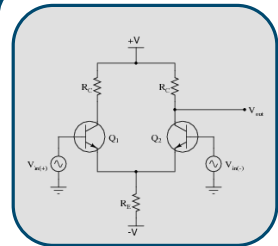
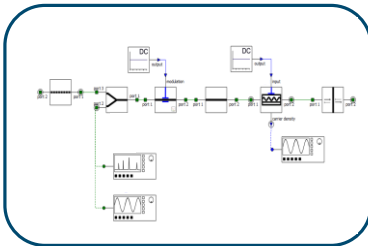


Transmitter



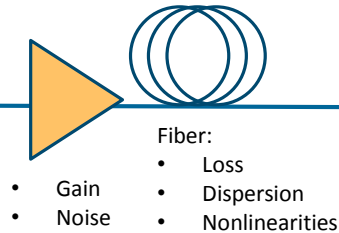
Electrical sub-circuit:

- Pre-emphasis
- Feedback loops
- D/A



Optical sub-circuit:

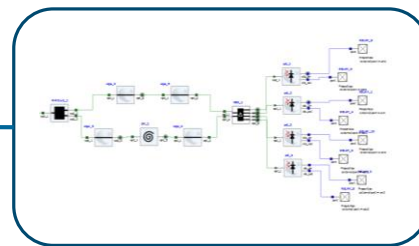
- Wavelength
- Linewidth
- Reflections
- Carrier dynamics
- Mode
- Loss
- Coupling



Analysis:

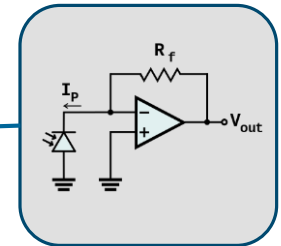
- BER
- Loss
- Dispersion
- Phase noise
- Chirp
- Polarization dynamics
- Inter-symbol interference
- Duty cycle distortion)
- Interaction of Noise and Signal

Receiver



Optical sub-circuit:

- Wavelength
- Linewidth
- Reflections
- Carrier dynamics
- Mode
- Loss
- Coupling



Electrical sub-circuit:

- TIA
- Amplification
- A/D

DSP

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

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)

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)

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

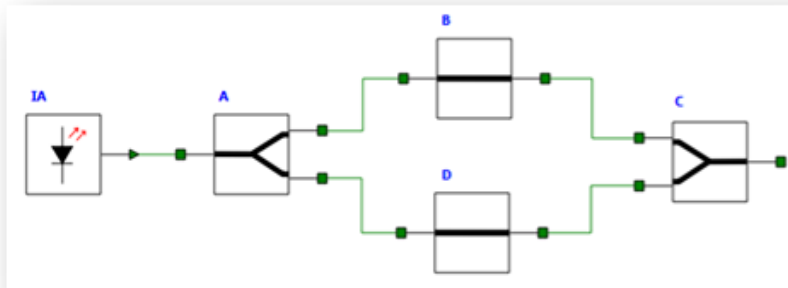
- Time & Frequency domain analysis
- Bidirectional signal propagation
- Multimode & Multichannel support
- SPICE interface

Visualization and Data Analysis

- Optimization Framework
- Statistical and yield analysis

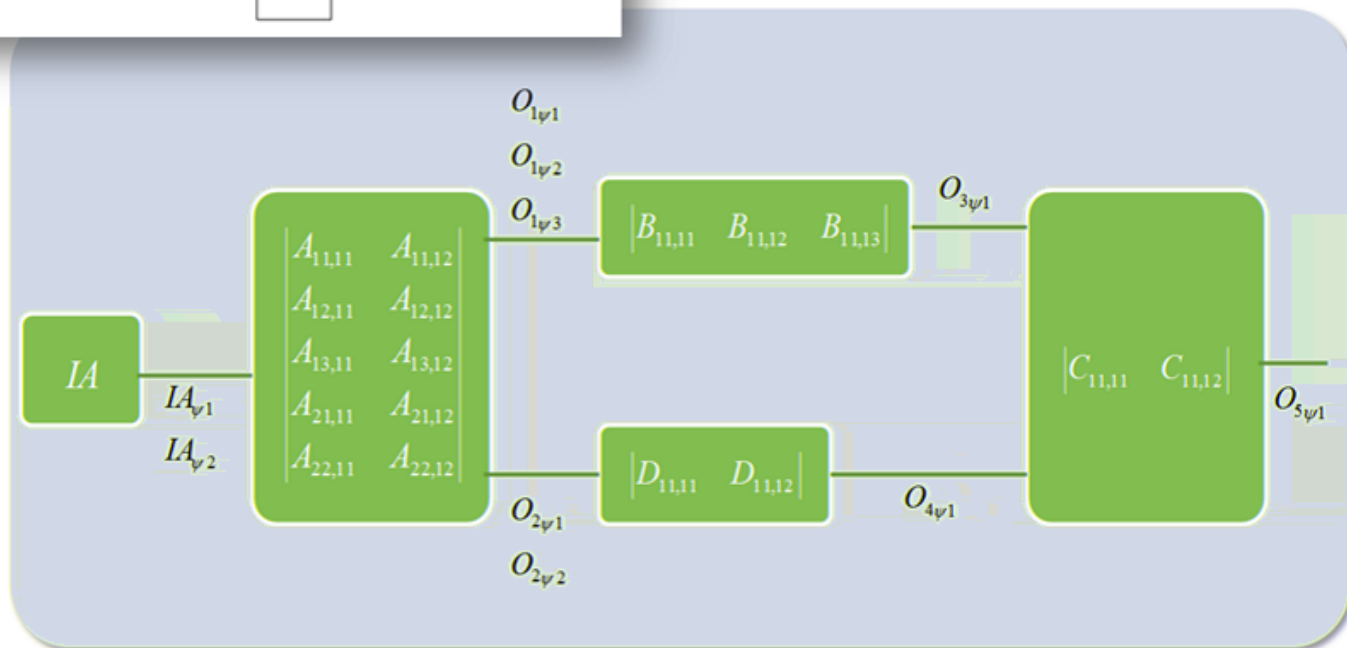
Compact Model Generation & Management

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

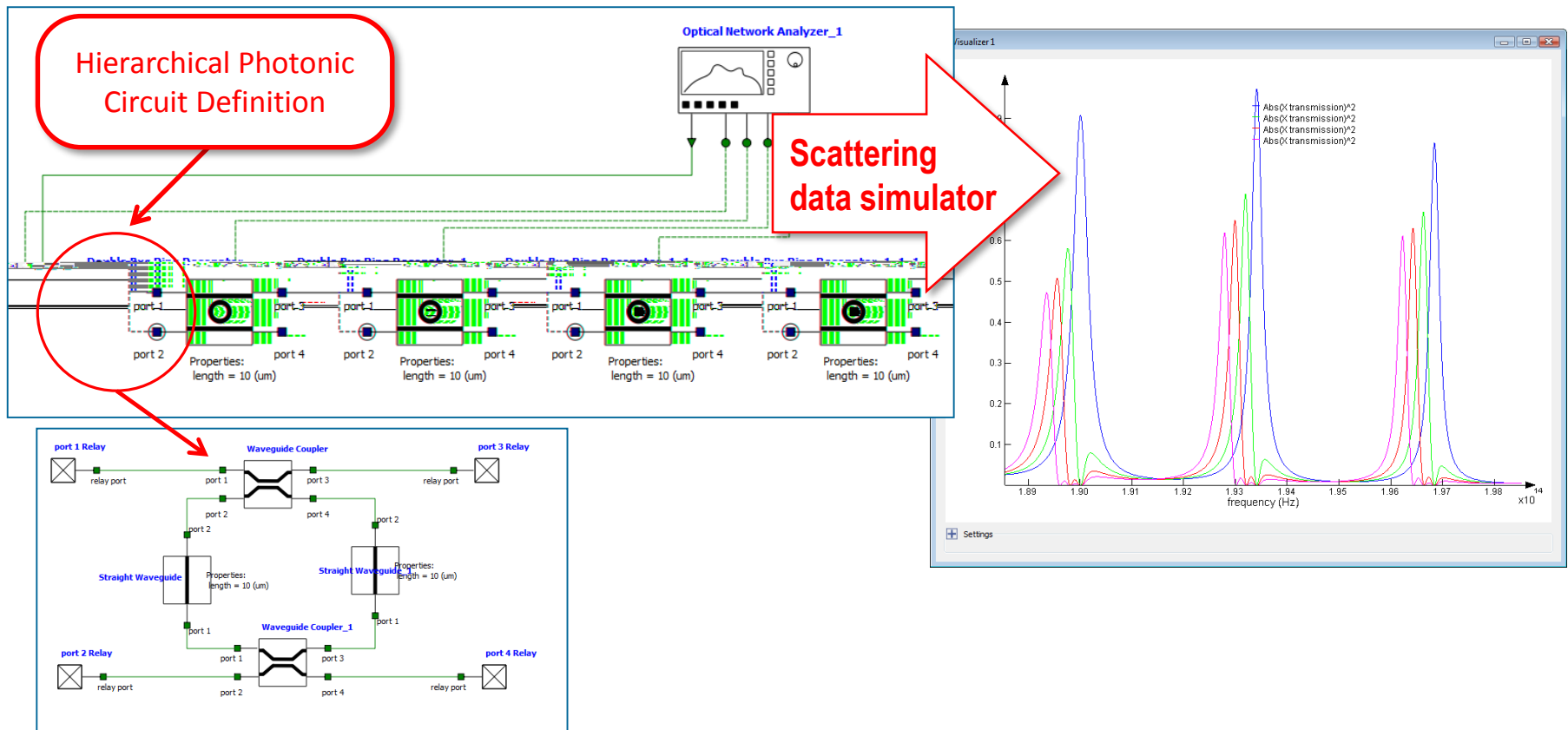


Assembly of s-matrices

- Solving of a sparse system of linear equations



Transmission spectrum



Time domain: sampled mode signal representation

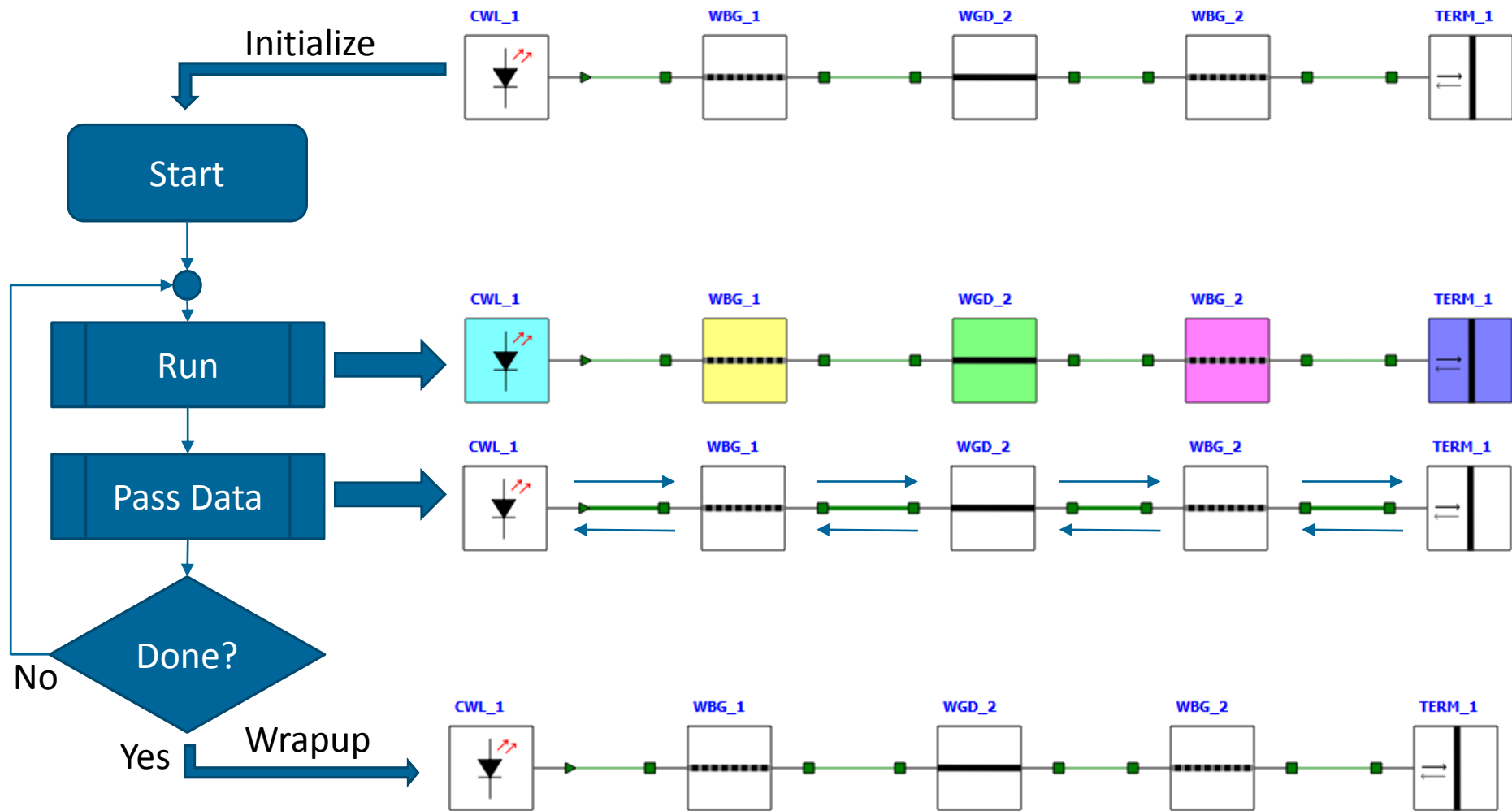
For active / dynamically tunable devices time domain sample by sample is required

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)

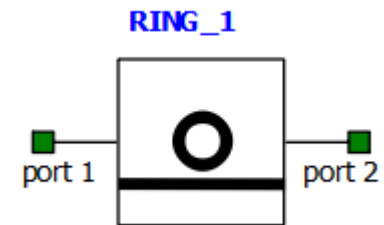
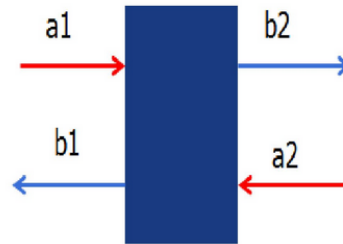
- Considers mainly unidirectional iteration between elements
- Data is passed between element one block or waveform at a time (iteration by iteration)



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 $2N \times 2N$ 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)

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.

$$x(n) \rightarrow \boxed{\text{Gaussian Filter}} \rightarrow y(n) = \sum_{k=0}^{M-1} b_k \cdot x(n - k)$$

Where b_k are the filter tap coefficients

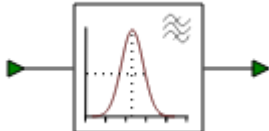
The filter transfer function in z-domain:

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

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

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.

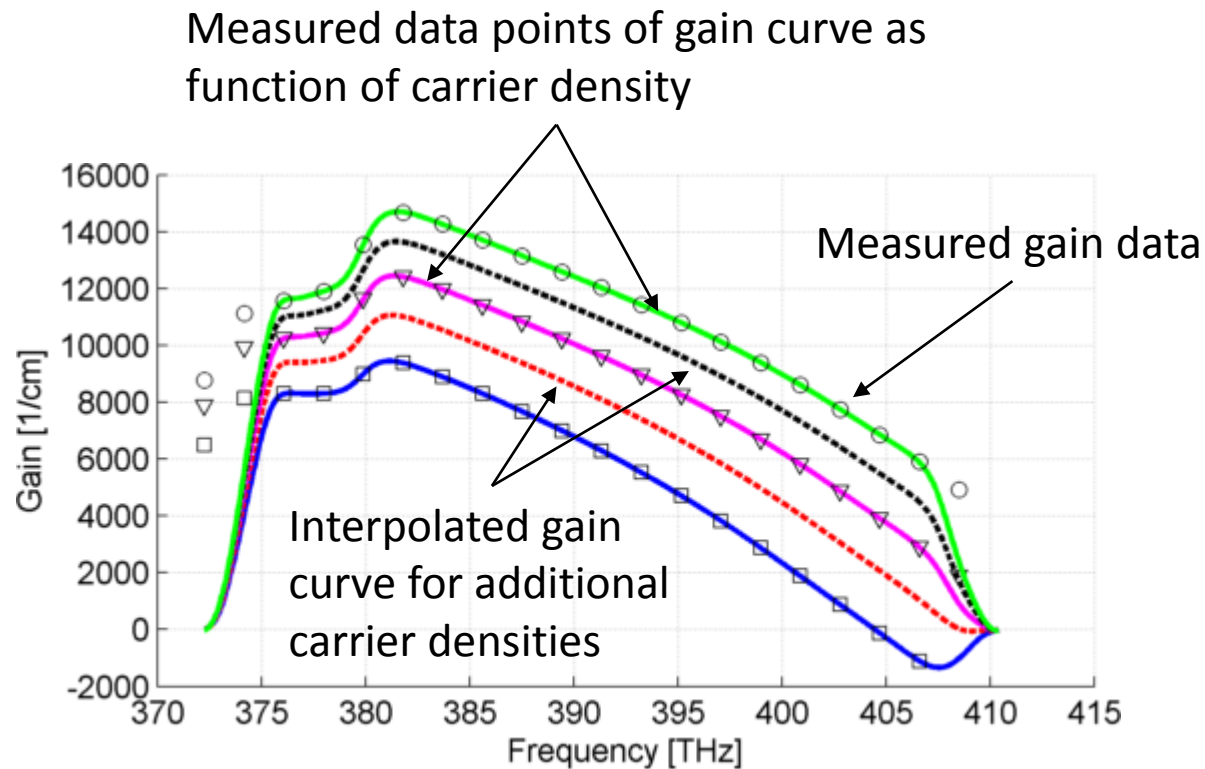
$x(n)$  $y(n) = - \sum_{k=1}^N a_k \cdot y(n-k) + \sum_{k=0}^M b_k \cdot x(n-k)$

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

The filter transfer function in z-domain:

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

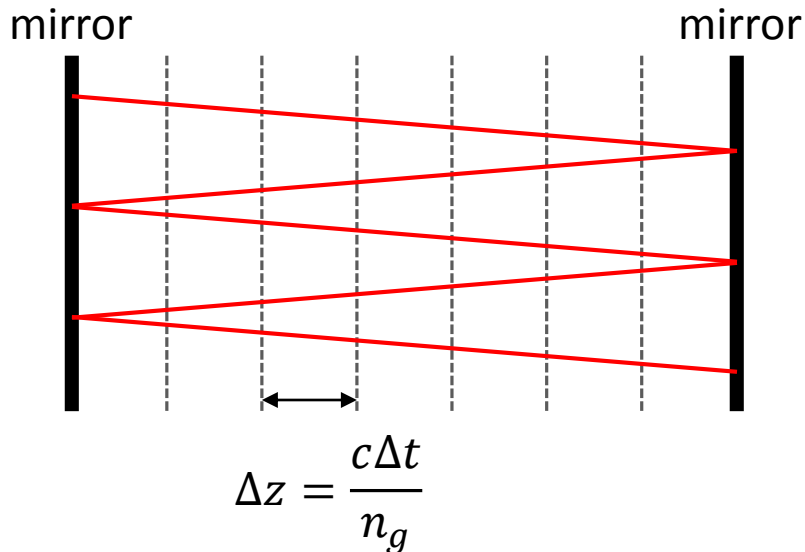
Automatic gain fitting using IIR filter



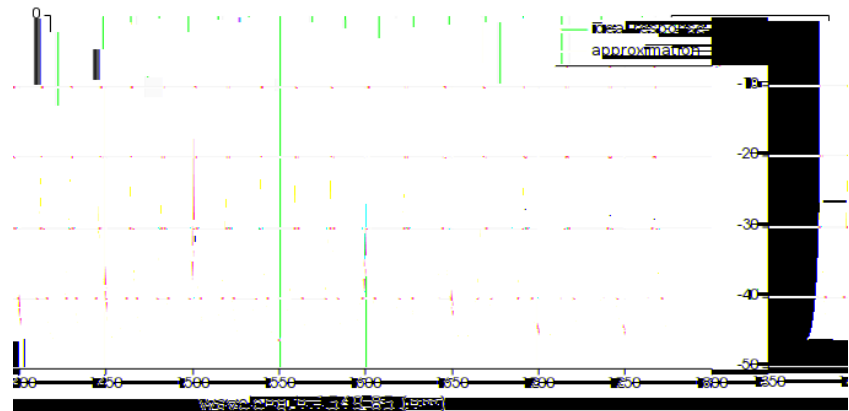
Time discretization: $t \rightarrow t_n = n\Delta t$, with $f_s = \frac{1}{\Delta t}$ (f_s : sampling rate)

Consider the case of a Fabry- Perot cavity:

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



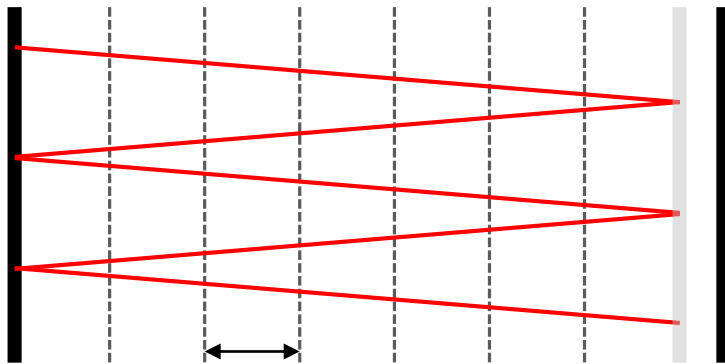
For a single device section, the simulation bandwidth, f_s , can be adjusted so that the length of an element (e.g. waveguide) is a multiple of the group delay.



Time Resolution: $\Delta t \sim 100 \text{ fs} - 1 \text{ ps}$

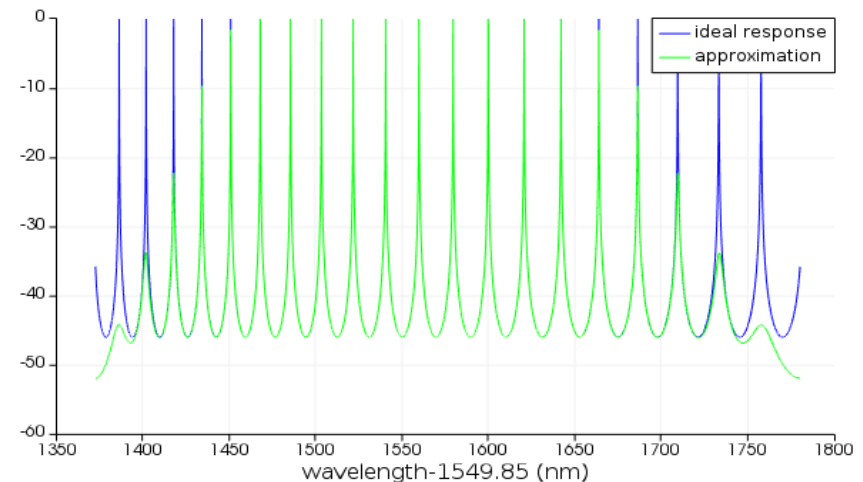
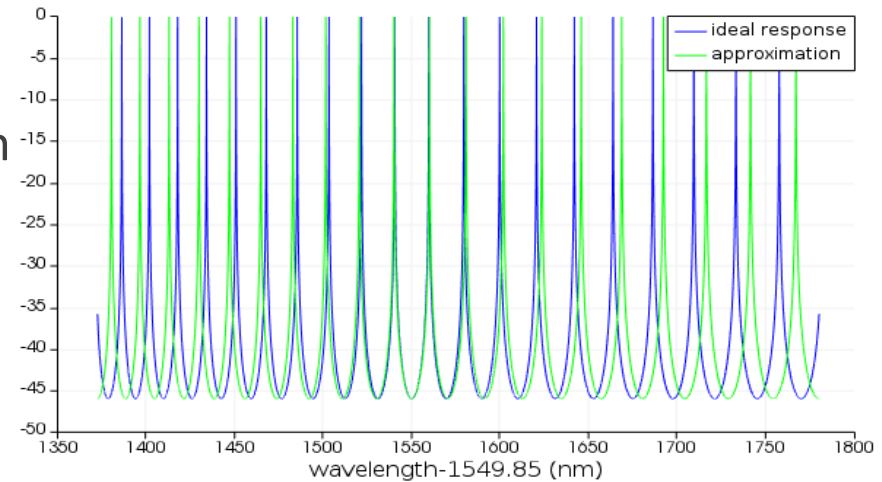
-> Spatial Resolution: $\Delta z \sim 10 - 100 \text{ } \mu\text{m}$

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



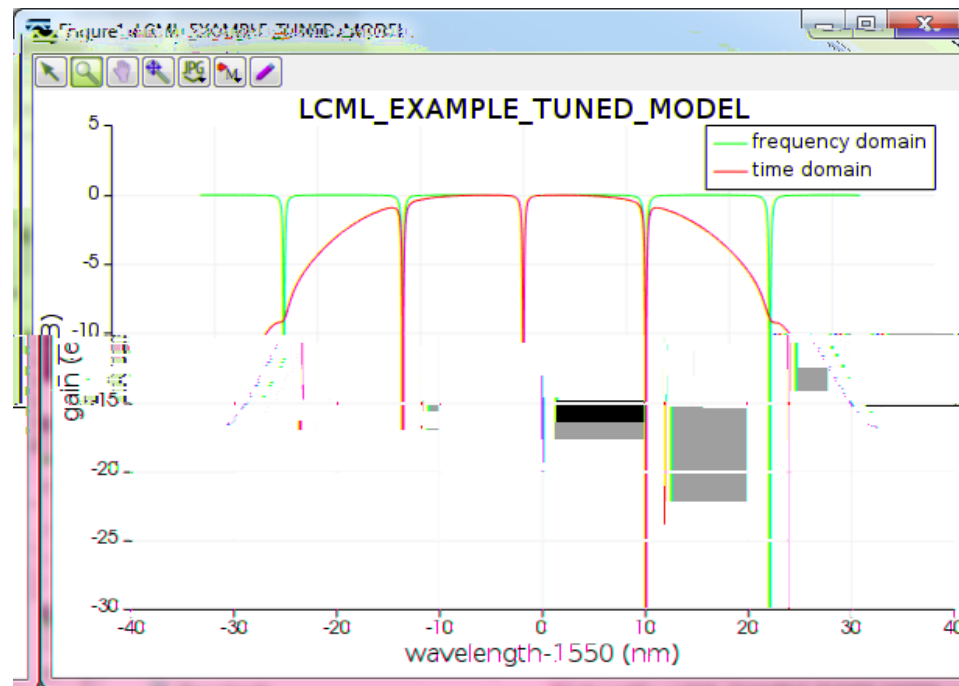
- Increase sampling rate (reduce time step)

-> Apply fractional delay



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

Errors are significant as the number of elements increases.



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

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

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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