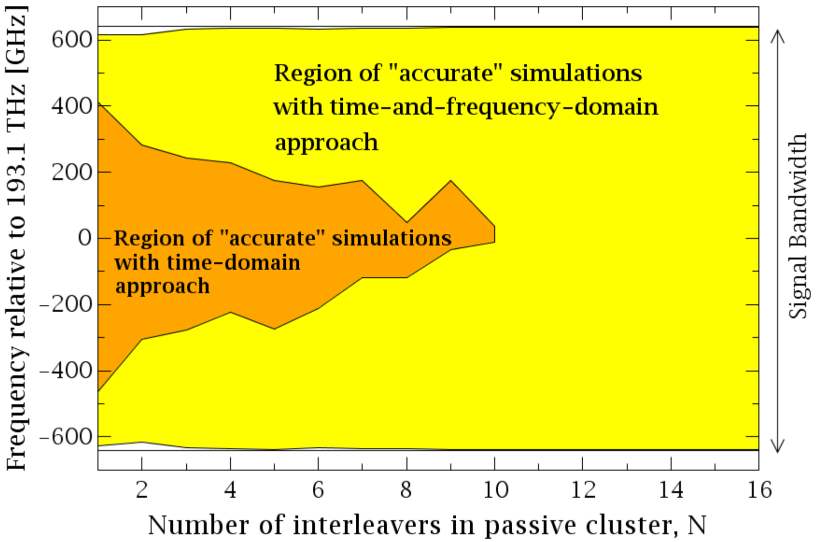
a great way to scale up!



Optical error spectra after passing N=5 interleavers



Central frequency regions with errors below 0.1%



S. Mingaleev et al., *Hybrid time-and-frequency-domain approach for modeling photonic integrated circuits*, Proc. IEEE NUSOD, p. 183 (2011).

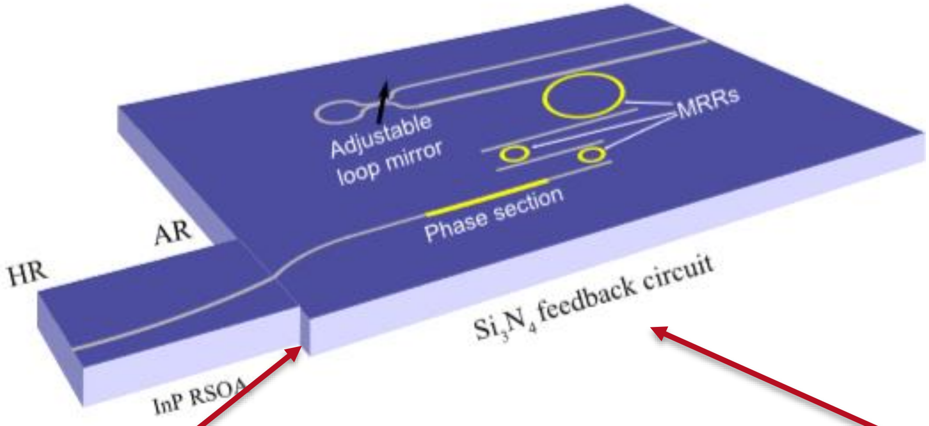
Hybrid Photonic Circuits Design Example
Widely Tunable Laser Source

External cavity laser:

- InP gain section
- TriPleX tunable low loss mirror
- Hybrid assembly

Main design goals:

- Wide tunability (C-band)
- Low linewidth



Design example, based on:
Y. Fan, et al., *“290 Hz intrinsic linewidth from an integrated optical chip-based widely tunable InP-Si3N4 hybrid laser”*, CLEO 2017, paper JTh5C.9.

Back reflections to laser ⇒ changes to carrier density, gain, effective index ⇒ laser instabilities, noise

Contains small-size devices with small group delays

Hybrid Time-and-Frequency domain is needed!

Based on photonics PDK supporting TriPleX-foundry of LioniX International BV

Hybrid Photonic Circuits Design Example
Widely Tunable Laser Source

External cavity laser:

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- TriPleX tunable low loss mirror
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Main design goals:

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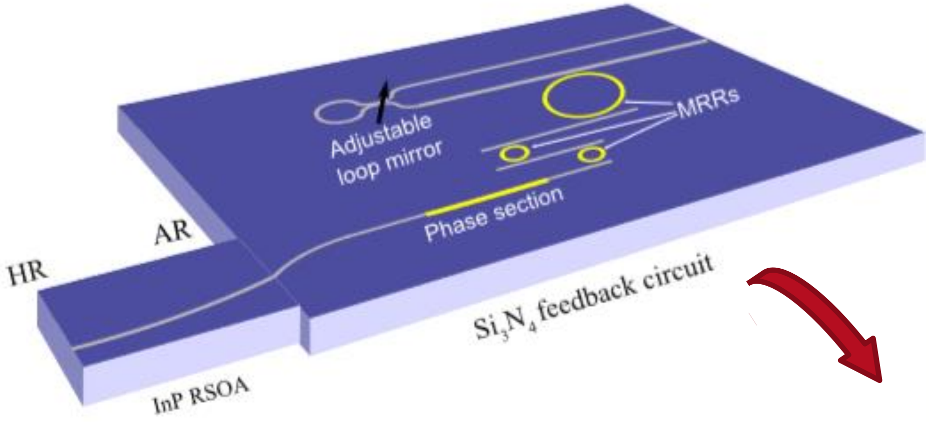
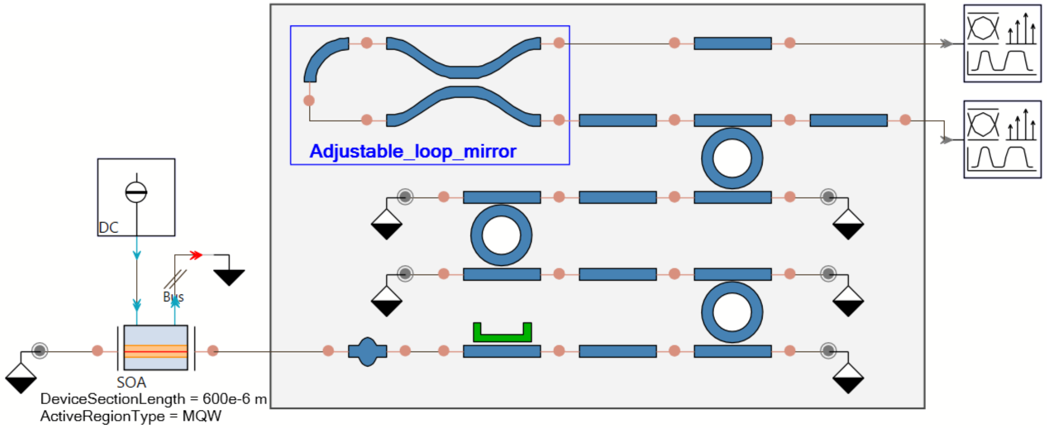


Design example, based on:
Y. Fan, et al., *"290 Hz intrinsic linewidth from an integrated optical chip-based widely tunable InP-Si3N4 hybrid laser"*, CLEO 2017, paper JTh5C.9.

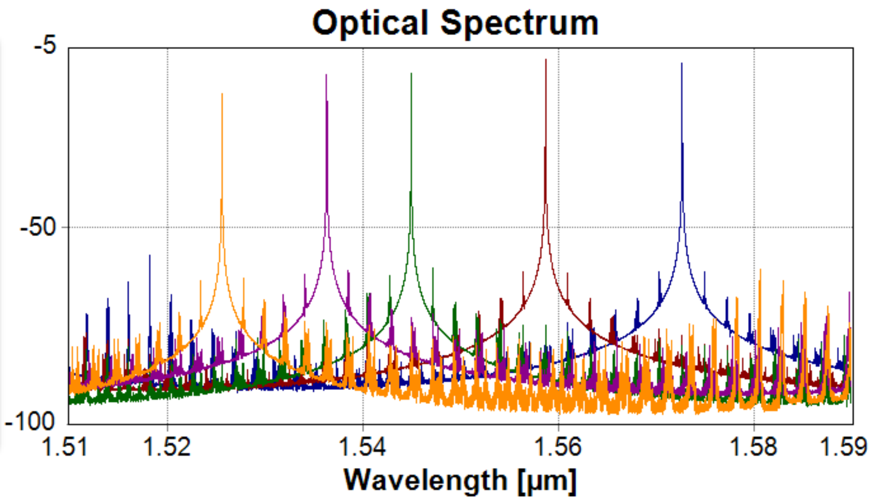
S-Matrix Assembly



Very tricky to simulate directly!

$\Delta f_{lw} < 100kHz$:

$T_W > 4/\Delta f_{lw} = 40\mu s$
$f_s \approx 2.5THz$
$\Rightarrow$ $\#_{samples} > 10^8$



Simulated tuning characteristics

Based on photonics PDK supporting TriPleX-foundry of LioniX International BV

Hybrid Photonic Circuits Design Example

Indirect Estimation of Narrow Laser Linewidth

Spectral scaling (upper bound)

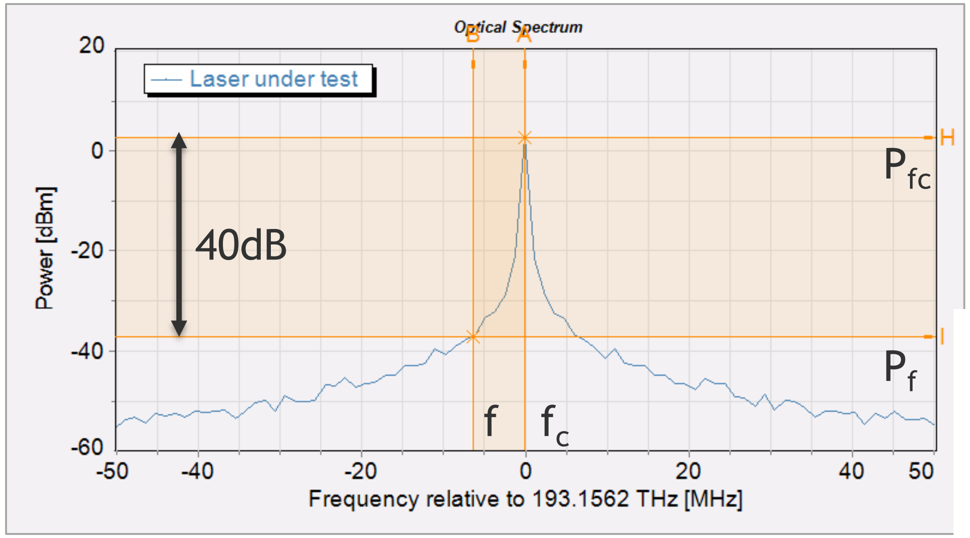
- Voigt shape fitting (assumes mix of Lorentzian & Gaussian spectral shape):

$$\Delta f_{lw} = 2(f_c - f)\sqrt{\frac{P_{fc}}{P_f}}$$

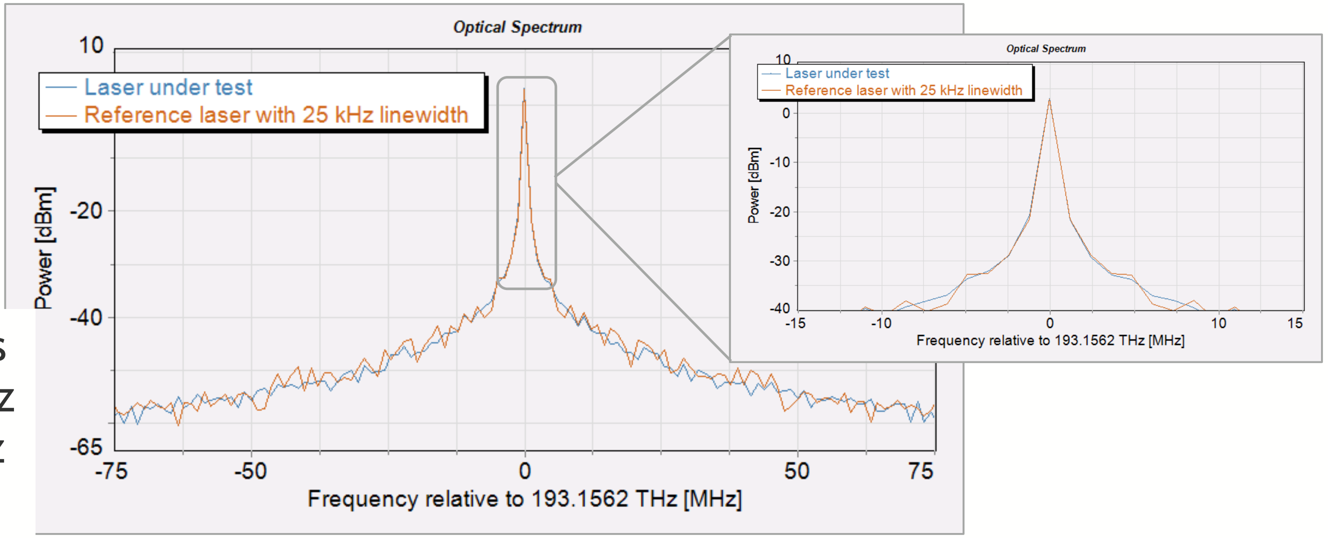
- Factor 200 (-40dB), factor 2000 (-60dB)
- Estimated linewidth: approx. 35kHz

Spectral fitting (more accurate)

- Spectral shape fitting using reference laser with phase change modelled by random walk (Wiener process)
- Manually adjust parameters for linewidth and optical peak power
- Estimated linewidth: approx. 25kHz



$T_W \approx 0.8\mu s$
$\Delta f \approx 1.2 MHz$
$f_s \approx 2.5 THz$
$\#_{sa} \approx 2x10^6$



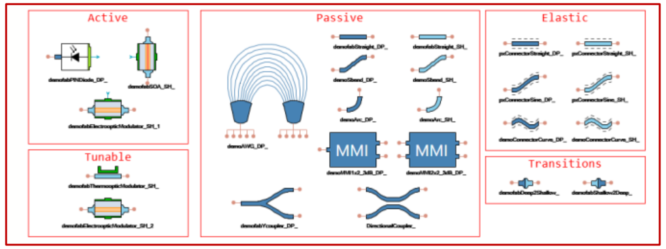
Layout-aware design approach and PDKs

- Introduction to Process Design Kits (PDKs)
- Layout-aware simulation
- Design Example: Integrated Optical Buffer

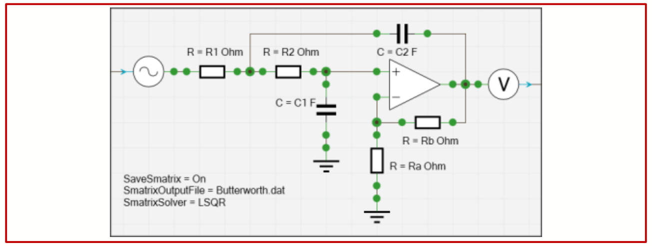
VPIphotonics DESIGN AUTOMATION

Photonic Circuit Design & Analysis

PDK Building Block Libraries



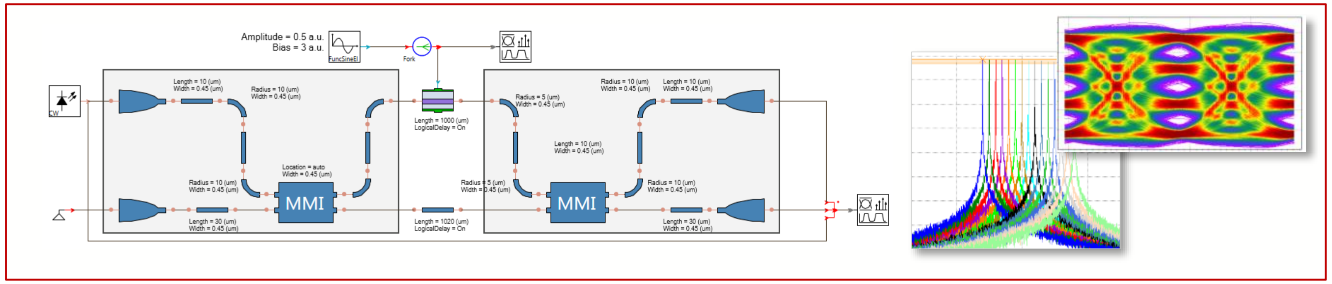
Electronic Design Automation



Foundry-specific models

Extract device parameters

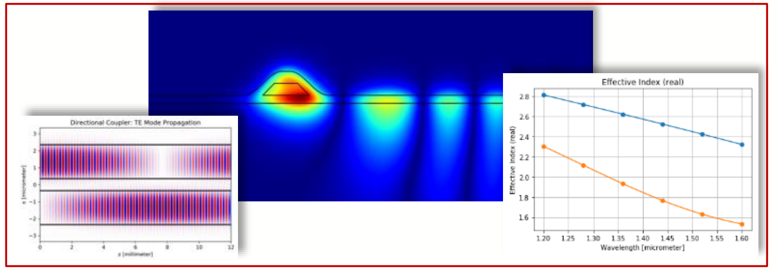
Photonic Circuit Simulation & System Validation



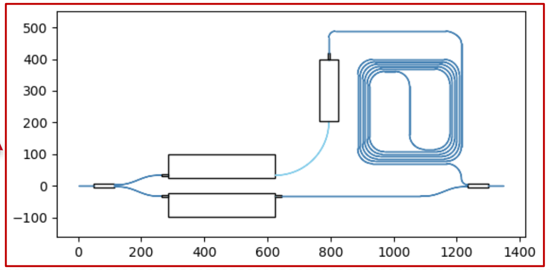
Optoelectronics and electrical simulation

Layout design & DRCs, verification of layout

Device Modeling



Layout Design

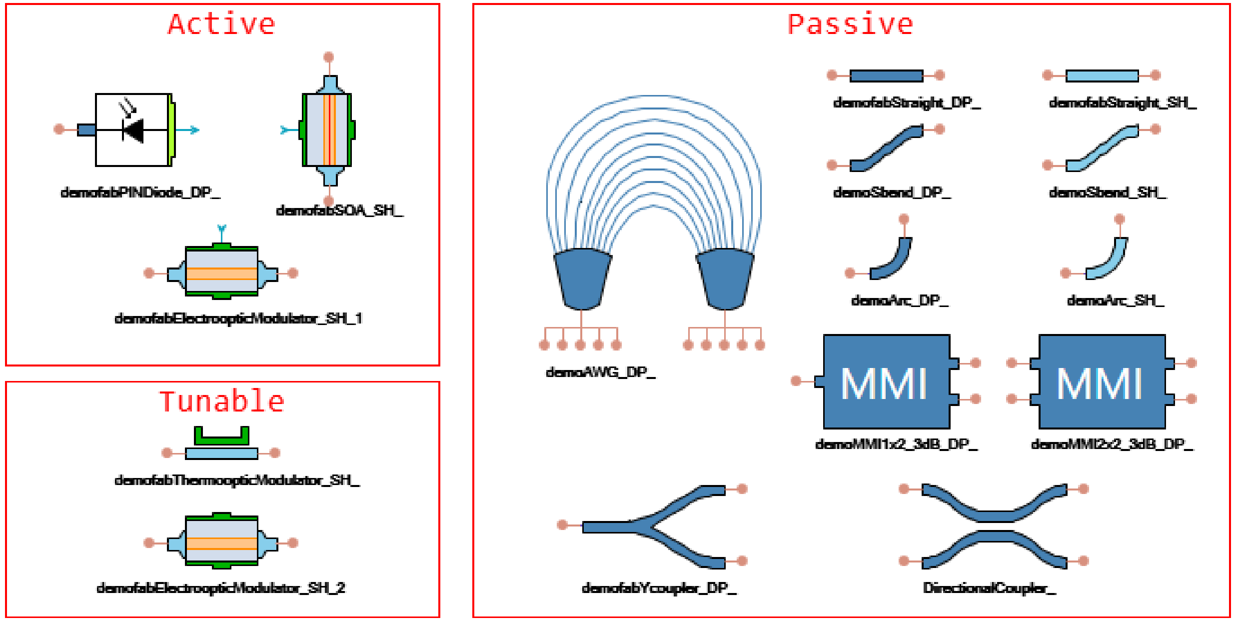


Introduction to Process Design Kit (PDK)

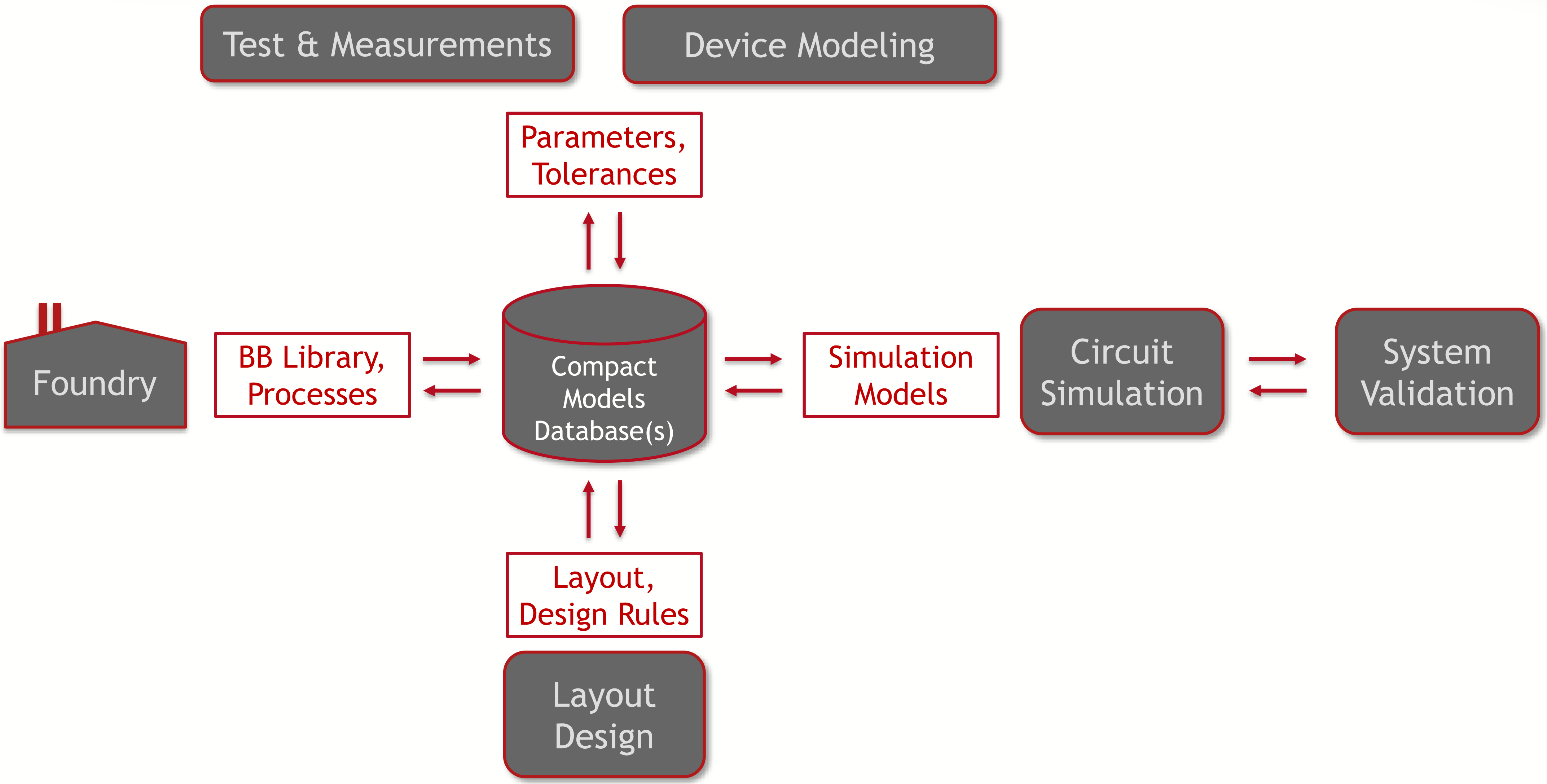
Foundry-Specific Process Design Kit (PDK):

- list of components
- corresponding certified compact models
- and geometric layout
- fabrication process info, design rules
- process variations

Design simplicity and predictability for the particular foundry



PDK BBs Models Characterization

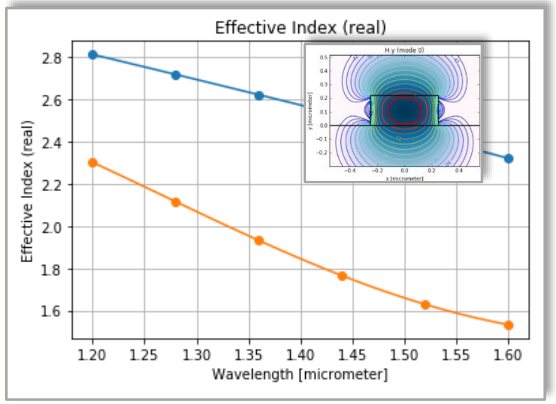


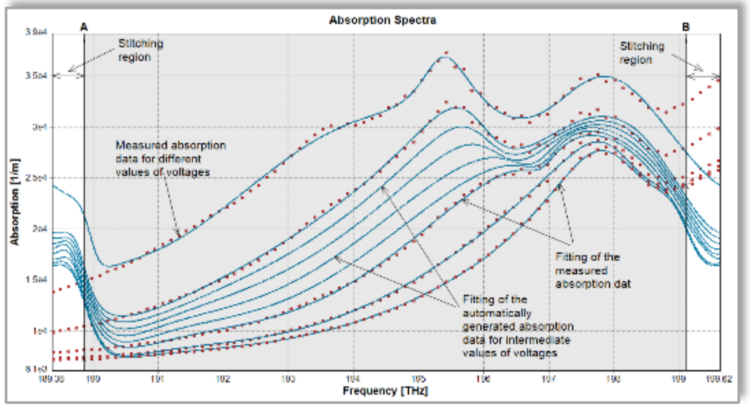
PDK BBs Models Characterization

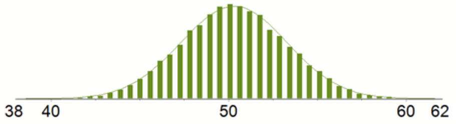
Built-in Modules

- Parameters
- Expressions
- Data Files
- Code

Measured and calculated parameters and their variations for analytical models







Measured and co-simulated models

```
// Comment line or lines, if required
# SMatrix MMI_M_N
# NumberOfInputPorts 5
# NumberOfOutputPorts 5
// Comment line or lines, if required
# InputPort  left#1 TE
# OutputPort right#1 TE
# Frequency          Magnitude          Phase
# (Hz)               (dB)               (deg)
1.92100e+014         2.6938271e-001     -9.001622e+001
1.92110e+014         2.6970974e-001     -1.344023e+002
..................................................
1.94090e+014         2.7012581e-001     -8.927487e+003
1.94100e+014         2.6980897e-001
// Comment line or lines, if
```

ModelType = Measured

```
class WgGrating(object):
    '''
    Waveguide Grating - 'BraggGrating' analytical model.
    '''
    #=====================================================================
    def __init__(self, module_parameters):
        '''
        Method called during the module initialization.
        Inputs:
            module_parameters - dict of module parameters and their values.
        '''
        # create a list of all module states:
        self.states = GetParameters(module_parameters)
..........................................................................
..........................................................................
    #=====================================================================
    def transferv(self, port_out, port_in, mode_out, mode_in,
        # main S-matrix calculations (assum
        sigma = self._mode[mode_in]
```

MATLAB SIMULINK

python

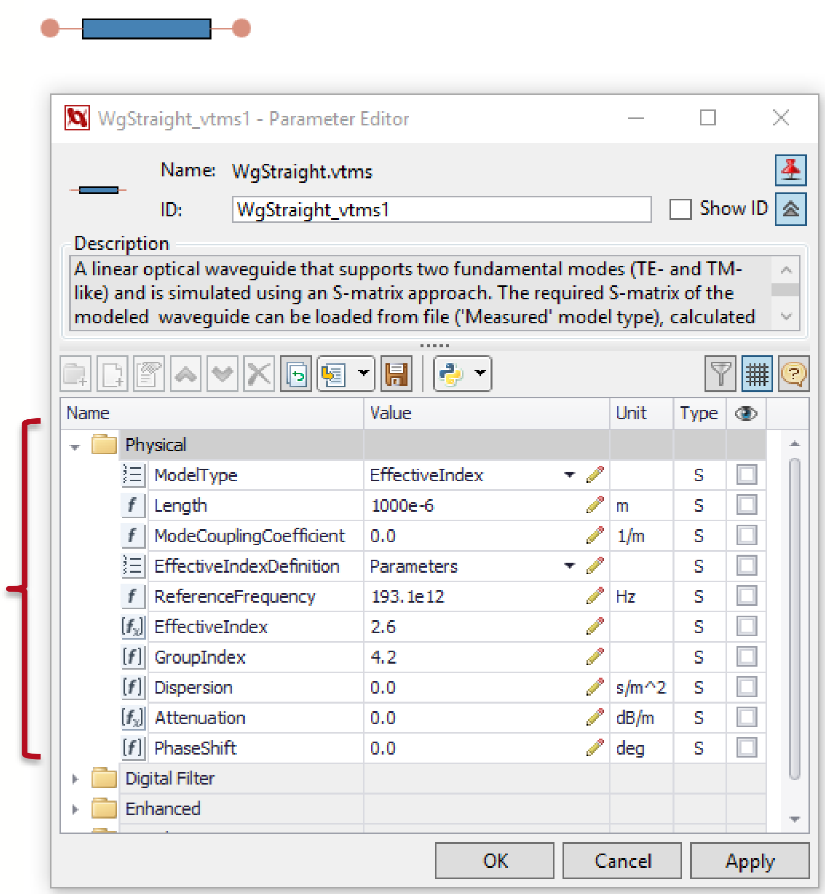
DLL

Microsoft COM+

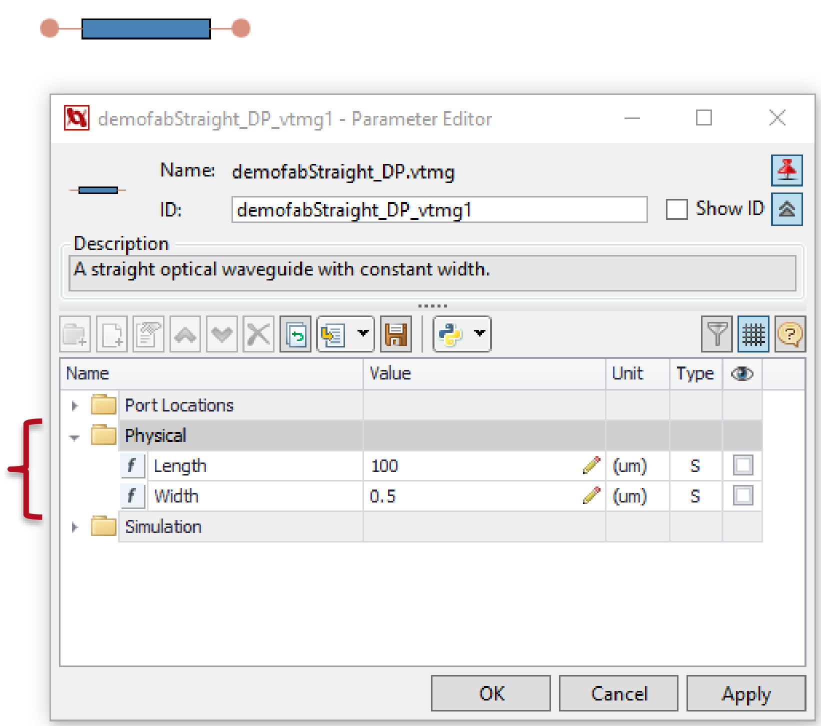
VPIphotonics DESIGN AUTOMATION

Generic vs. PDK Components

Build-in Module



Demo PDK BB

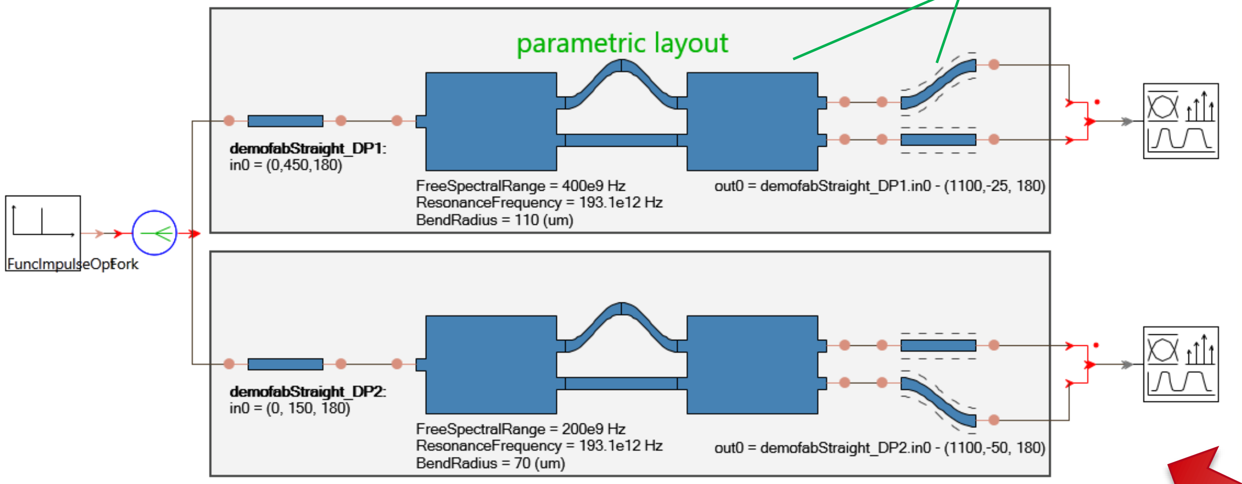


Using PDK Libraries

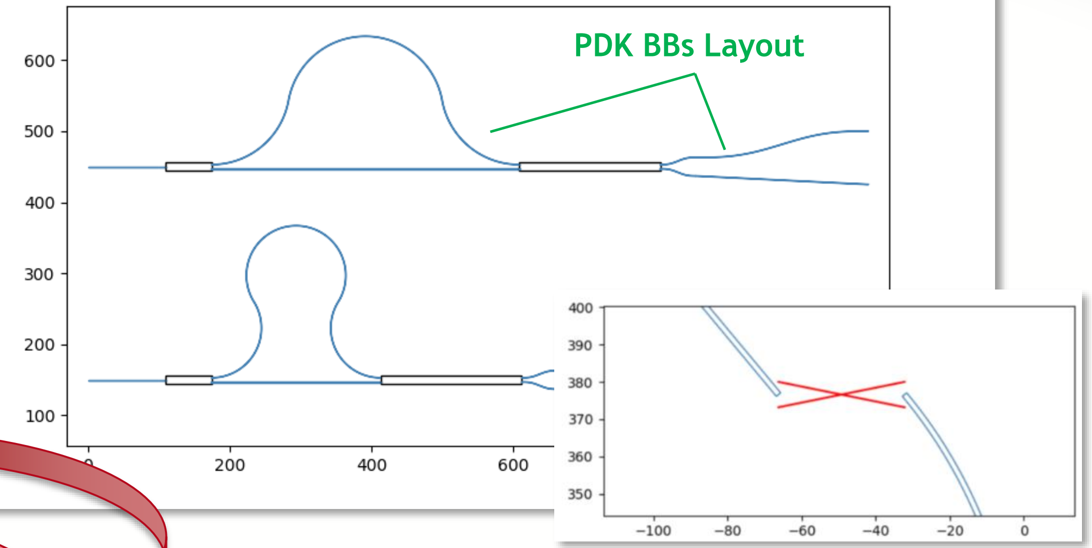
- Simplifies Design: only few variable parameters are available
- Certified operation
- Still having accurate, flexible models inside
- All features and domain are supported similarly to the build-in components
- Allows for automatic conversion into layout for subsequent mask generation and fabrication

Design of Photonic Circuits using PDK

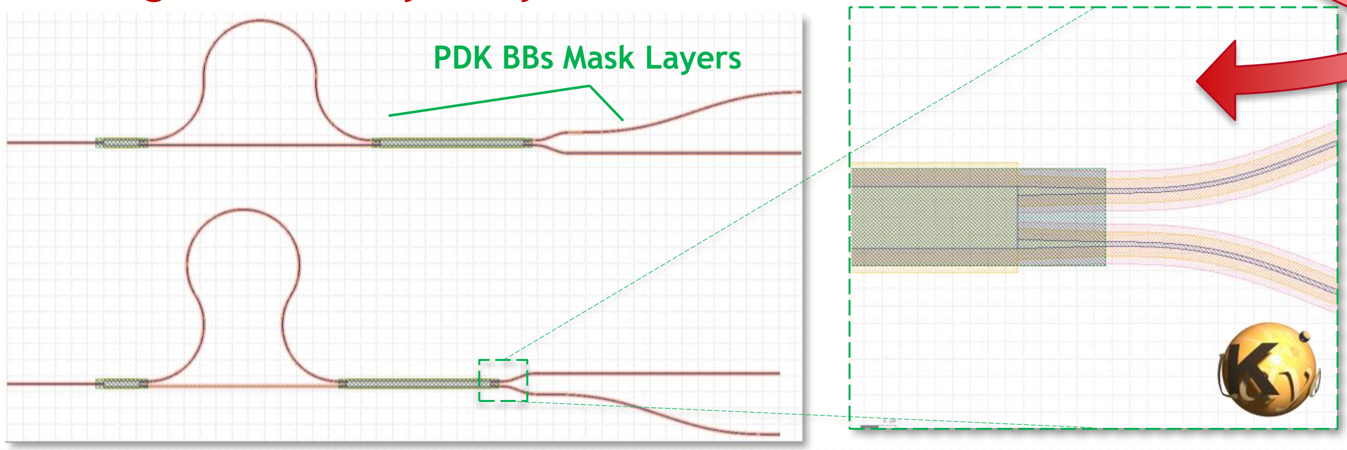
Circuit Schematic



Corresponding Top Layout View



Mask generated by a layout tool

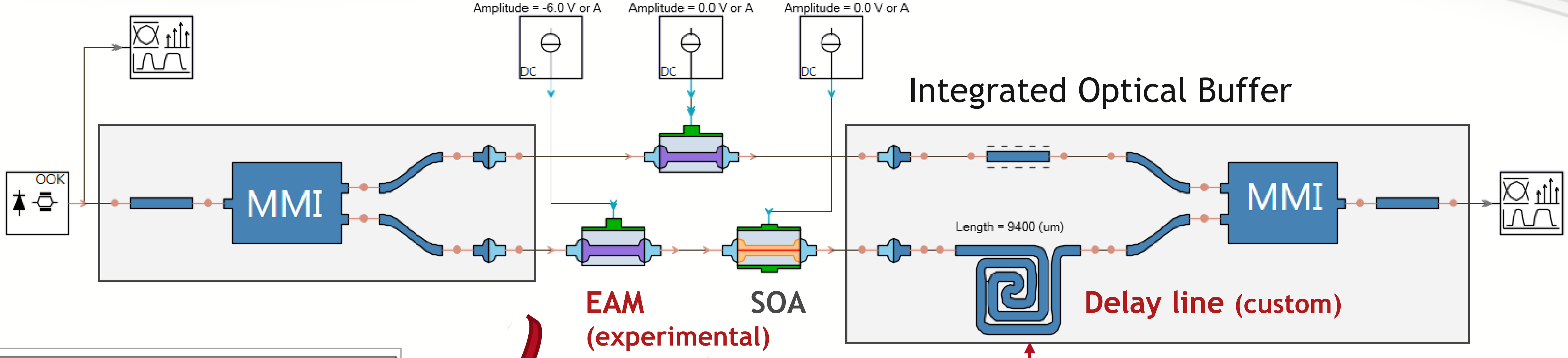


Circuit layout contains information:

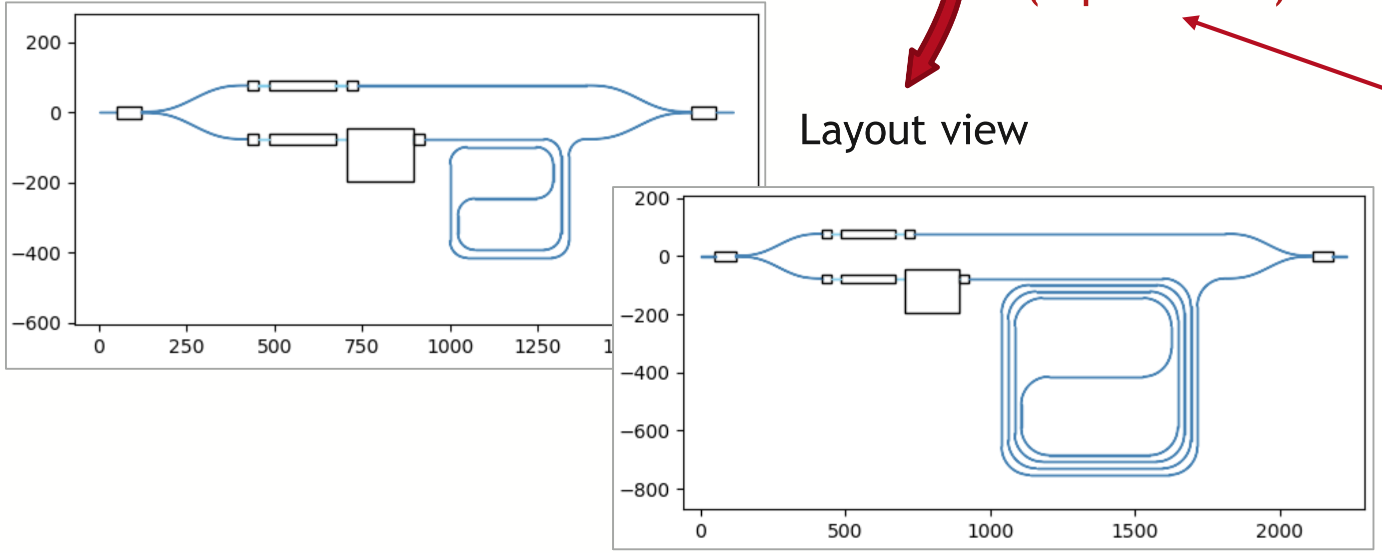
- components connections,
- their positions,
- geometrical properties and
- corresponding process stages (mask layers)

Design rule checking is important at this stage!

Design of Photonic Circuits using PDK
Custom and experimental BBs



Layout view

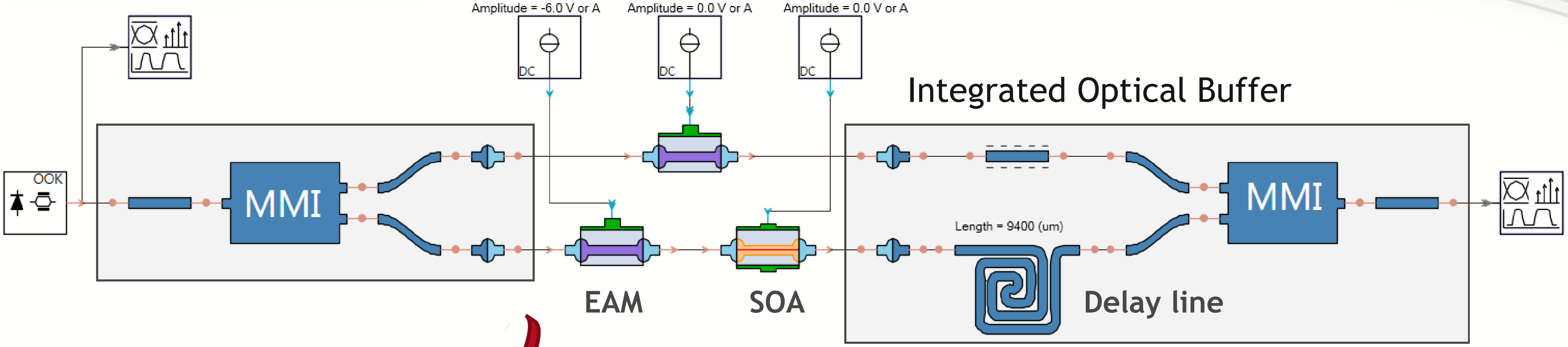


Experimental and custom BBs
- ✓ user-defined layout
- ✓ user-defined simulation model
- ✓ easily added by users

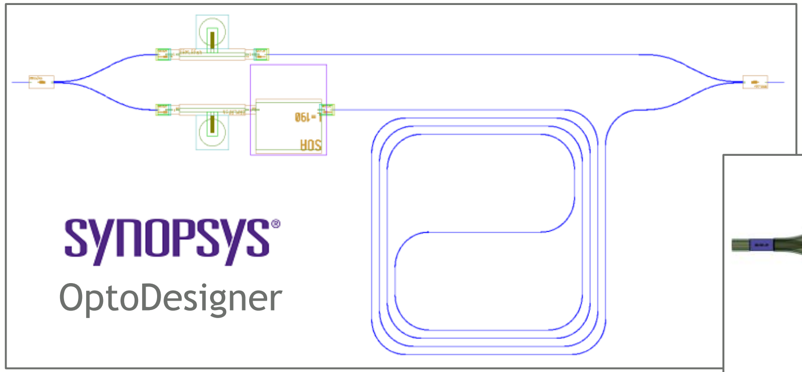
Based on photonics PDK supporting InP-foundry of SMART Photonics

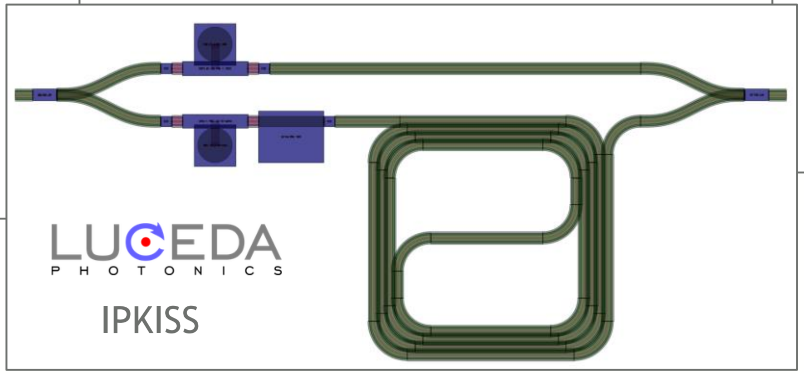
Design of Photonic Circuits using PDKs

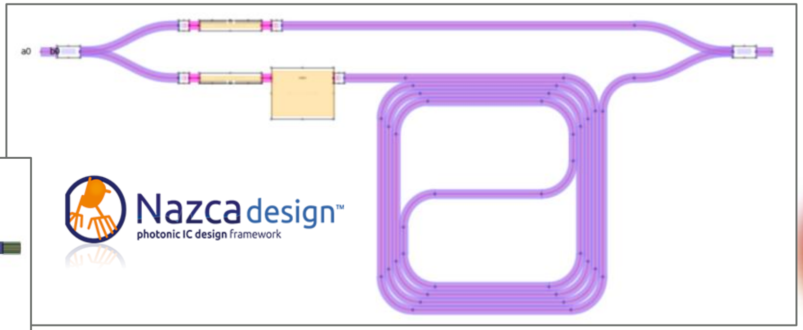
DRCs and GDS mask generation



Automated export to 3rd party layout tool for DRC and GDS mask







Based on photonics PDK supporting InP-foundry of SMART Photonics

Why Should be Aware of Circuit Layout?

Standard schematic-driven approach

- BB layout determined by its parameters (length, bend angle, etc.)

⇨ IC layout fully determined by connectivity between BBs

⇨ Allows immediate IC simulation as BB model is known at each design step

BB – Building Block
IC - Integrated Circuit

Two roles of optical waveguides

- Could act as connecting device: routes optical signals between building blocks of the circuit

⇨ Detailed properties (length, width, shape) are not critical, may be ignored

- Could act as functional device: determine interference between signals traveling in different paths

⇨ Detailed properties are very important, already at the beginning of circuit design

Problem: Often, no clear separation possible!

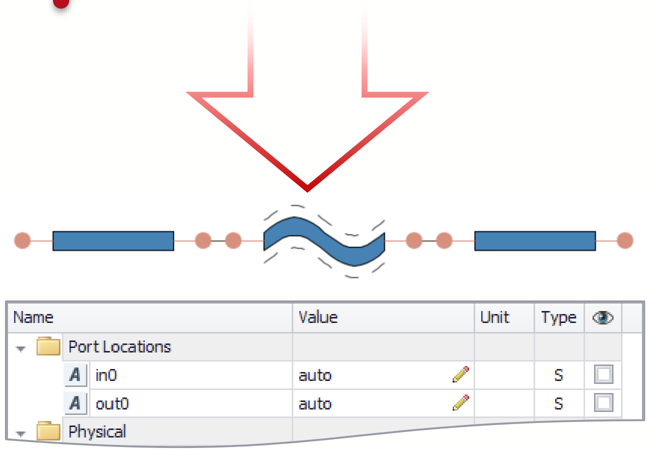
Photonic IC design ≠ circuit design + layout design

⇨ Tight interaction between layout and circuit design necessary

Layout-Aware Schematic-Driven Design Flow

How to connect arbitrary oriented components on the layout?

Dedicated “elastic” elements introduces, which automatically adapted to best fit layout

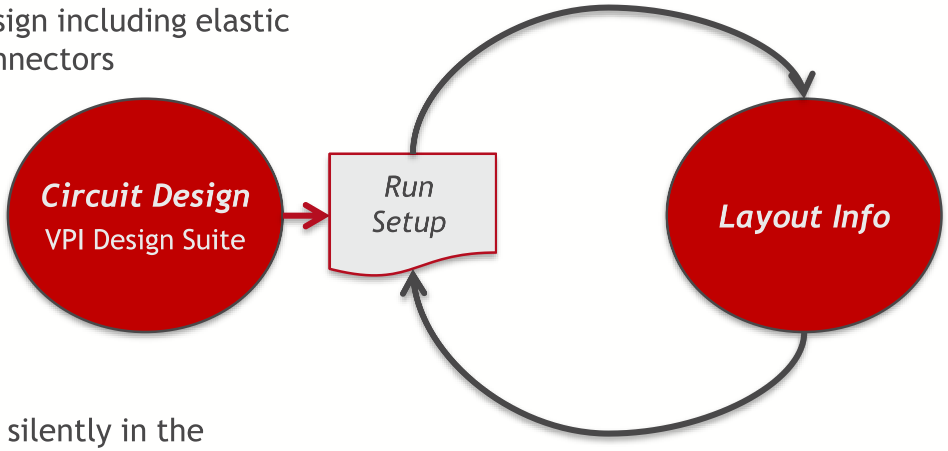


- Corresponding circuit representation usually has no geometrical parameters
- At least some BBs require specification of the ports locations in the circuit simulator

How could circuit with adaptive layout elements be simulated?

Use layout information to “resolve” it: find port locations and directions for all elastic connectors

Create complete circuit design including elastic connectors



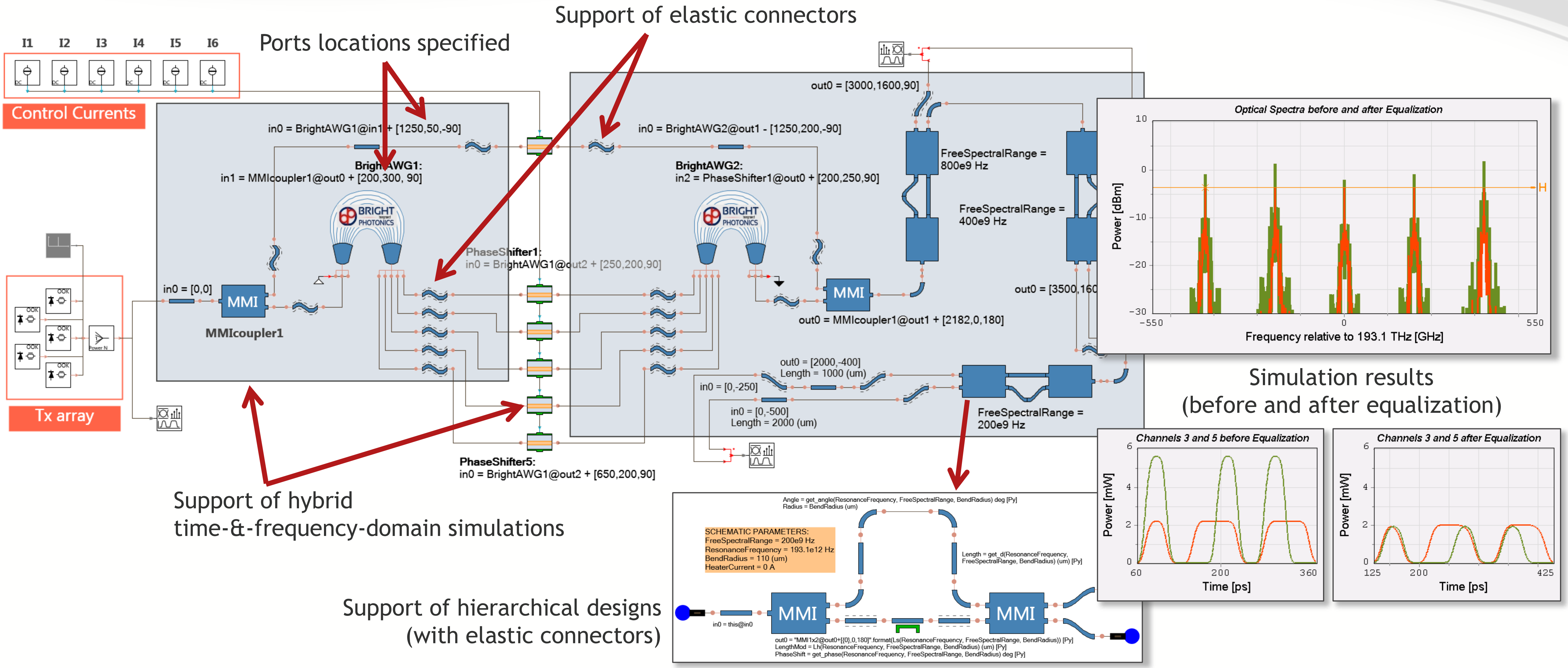
Convert port locations and directions for elastic connectors into waveguide lengths required by simulation models

Runs silently in the background, no manual user action needed!

Create simulation models for elastic connectors, run simulation for the whole circuit

Layout-Aware Schematic-Driven Design Flow

Dynamic WDM Channel Equalizer



Design automation techniques

- Design Example: 2D Beam Scanner for LIDAR
- Simulating arrays and chains of modules
- Scripting for schematic capture
- Design Example: High-Order Ring-Based Optical Filter
- Optimization and automated parameters settings
- Design robustness & sensitivity

Hybrid III-V / Silicon Design Example
2D Beam Scanner for LIDAR

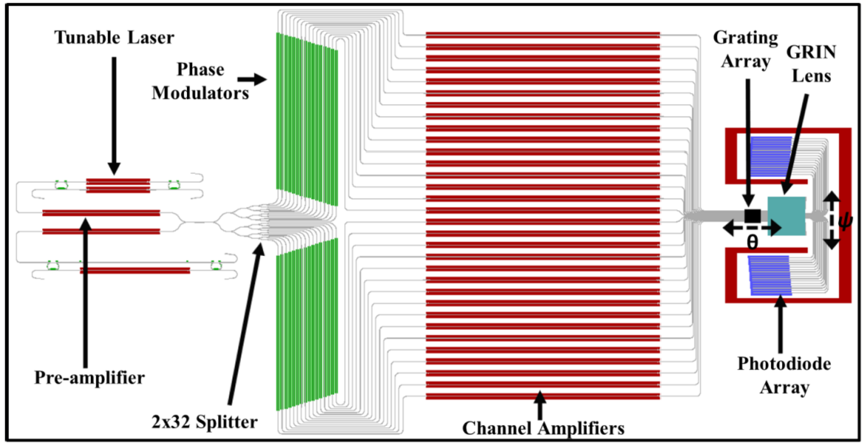


Figure taken from *

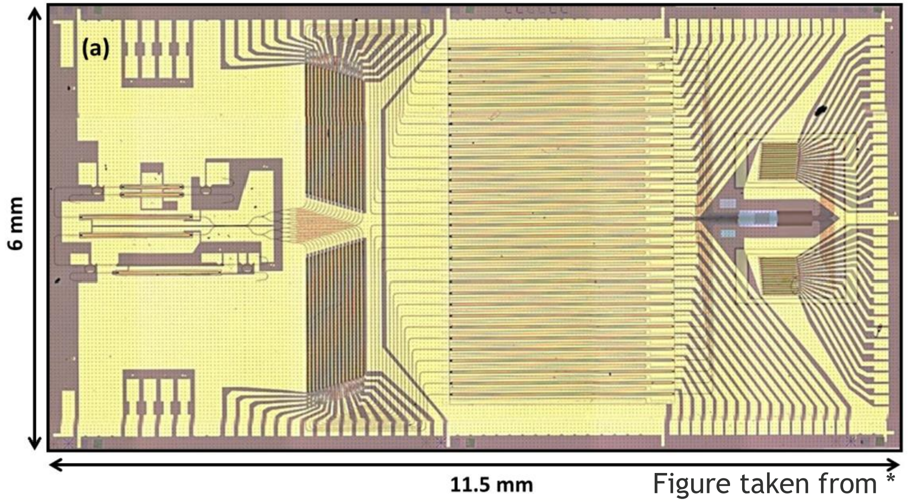
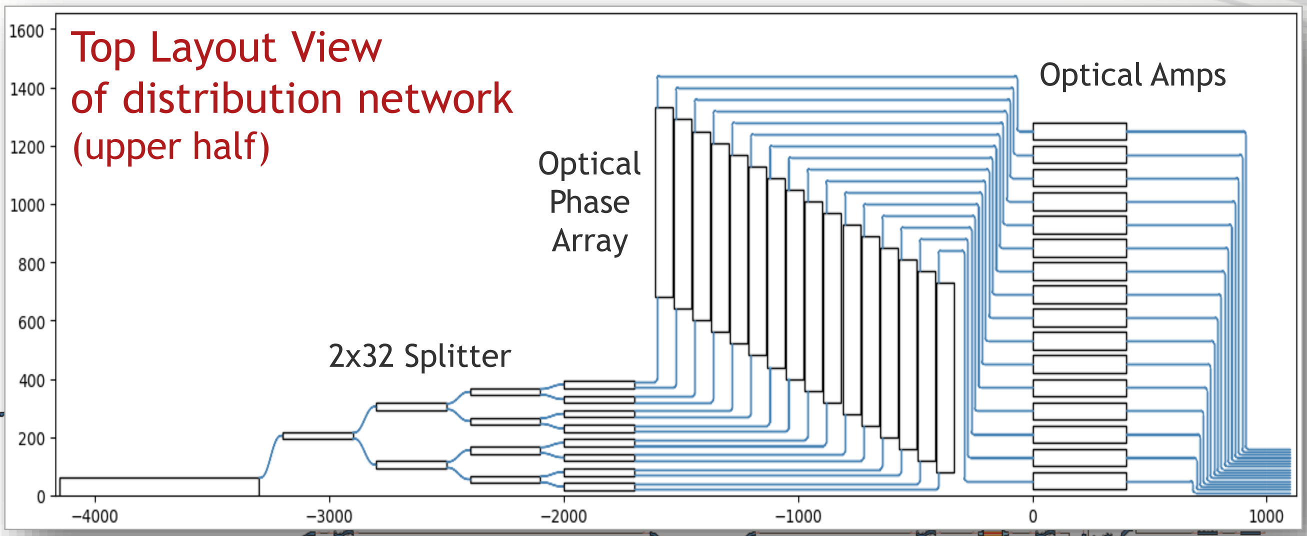
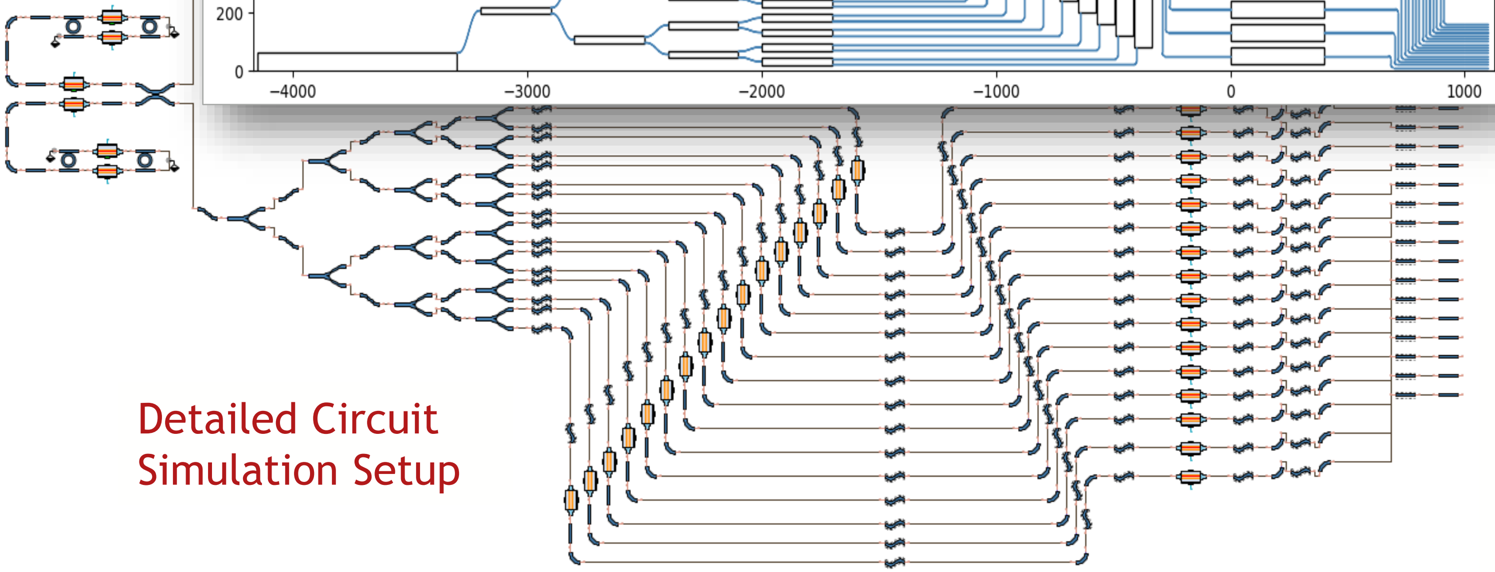


Figure taken from *





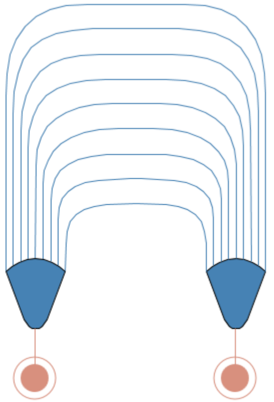
Detailed Circuit Simulation Setup

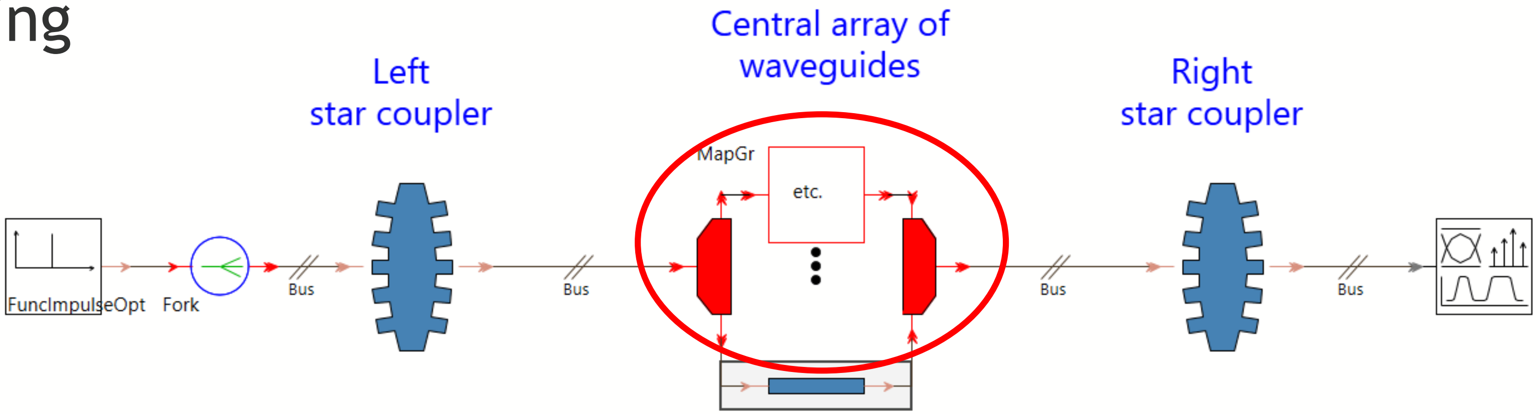
Design example, based on works performed by University of California Santa Barbara:

* J.C. Hulme et al., Fully integrated hybrid silicon two dimensional beam scanner, Opt. Express 23, 5861-5874 (Feb 2015).

Simulating Arrays and Chains of Modules

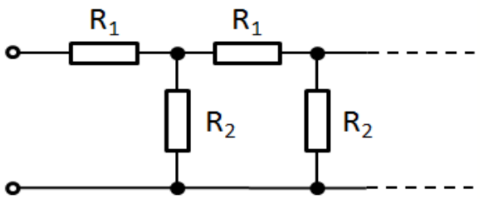
Arrayed Waveguide Grating

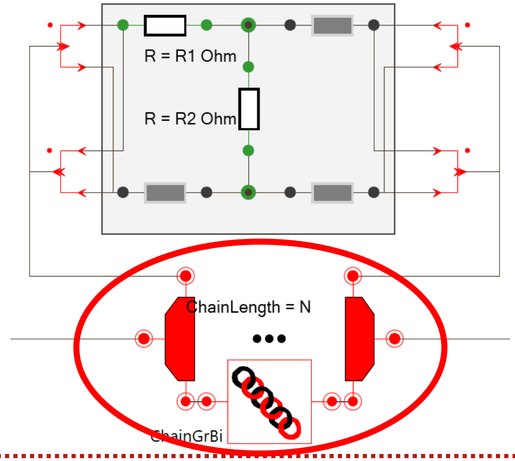




Length = !" expr {WgMinimumLength}+({WgNumber}-{NumberOfWaveguides}/2)*({LengthIncrement}+(0.5-{WgNumber}%2)*{IncrementDifference})" m
PhaseShift = !" expr {PhaseShiftVariation}*(0.5-rand())" deg

Infinite Resistor Series



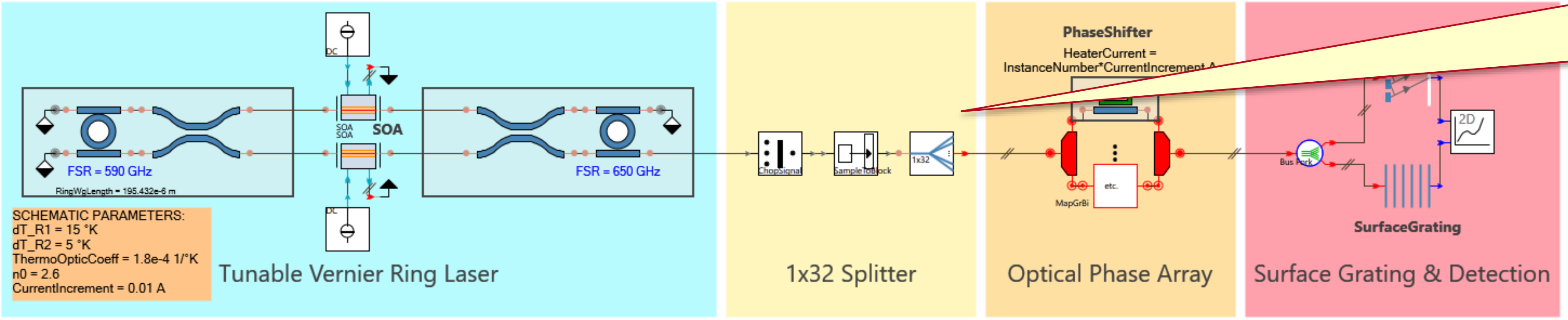


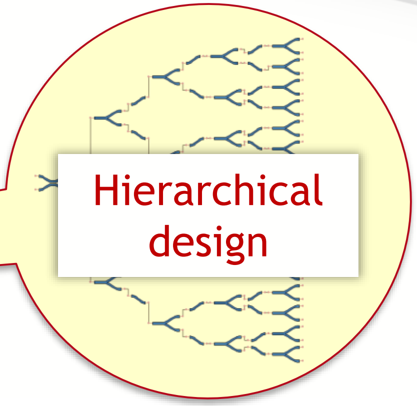
- Graphical solution: higher-order function modules repeat connected blocks the specified number of times
- Parameter expressions could be used to set the parameters for each instance to different values

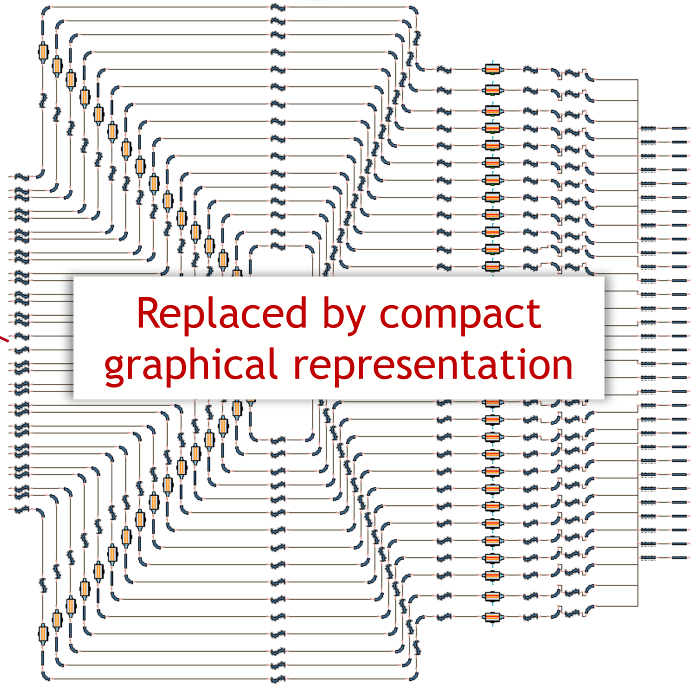
Hybrid III-V / Silicon Design Example

2D Beam Scanner for LIDAR

Simulation Setup for Testing the Scanning Performance



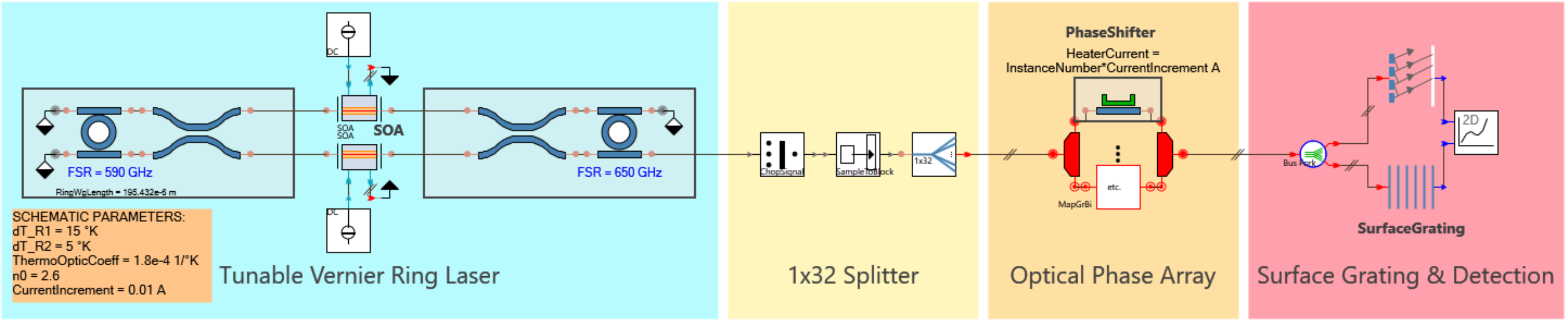


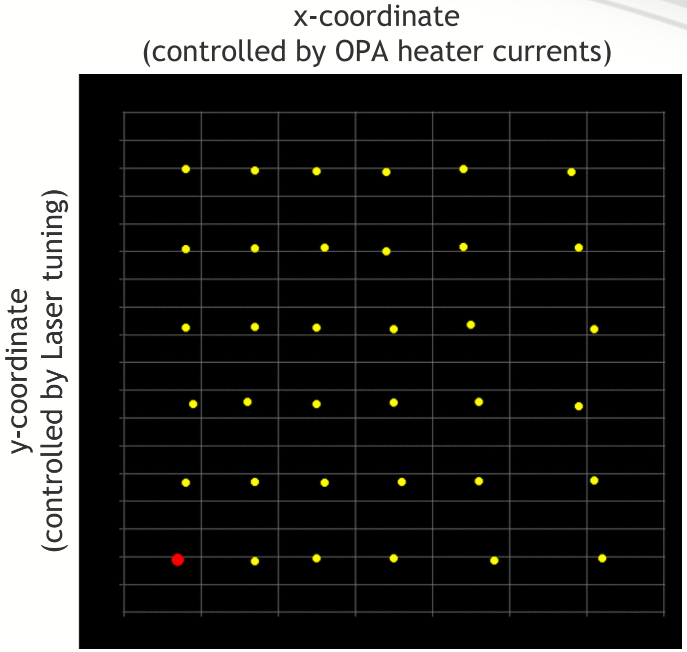


- ✓ Hybrid time-and-frequency domain modeling for accurate simulation of tunable laser characteristics
- ✓ Hierarchical designs to easily manage system complexity (1x32 splitter)
- ✓ Graphical solution to concisely represent serial or parallel structures (phase shifter array)
- ✓ Python cosimulation to address custom components or technologies (beam propagation and projection)

Hybrid III-V / Silicon Design Example
2D Beam Scanner for LIDAR

Simulation Setup for Testing the Scanning Performance





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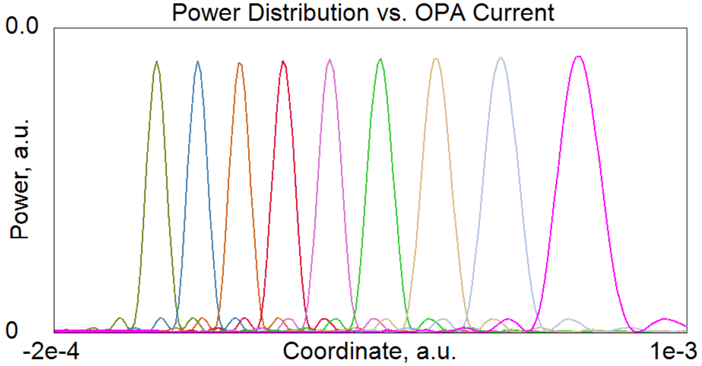
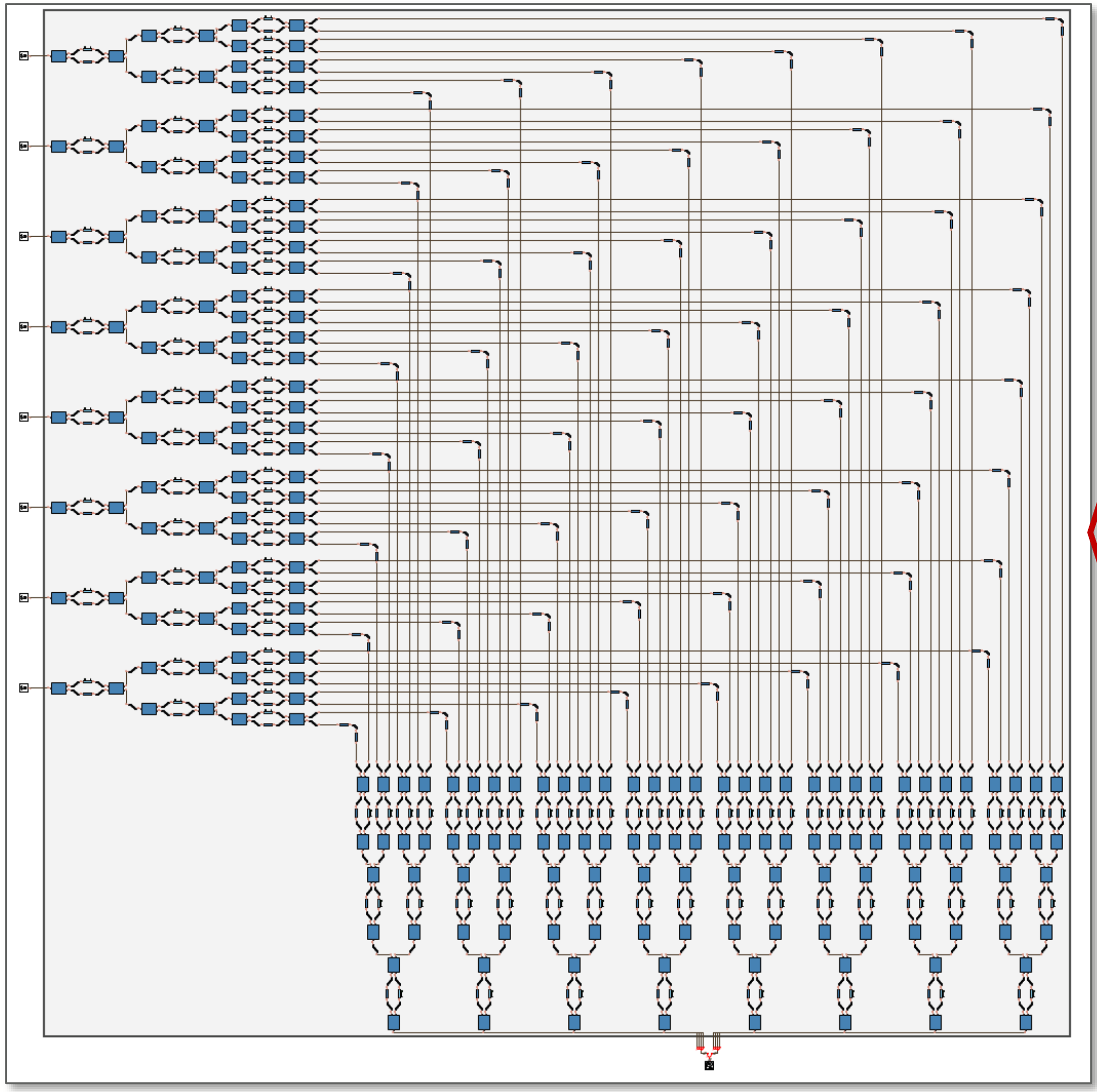


Automation with Scripting

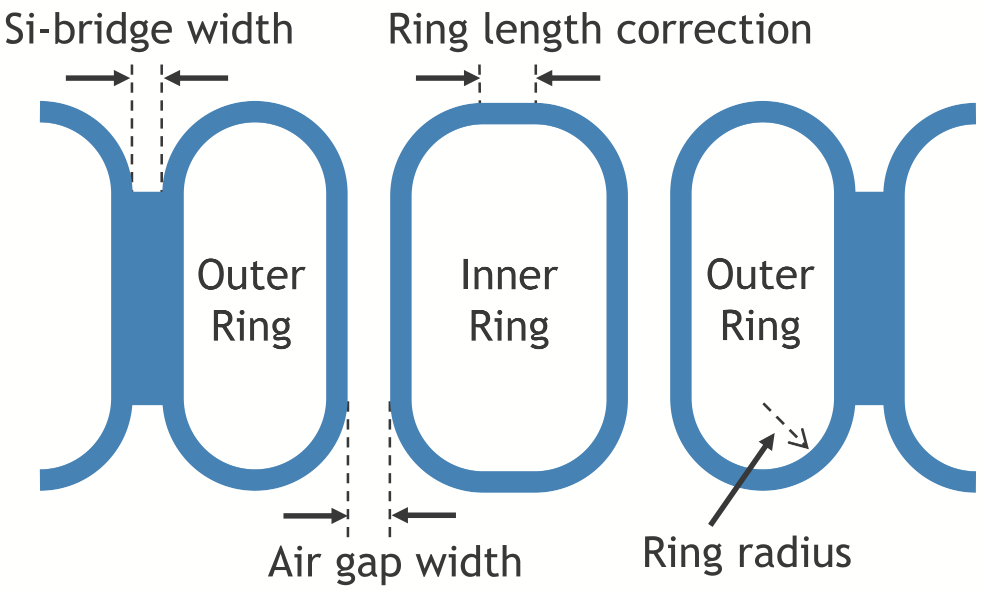


Python script for creation of an NxN optical switch

```
def create(self):
    id = self.id
    x = self.x
    y = self.y
    xx = self.xx
    yy = self.yy
    phase = self.phase
    L = self.L
    w = self.w

    L_to = L
    L_wg = L+100.0
    L_sb = 20.0
    H_sb = 15.0

    mmi1x2_id = id + "_mmi1x2"
    pde.star(mmi1x2_id, "URN:TKIT_LIB::PDK DFO Modules\Passive\demoMMI1x2_3dB_DP.vtmg:")
    pde.setpos(mmi1x2_id, x+5, y)
    if self.fixed:
        pde.setstate(mmi1x2_id, "in0", '[{0},{1}]'.format(xx,yy))

    mmi2x2_id = id + "_mmi2x2"
    pde.star(mmi2x2_id, "URN:TKIT_LIB::PDK DFO Modules\Passive\demoMMI2x2_3dB_DP.vtmg:")
    pde.setpos(mmi2x2_id, x+33, y)

    to_id = id + "_to"
    pde.star(to_id, "URN:TKIT_LIB::PDK DFO Modules\Tunable\demofabThermoopticModulator_SH.vtmg:")
    pde.setpos(to_id, x+19, y-3)
    pde.setstate(to_id, "LengthMod", L_to)
    pde.setstate(to_id, "WidthWaveguide", w)
    pde.setstate(to_id, "PhaseShift", phase, show=False)

    wg_id = id + "_wg"
    pde.star(wg_id, "URN:TKIT_LIB::PDK DFO Modules\Passive\demofabStraight_DP.vtmg:")
    pde.setpos(wg_id, x+19, y+3)
    pde.setstate(wg_id, "Length", L_wg)
    pde.setstate(wg_id, "Width", w)
    #pde.setstate(wg_id, "PhaseShift", '90')

    sb1_id = id + "_sb1"
    pde.star(sb1_id, "URN:TKIT_LIB::PDK DFO Modules\Passive
    pde.setpos(sb1_id, x+13, y-2)
    pde.setstate(sb1_id, "Length", L_sb)
    pde.setstate(sb1_id, "Height", H_sb)
    ...tate(sb1_id, "Width", w)
```

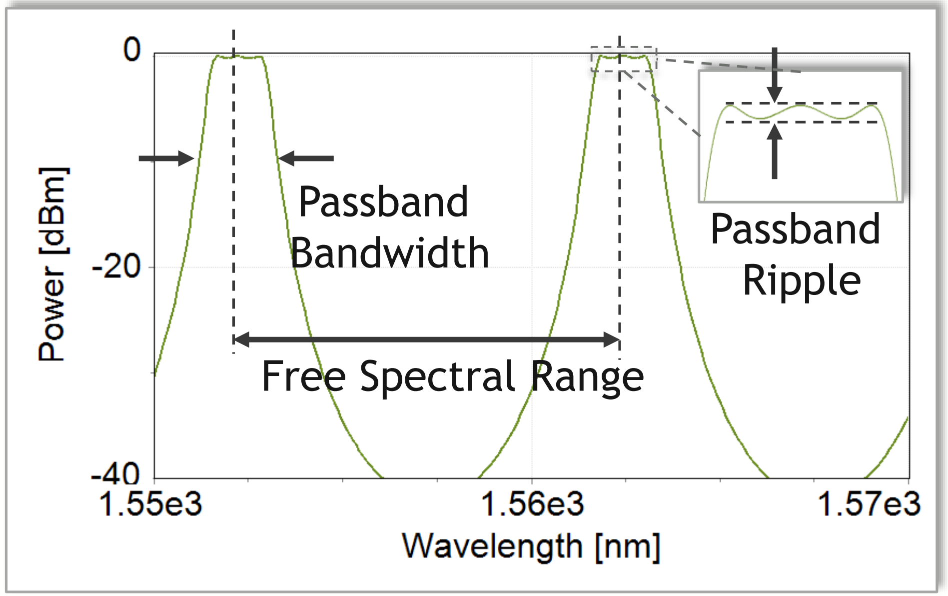
Design of Photonic Circuits using PDKs
Design Robustness & Sensitivity

Optimization of 3-Ring Filter



?

Desired filter performance



Find optimum circuit parameters that

- ✓ Meet design specifications (e.g. flat pass band, desired bandwidth, FSR)
- ✓ Provide min sensitivity to fabrication imperfections and high yield

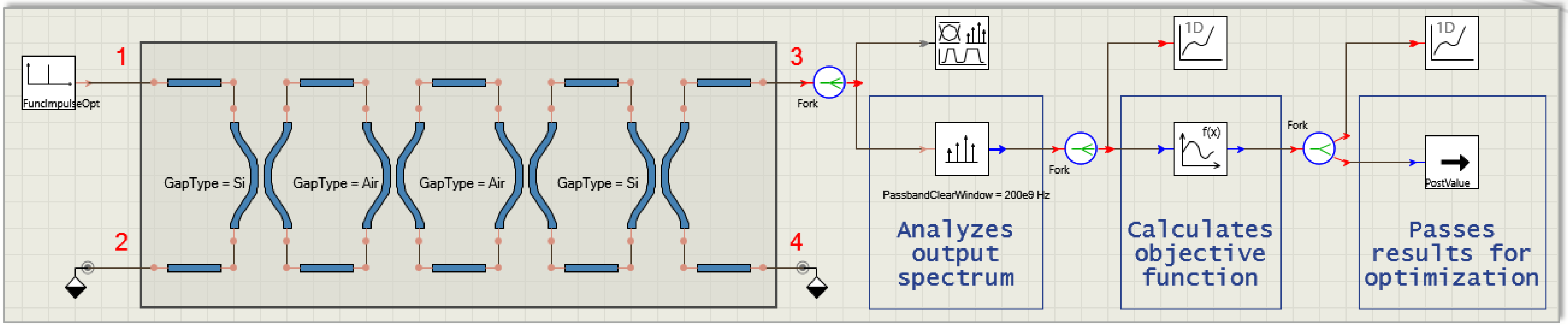
⇨ Multi-parameter optimization

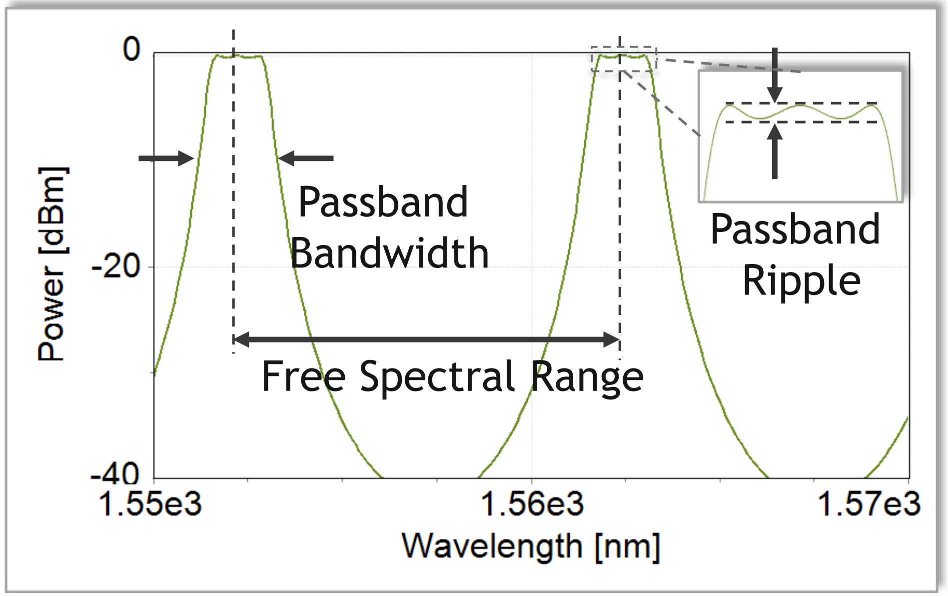
⇨ Monte-Carlo simulations (high effort)

⇨ Corner analysis, Sensitivity analysis, Yield analysis

Multi-Parameter Optimization

https://youtu.be/Zi2XBGXT7Mo





Custom optimization routines (in Python or Tcl) could be used.
Differential evolution method implemented in SciPy is used::

simulation_script.tcl

```
pythonScript {
import vpi_ptcl_script as vpi
from scipy.optimize import differential_evolution
def RunOnce(x):
    vpi.setstate('this', 'AirGapWidth', x[0])
    vpi.setstate('this', 'RingLengthCorrection', x[1])
    vpi.run(1)
    objective_function = vpi.statevalue('ObjectiveFunction', 'InputValue')
    return objective_function
res = differential_evolution(RunOnce, bounds = [(20,120),(-300,300)])
vpi.ptclmessage("Global optimization result:"+str(res.x))
}
```

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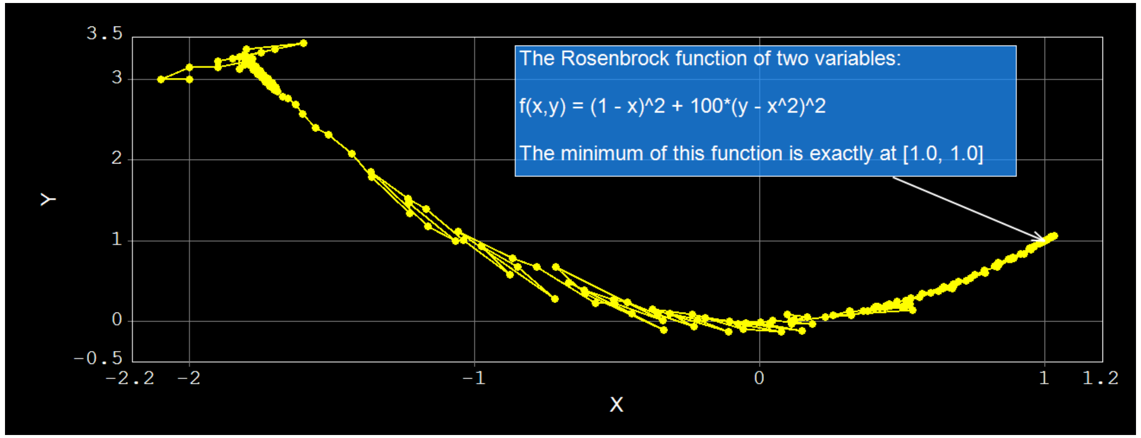
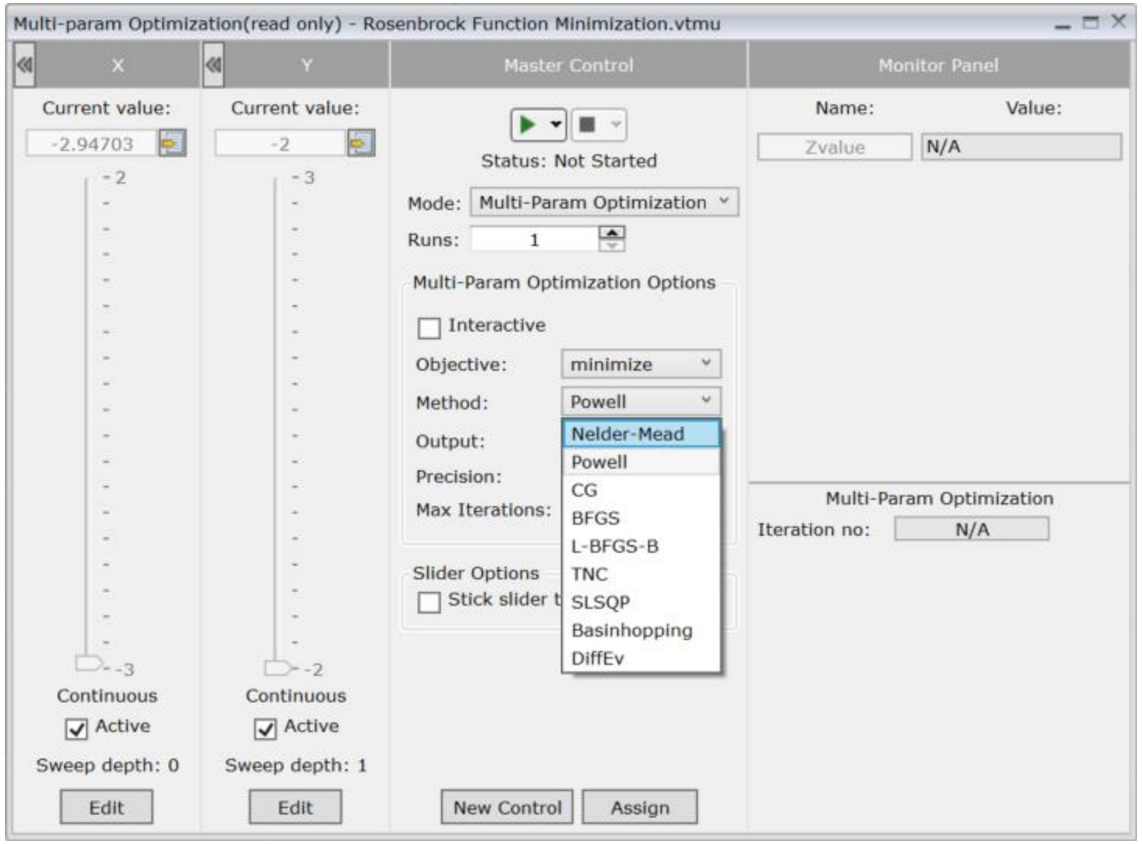
Multidimensional Optimizations

Automatic definition of the schematic parameters providing optimum performance of the design

- Commonly used optimization algorithms
- Control precision and maximum number of iterations





Design of Photonic Circuits using PDKs
Design Robustness & Sensitivity

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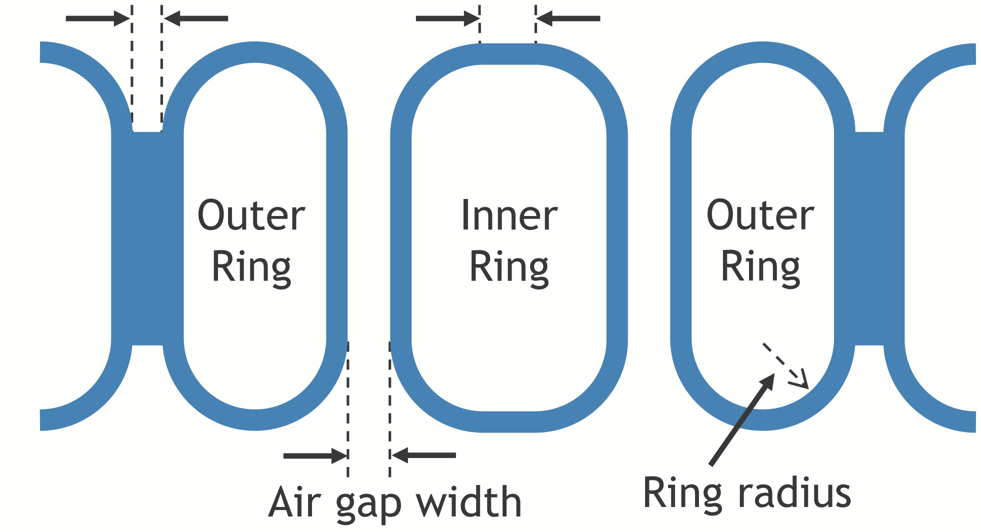
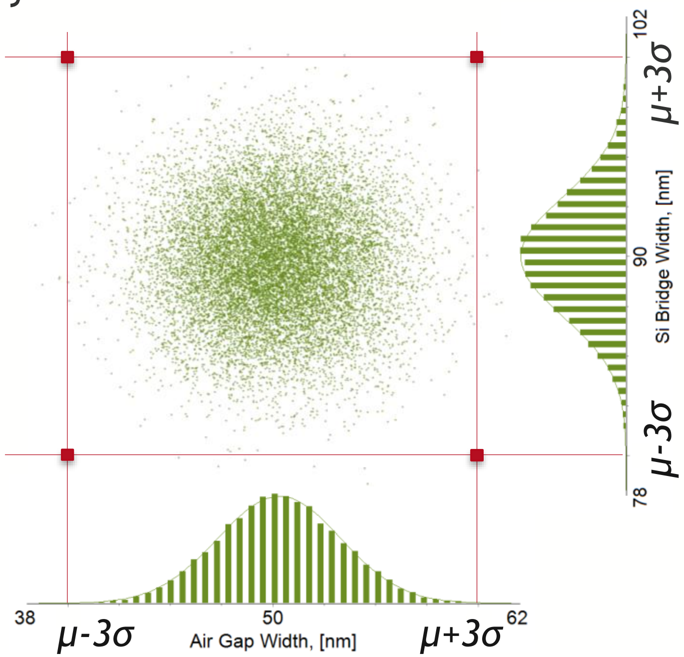


Find optimum circuit parameters that

- ✓ Meet design specifications (e.g. flat pass band, desired bandwidth, FSR)
- ✓ Provide min sensitivity to fabrication imperfections

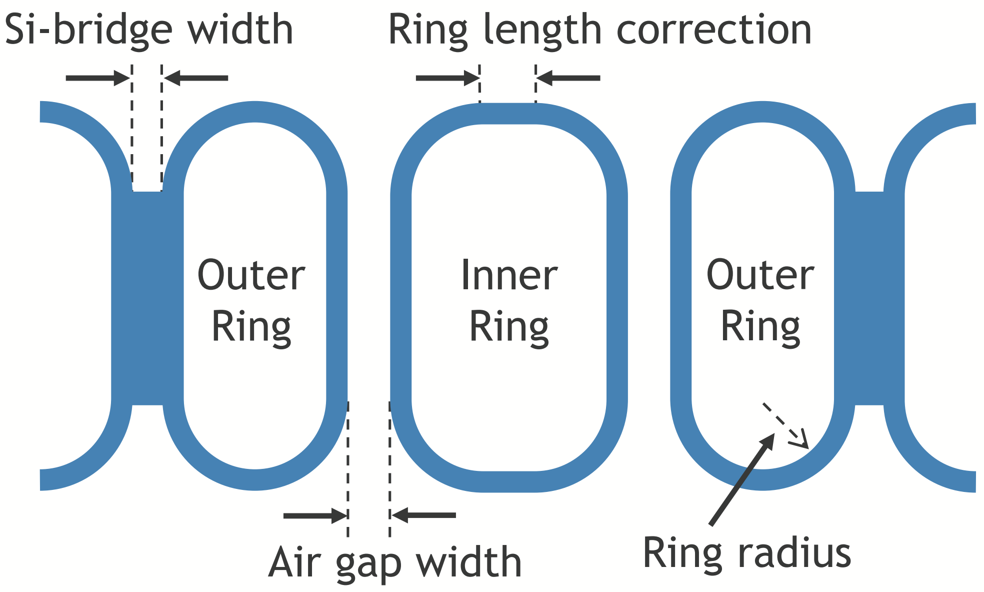
Corner Analysis



- ✓ Verify circuit robustness with comparatively small number of tests
- ✓ Verify that circuit performance characteristics falls within specification limits

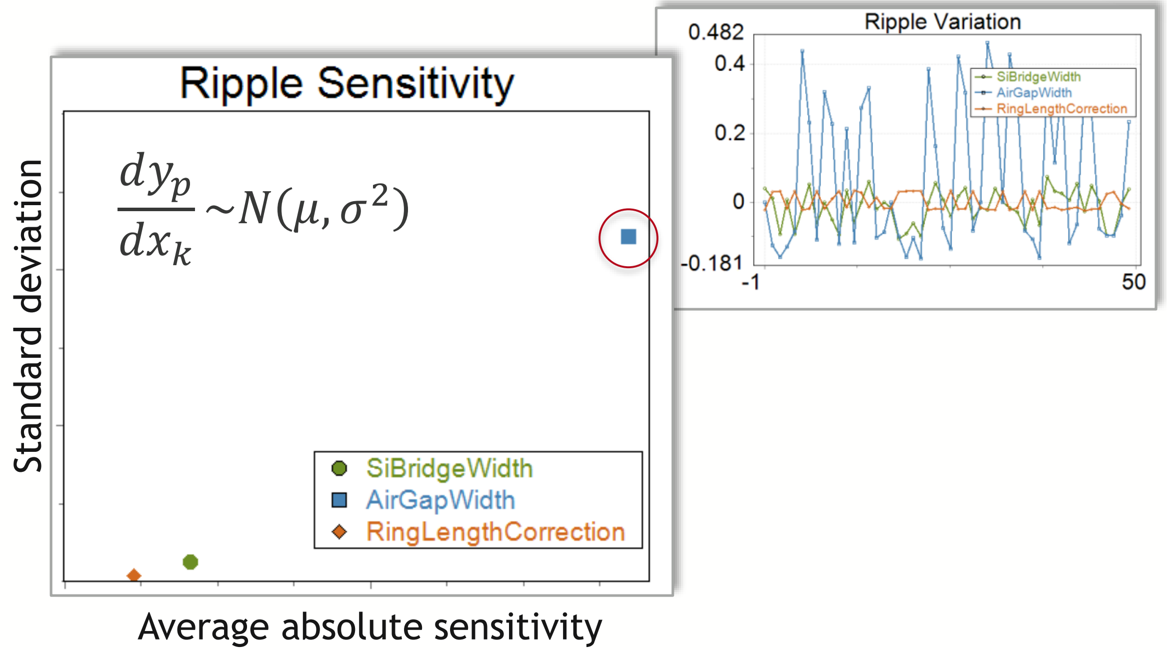
Design of Photonic Circuits using PDKs
Design Robustness & Sensitivity

Optimization of 3-Ring Filter



Find optimum circuit parameters that
- ✓ Meet design specifications (e.g. flat pass band, desired bandwidth, FSR)
- ✓ Provide min sensitivity to fabrication imperfections

Sensitivity Analysis

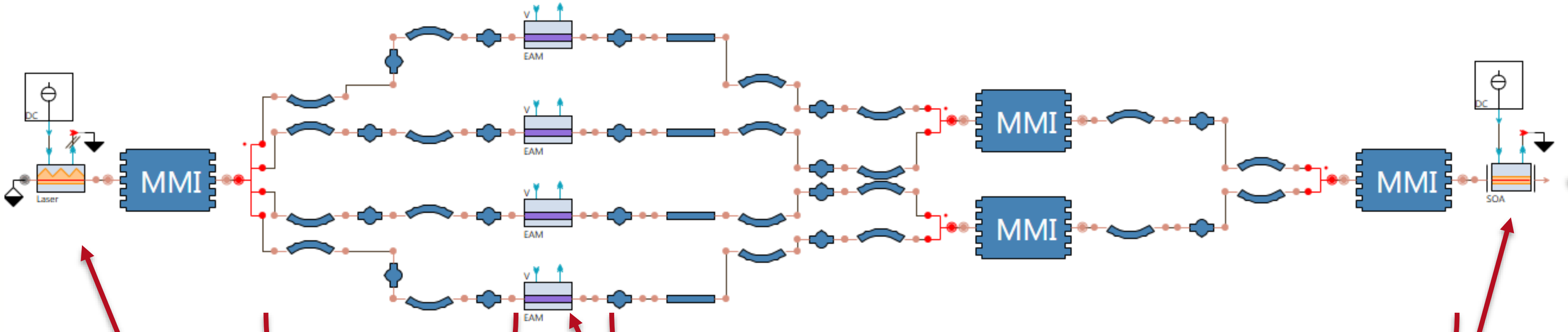


- ✓ Vary one parameter at a time (for different start conditions of other parameters)
- ✓ Determine its impact on circuit performance characteristics

System-level performance verification

Monolithic Integrated InP-based Tx & Rx

IQ Transmitter



Wavelength
Linewidth
Response to reflections
Carrier Dynamics

Mode
Loss
Length
Coupling

EA Characteristics
Response to reflections
Carrier Dynamics

Mode
Loss
Length
Coupling

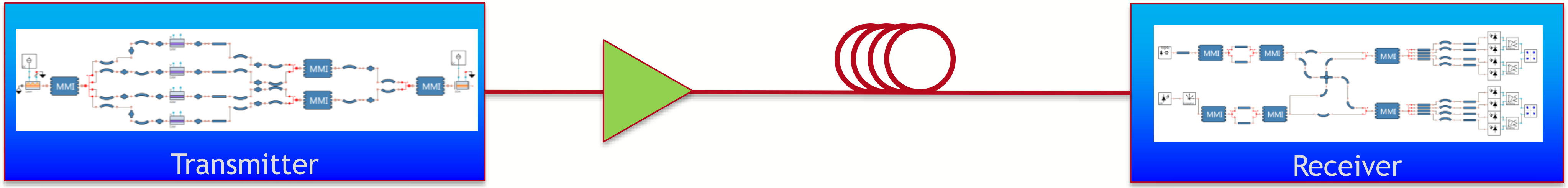
Gain Shape
Gain
Response to reflections
Carrier Dynamics

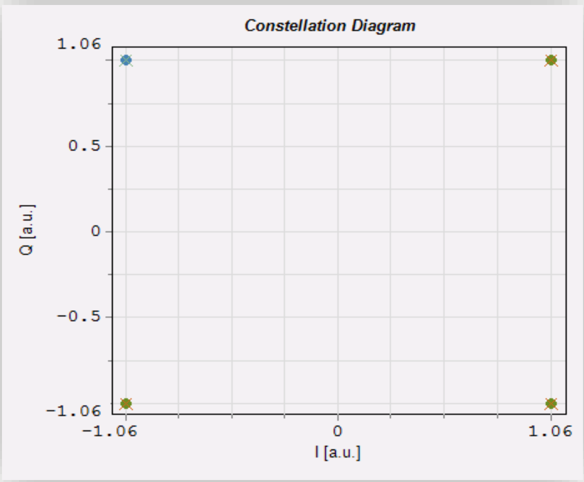
Subsystem Characteristics

System Characteristics

Pulse Shape
Chirp
OSNR
Phase Noise
Polarization Dynamics
…

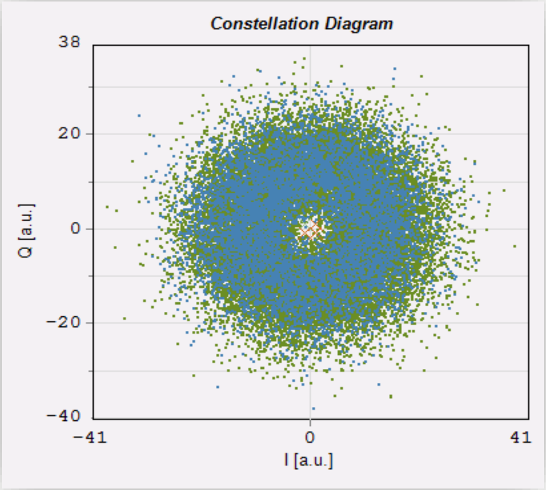
System Performance





EDFA
Gain
Noise

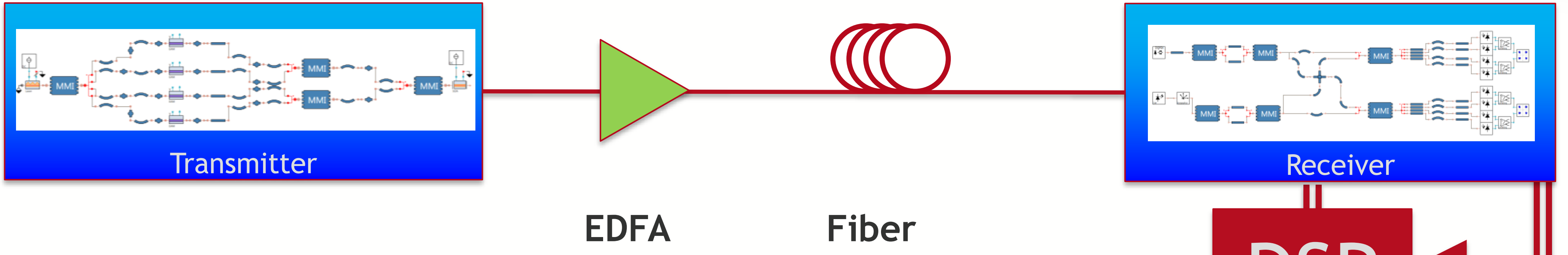
Fiber
Loss
Dispersion
Nonlinearities
PMD
.
.
.

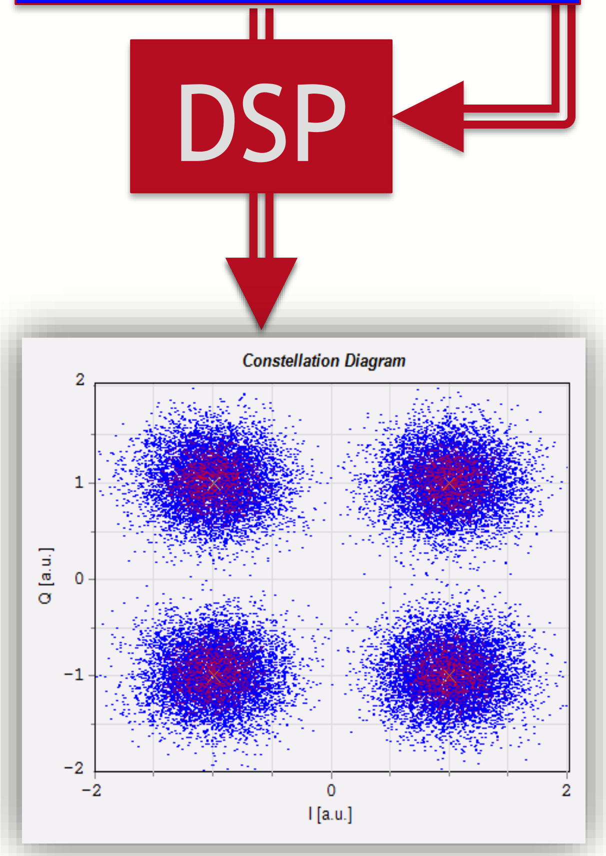


This tells us NOTHING about end to end performance

- The EDFA affects OSNR
- With the addition of fiber, things get interesting: Loss, Dispersion, SPM, XPM, FWM, Interaction of Noise and Signal

System Performance





DSP needed

- Dispersion
- LO Frequency Offset
- Phase Tracking
- Polarization Crosstalk
- Synchronization
- Filtering

Role of System Modeling

Use off-the-shelf components to perform the full system simulation for:

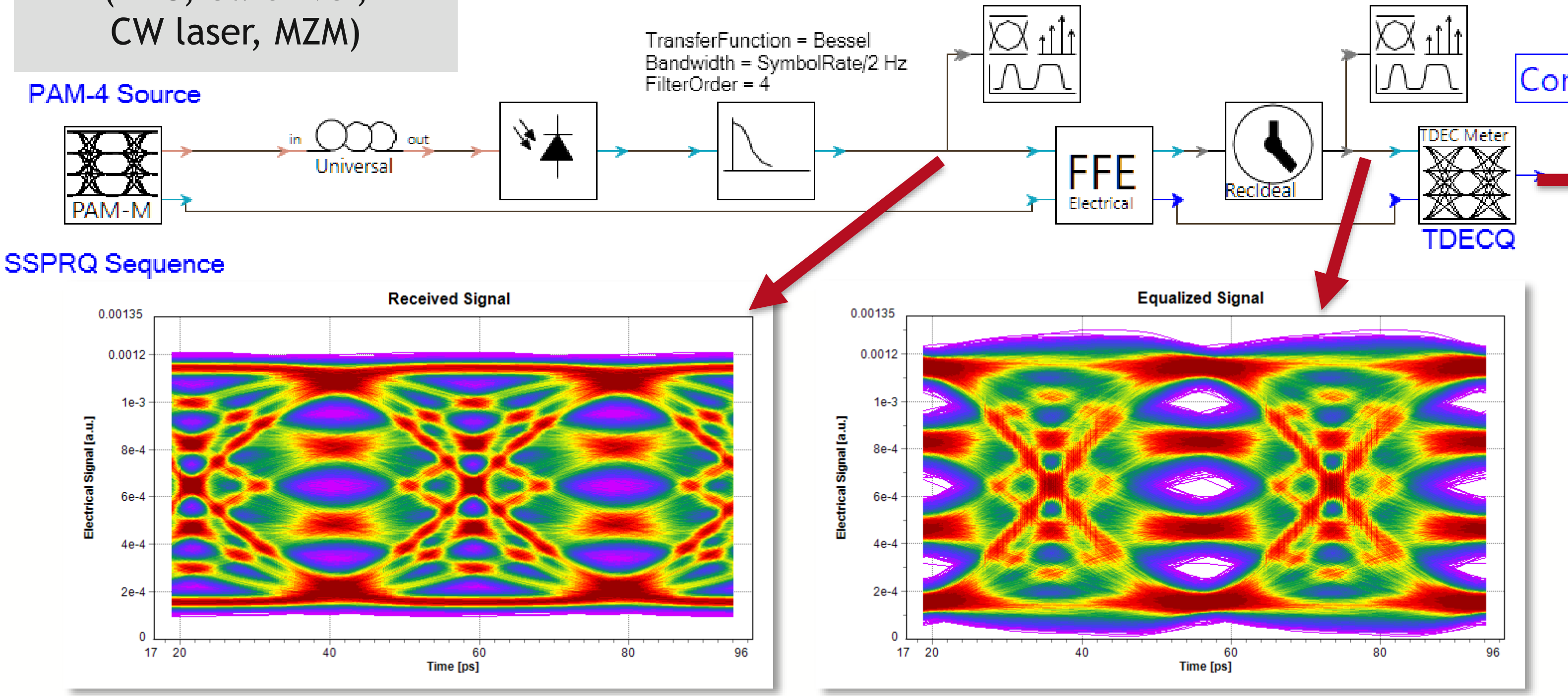
- Verification
- Benchmarking
- Yield estimate and sensitivity analysis
- Troubleshooting problems

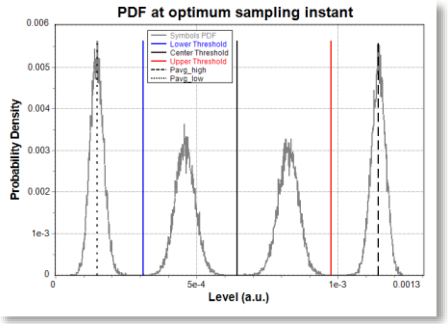
Design without system modeling is risky!

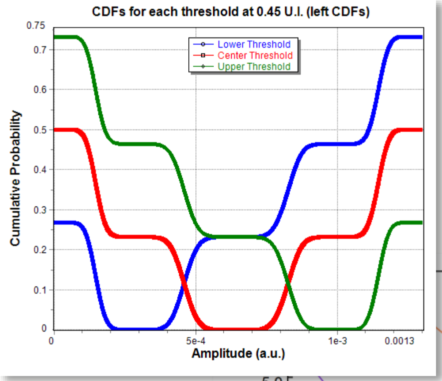
System Verification Example

PAM-4 Tx under Test
(DAC, el. driver,
CW laser, MZM)

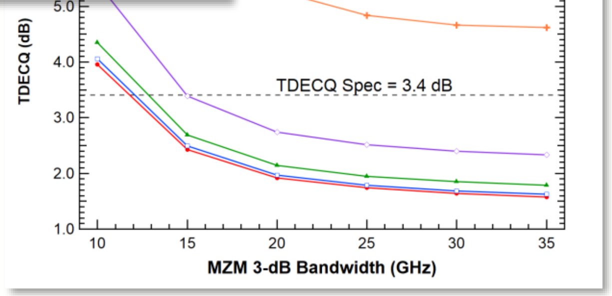
TDEC* Assessment of PAM-4 Transmitters







Visualization of performance characteristics



- Reference equalizer taps updated with MMSE criterion
- Calculates equalization noise enhancement factor
- OMA and thresholds can be determined automatically

* TDEC - Transmitter and Dispersion Eye Closure, defined in IEEE P802.3bs/D2.2 Draft Standard for Ethernet Amendment 10: Media Access Control Parameters, Physical Layers and Management Parameters for 200 Gb/s and 400 Gb/s Operation

Summary

- ✓ Accurate parametrized models of passive and optoelectronic components (including SOAs, DBR/DFB lasers and etc.)
- ✓ Multi-domain simulation engines
- ✓ Seamless integration of circuit and layout design tools with layout aware simulation
- ✓ Integration of circuit- and device-level simulations

→ Definition of PDK libraries with validated models for active and passive photonic circuits.

- ✓ Automated means for sweeps, optimizations, sensitivity analysis
- ✓ Scripting capabilities for automation of repeating tasks

→ Design for manufacturing: development of circuits resistance to device/circuit/system variation

- ✓ Integration of circuit- and system-level simulations

→ System verification and electronic-photonic synergy