SC454 Silicon Photonics Circuits and Systems Design

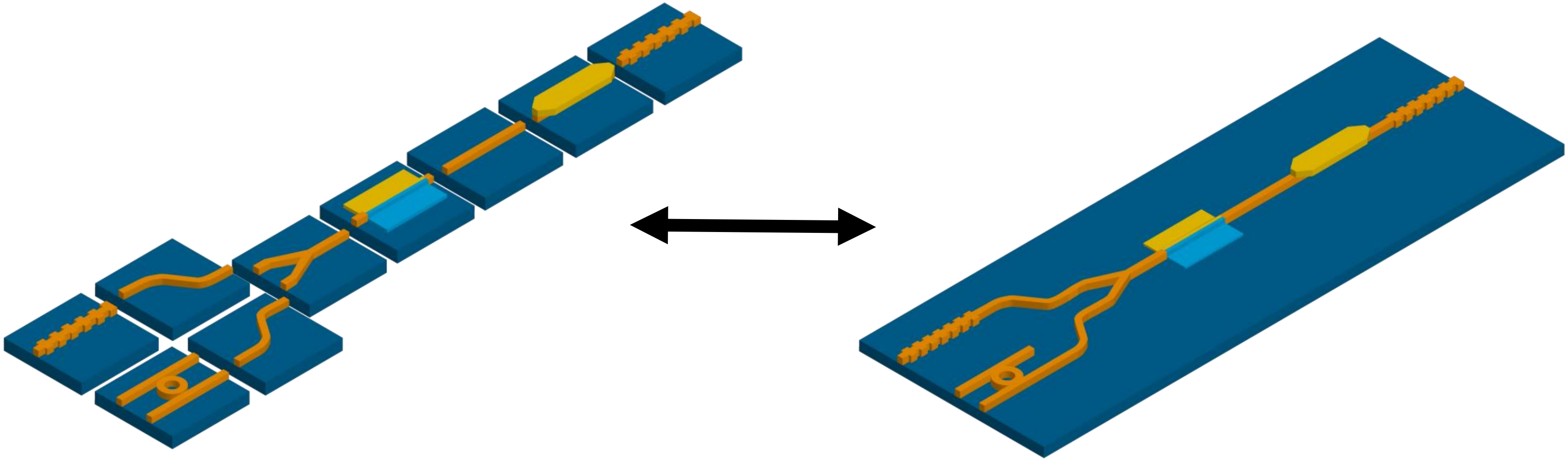
OFC SHORT COURSE MARCH – 20TH, 2017

INTERCONNECT

Photonic Integrated Circuit Simulator

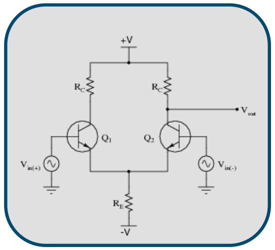
Photonic Circuit simulation

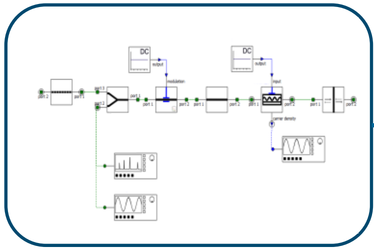
Circuit vs component



System modeling

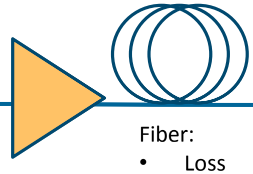
Transmitter





Electrical sub-circuit:
- Pre-emphasis
- Feedback loops
- D/A

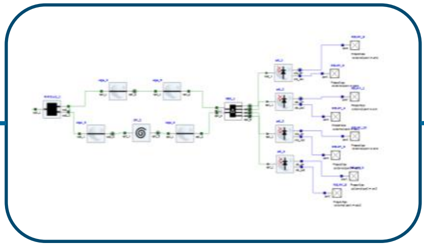
Optical sub-circuit:
- Wavelength
- Linewidth
- Reflections
- Carrier dynamics
- Mode
- Loss
- Coupling

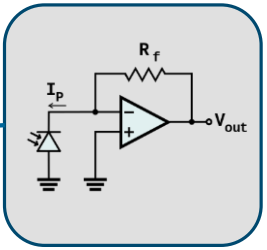


- Gain
- Noise

Fiber:
- Loss
- Dispersion
- Nonlinearities

Receiver





Optical sub-circuit:
- Wavelength
- Linewidth
- Reflections
- Carrier dynamics
- Mode
- Loss
- Coupling

Electrical sub-circuit:
- TIA
- Amplification
- A/D

Analysis:
- BER
- Loss
- Dispersion
- Phase noise
- Chirp
- Polarization dynamics
- Inter-symbol interference
- Duty cycle distortion)
- Interaction of Noise and Signal

DSP
- Equalization (FFE / DEF
- Dispersion compensation
- LO Frequency Offset
- Phase Tracking
- Polarization crosstalk
- Synchronization
- Filtering

Modelling of PICs

PIC simulation needs to support:

- Frequency domain simulation, e.g. transmission spectrum, IL, …
- Time domain simulation, e.g. BER, …

The optical signal:

- Bidirectional propagation (reflections!) and phase sensitivity
- Multi-mode (more than one optical mode supported in waveguides)
- Multiple frequency bands

Compact models calibrated to fabrication processes

Many applications further require:

- Interoperable with electronic simulation
  - … and also thermal
- Digital signal processing
- Optimization / analysis framework
- Interoperable with SDL (larger design framework including layout)

INTERCONNECT

Photonic Integrated Circuit (PIC) design software for

- Integrated circuits
- Silicon photonics components
- System Simulation

Supports

- Time domain analysis with dynamic data flow simulator (DDF)
- Block mode (coming soon)
- Frequency domain analysis with scattering data analyzer (SDA)

INTERCONNECT Key Features

Hierarchical Schematic Editor

- GUI and Scripted Design Interface

Extensive Element Library

- Passive and active optoelectronic building blocks
- Optical sources and measurement elements

EDA and PDA Interoperability

- Design and simulate integrated photonics within familiar EDA design tools
  - Cadence Virtuoso
  - PhoeniX OptoDesigner
  - Mentor Graphics Pyxis
  - KLayout

Circuit Solver

- Time & Frequency domain analysis
- Bidirectional signal propagation
- Multimode & Multichannel support
- SPICE interface

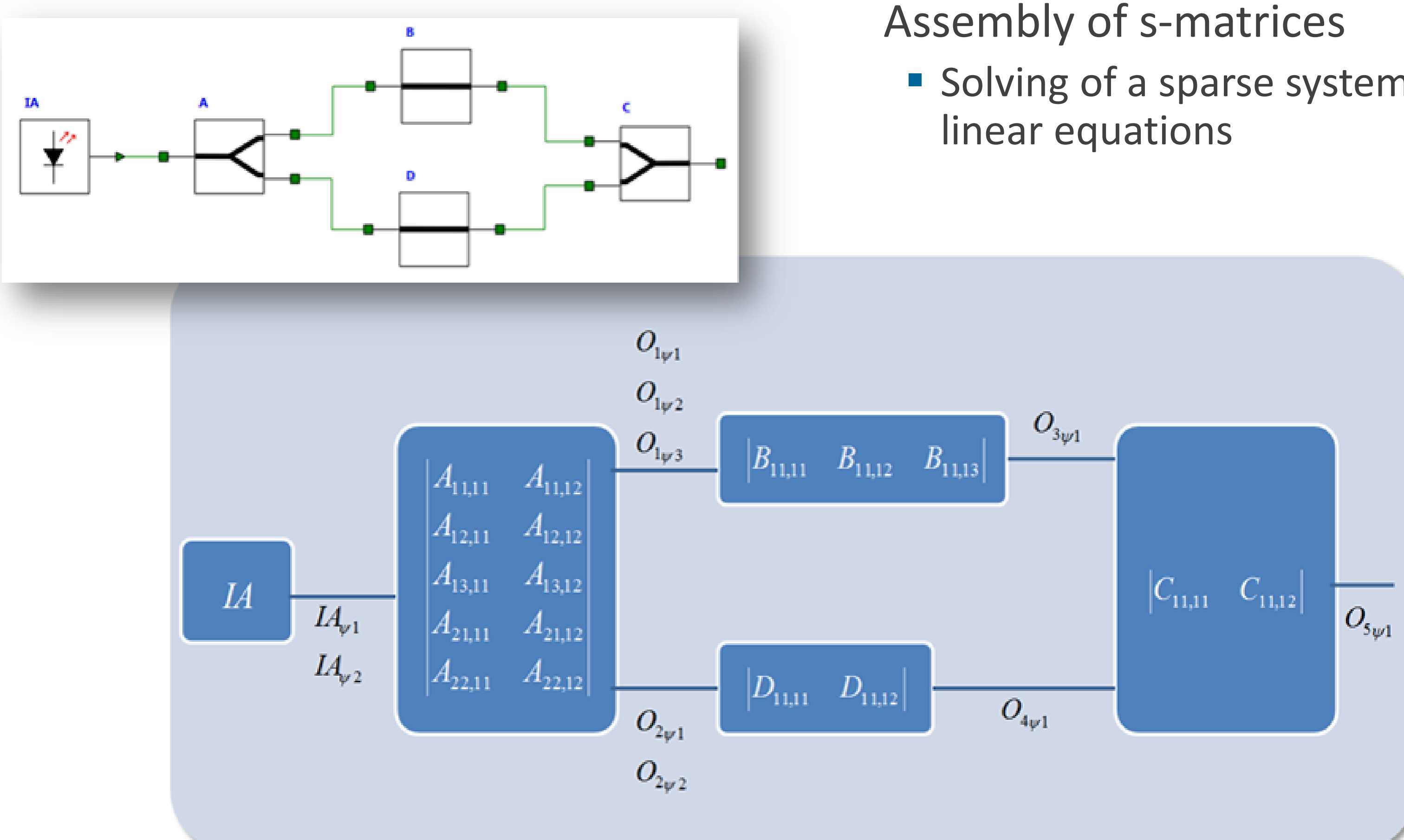
Visualization and Data Analysis

- Optimization Framework
- Statistical and yield analysis

Compact Model Generation & Management

- Import parameters from component design tools & measurements
- Manage library distribution
- Import foundry calibrated model libraries

Frequency analysis

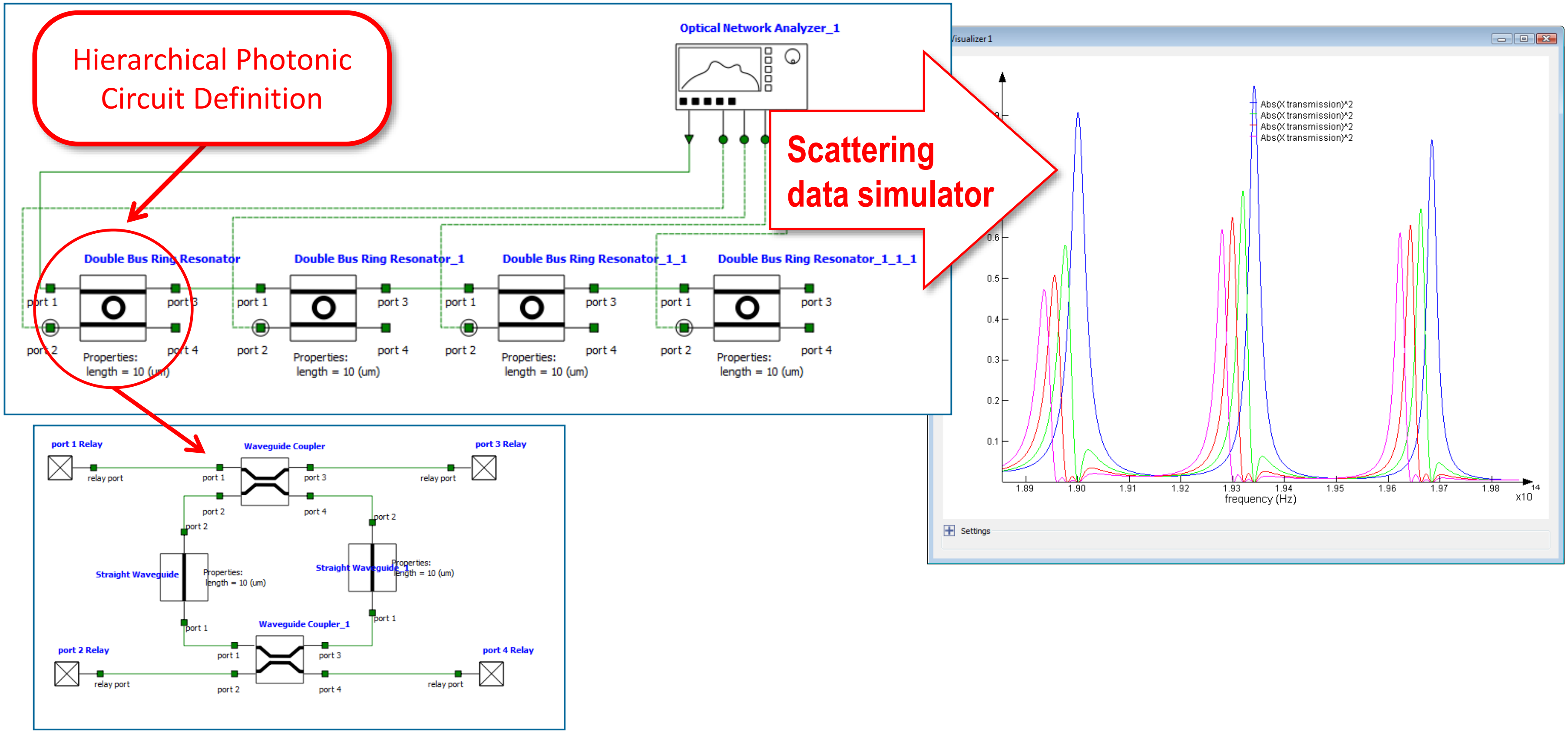


Assembly of s-matrices

- Solving of a sparse system of linear equations

Frequency analysis

Transmission spectrum



Dynamic Data Flow Scheduler (DDF)

Time domain: sampled mode signal representation

For active / dynamically tunable devices time domain sample by sample is required

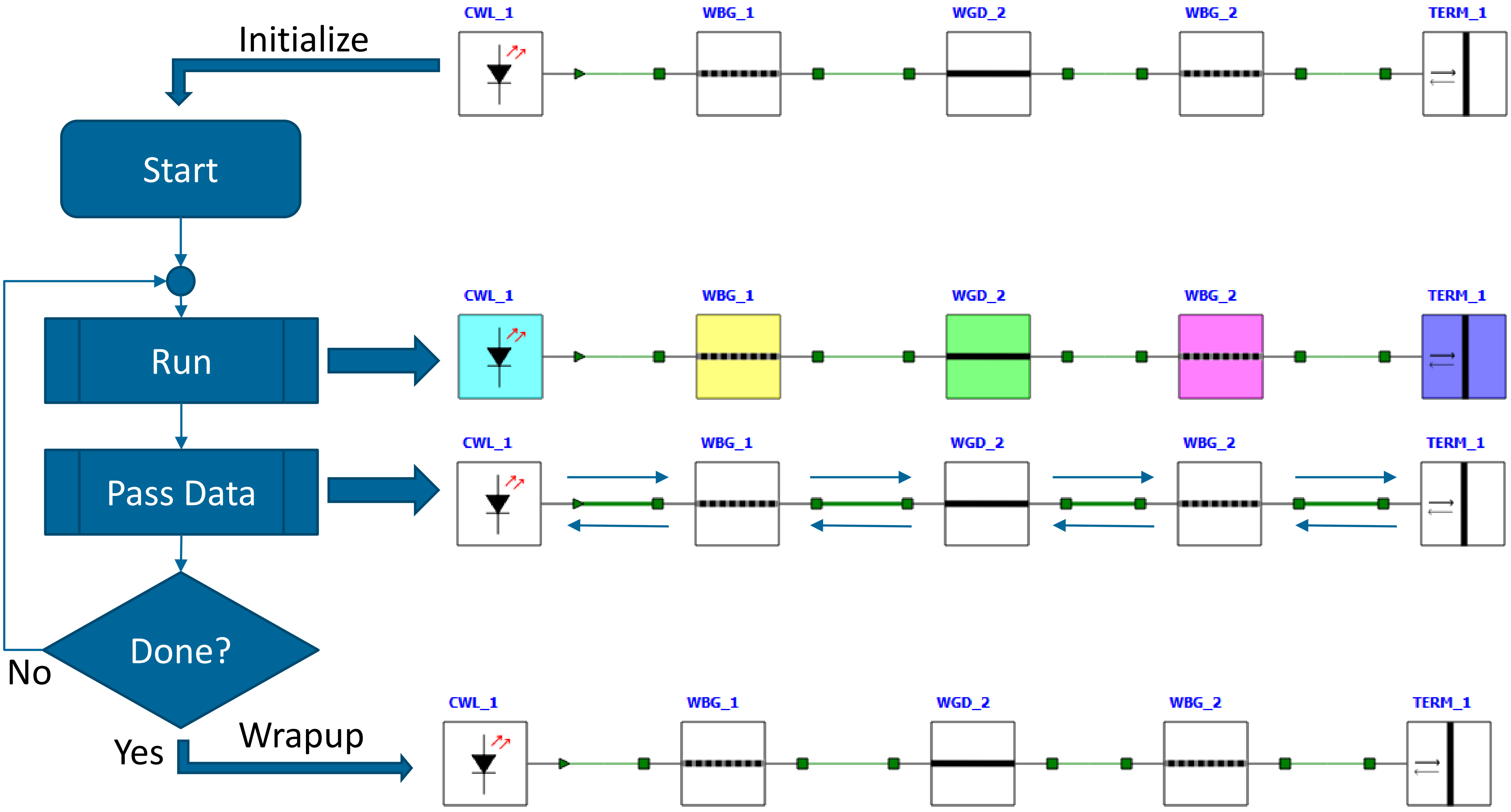
Data is passed between element one sample at a time (iteration by iteration) - complex-envelope baseband transformation

- Optical Sample: complex envelope of a time domain optical signal, where the signal is modeled relative to the center frequency, and the sampling frequency only needs to accommodate the frequency band of interest.
- Electrical/Digital Sample: real amplitude of time domain signal

Block Mode (System Simulations)

- Considers mainly unidirectional iteration between elements
- Data is passed between element one block or waveform at a time (iteration by iteration)

Tutorial 2 – Dynamic Data Flow

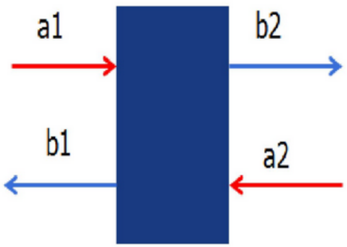


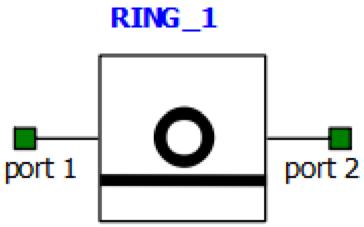
Frequency domain models

Photonic building blocks (or models) can be considered as black boxes with N ports and are completely characterized by a scattering matrix (S-Matrix)

- An S-Matrix of a device with N bidirectional ports consists of 2Nx2N matrix of complex-valued frequency-dependent transfer functions

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11}(f) & S_{12}(f) \\ S_{21}(f) & S_{22}(f) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$





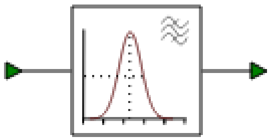
- Each transfer function relates complex amplitude of optical signal carried by a guided mode travelling towards and away from the device port
- S-parameters can be voltage dependent (or other input parameters)

Digital Filters

For time domain simulations, the frequency dependent elements rely on either IIR or FIR digital filters.

FIR filters can provide much better frequency responses provided the signal is composed of tones that fall exactly on the frequencies corresponding to the FIR taps.

Example: Gaussian filter and S-parameter elements rely on FIR digital filters.

$x(n)$ 

$$y(n) = \sum_{k=0}^{M-1} b_k . x(n-k)$$

Where b_k are the filter tap coefficients

The filter transfer function in z-domain:

$$H(z) = \sum_{k=0}^{M-1} b_k . z^{-k}$$

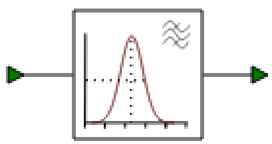
FIR filters introduce extra *M* delays, adding a constant group delay to the signal path.

Digital Filters

IIR filters provide a better overall response for arbitrary signals, though this is not guaranteed.

Example: Bessel, Butterworth Chebyshev filter elements rely on IIR digital filters.

$x(n)$



$$y(n) = -\sum_{k=1}^{N} a_k . y(n-k) \sum_{k=0}^{M} b_k . x(n-k)$$

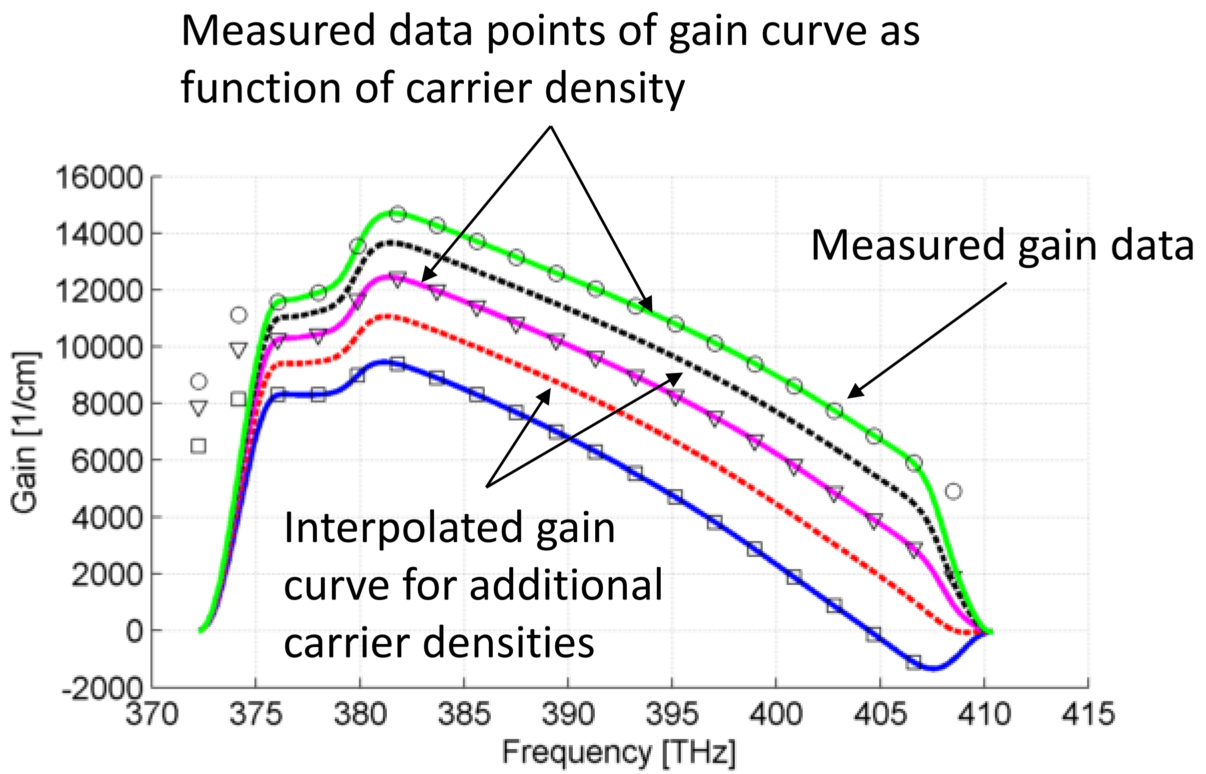
Where b_k are the filter tap coefficients, and a_k the feedback coefficients

The filter transfer function in z-domain:

$$H(z) = \frac{\sum_{k=0}^{M} b_k . z^{-k}}{1 + \sum_{k=1}^{N} a_k . z^{-k}}$$

IIR filter

Automatic gain fitting using IIR filter

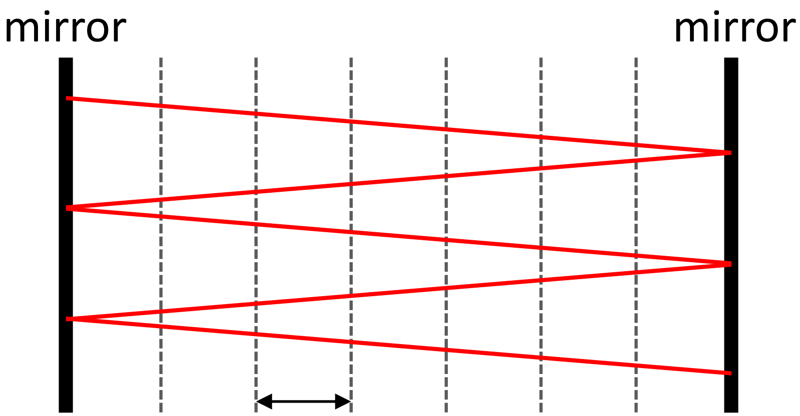


Time & Space Discretization

Time discretization: $t \rightarrow t_n = n\Delta t$, with $f_s = \dfrac{1}{\Delta t}$ (f_s : sampling rate)

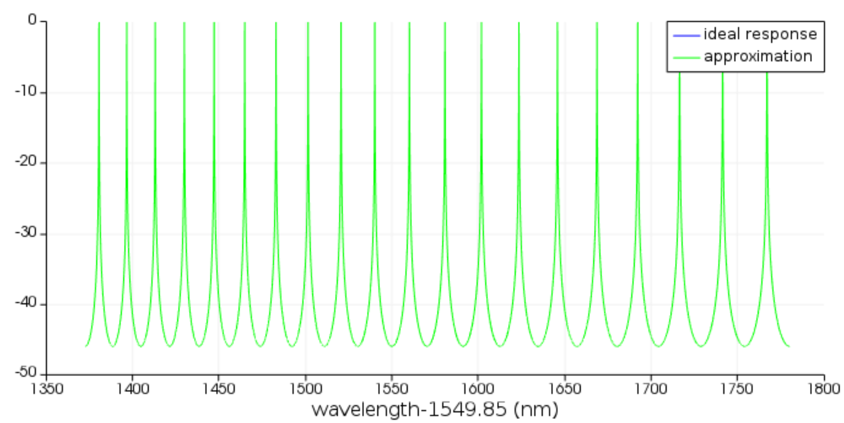
Consider the case of a Fabry- Perot cavity:

- The time step Δt is given by the simulation band width f_s



$$\Delta z = \frac{c\Delta t}{n_g}$$

For a single device section, the simulation bandwidth, f_s, can be adjusted so that the length of an element (e.g. waveguide) is a multiple of the group delay.

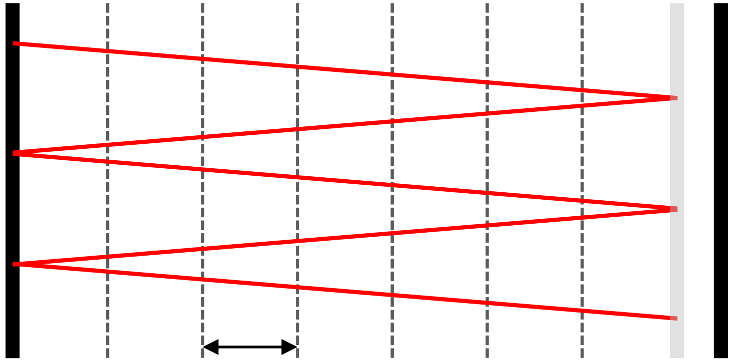


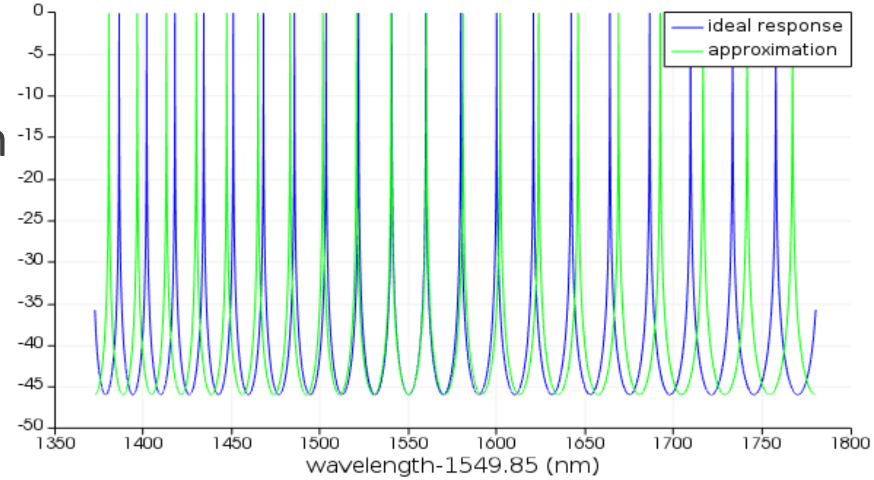
Time & Space Discretization

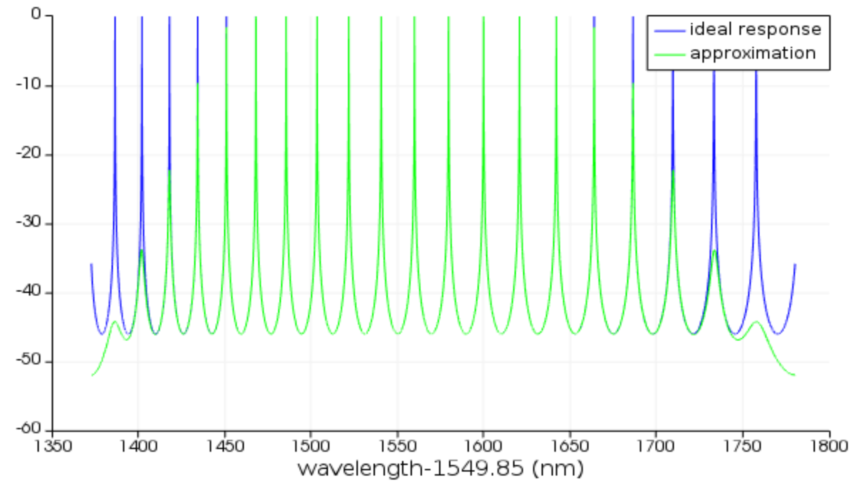
Time Resolution: Δt ~ 100 fs -1 ps

-> Spatial Resolution: Δz ~ 10 - 100 um

The group delay is not a multiple of the time step anymore:







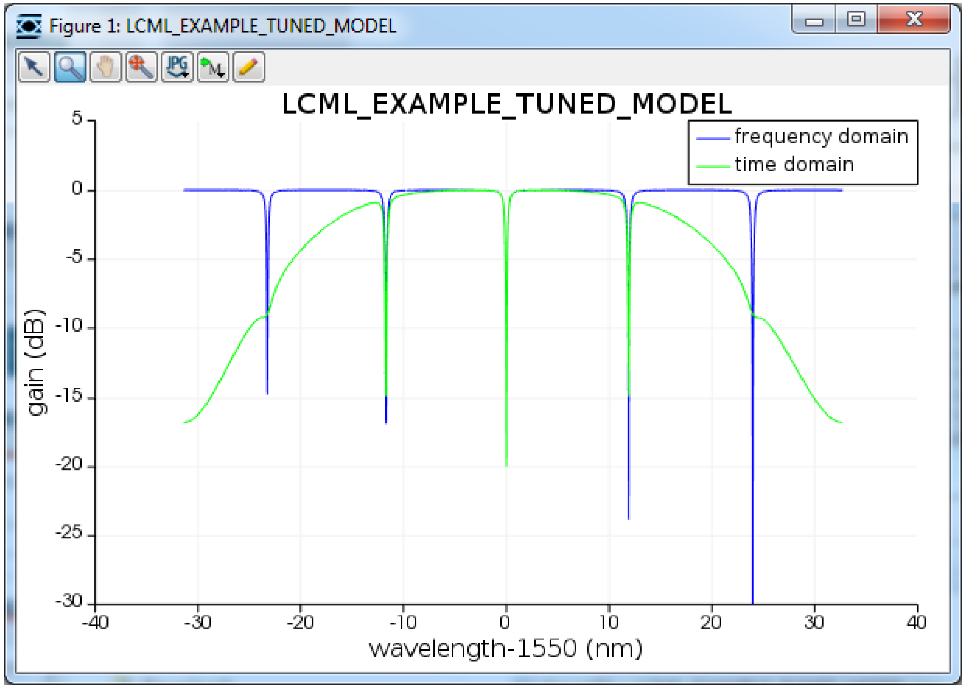
- Increase sampling rate (reduce time step)

-> Apply fractional delay

Accuracy limitations

Accuracy of FIR solution degrades at the edges of the simulation frequency band

Errors are significant as the number of elements increases.



Model generation

Start from standard set of generic models (example single bus ring modulator)

→ Collect foundry/process specific “design intent” parameters + physical parameters that are required to define the model

→ Calibration algorithm optimizes “design intent” parameters to be within acceptance range

→ Calibrated model parameters for specific foundry/process

Comments on the model definition

Design parameters / layout parameters: Mask design and material system choice

- Geometry (width, height, gap, radius, doping mask)
- Material properties
- Fabrication (doping profiles)

-> effective index, group index, loss, coupling coefficients

VS

“design intent” parameters: parameters we can measure and have statistical data on

- Free spectral range and resonance location
- Quality factor
- Modulation efficiency

Summary

Integrated photonic circuit simulation requires:

- Advanced hierarchical design capture capabilities / interoperability
- Support for both time and frequency domain simulation
- Advanced models for optoelectronic devices
  - Automatic conversion between time and frequency domain models
  - Need for calibrated models (for a specific foundry fab)
  - Statistical model performance
- Calibration algorithms to match fabricated device performance based on
  - Measurement
  - Simulation
- Convenient means for design automation

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