Waveguide Bragg Gratings and Resonators

JUNE 2016

© LUMERICAL SOLUTIONS INC

Outline

Introduction

Waveguide Bragg gratings

- Background
- Simulation challenges and solutions
- Photolithography simulation

Initial design with FDTD

- Band structure calculation and effect of geometric parameters

Simulation of the full device using EME

- Waveguide Bragg grating
- Phase shifted Bragg grating

Circuit simulations with INTERCONNECT

- Compact model for WBG
- Hybrid laser

Summary and Q/A

© LUMERICAL SOLUTIONS INC

Lumerical Products

Optical Simulation

FDTD Solutions
NANOPHOTONIC SOLVER (2D/3D)

MODE Solutions
WAVEGUIDE DESIGN ENVIRONMENT

Electrical Simulation

DEVICE
CHARGE TRANSPORT SOLVER (2D/3D)

Thermal Simulation

DEVICE
HEAT TRANSPORT SOLVER (2D/3D)

Component Design

Circuit Simulation

INTERCONNECT
PHOTONIC INTEGRATED CIRCUIT SIMULATOR

Interoperability
Cadence Virtuoso
Mentor Graphics Pyxis
PhoeniX OptoDesigner

Model Libraries
Compact Model Generation and Management

System Design

© LUMERICAL SOLUTIONS INC

Optical Solvers for Different Length Scales

Eigenmode analysis

- MODE Solutions
  - Eigenmode solver (FDE)

Propagation methods

- INTERCONNECT
  - **1D traveling wave**
- MODE Solutions
  - 2.5D variational FDTD (varFDTD)
  - **Bidirectional eigenmode expansion (EME)**
- FDTD Solutions
  - **2D/3D finite difference time domain (FDTD)**

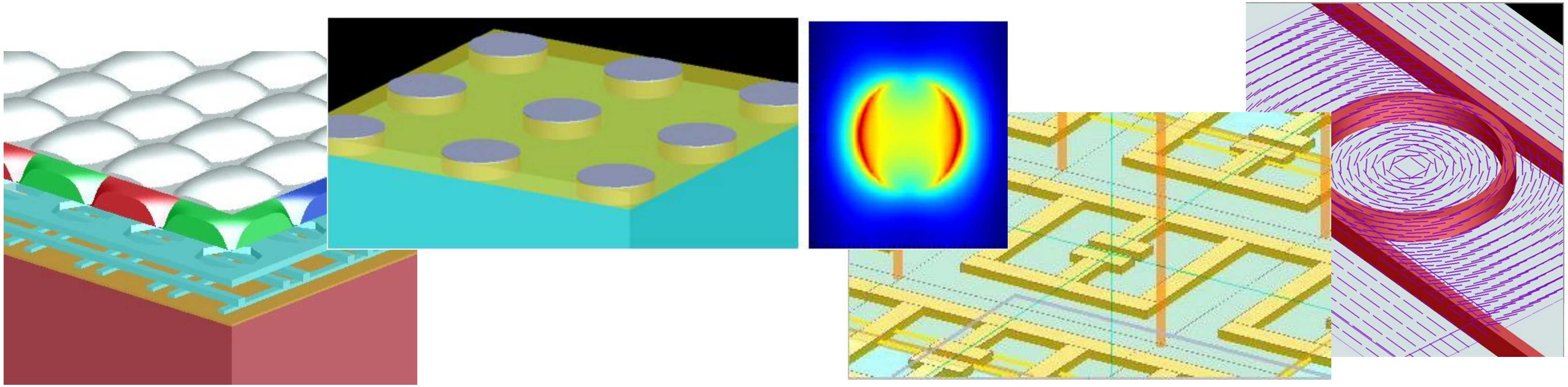
Increasing accuracy
Increasing computational cost

© LUMERICAL SOLUTIONS INC

Finite Difference Time Domain (FDTD) Solver

Rigorous time domain method for solving Maxwell's equations in complex geometries:

- Few inherent approximations
- General technique: many types of problems and geometries
- Broadband results from one simulation



© LUMERICAL SOLUTIONS INC

lumerical

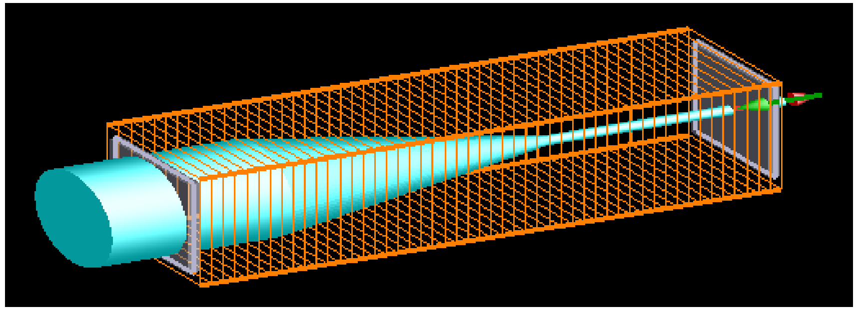
Eigenmode Expansion (EME) Solver

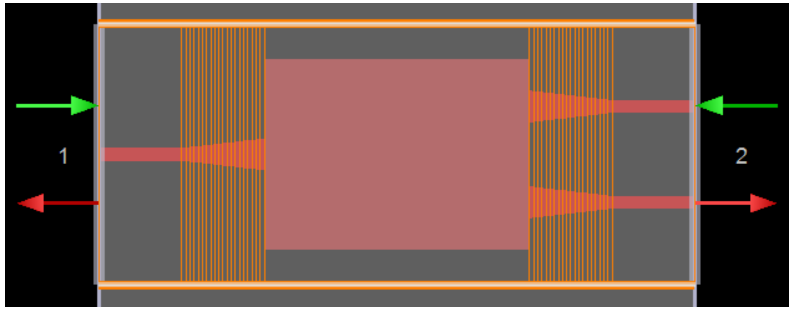
Rigorous frequency domain solver for Maxwell's equations

- Account for multiple-reflection events
- Only one simulation for all input/output modes and polarizations
- Ideal for long passive components: computational cost scales well with propagation distance

Scattering matrix formulation

- Define interfaces and calculate modes
- Boundary conditions applied at each interface





© LUMERICAL SOLUTIONS INC
lumerical

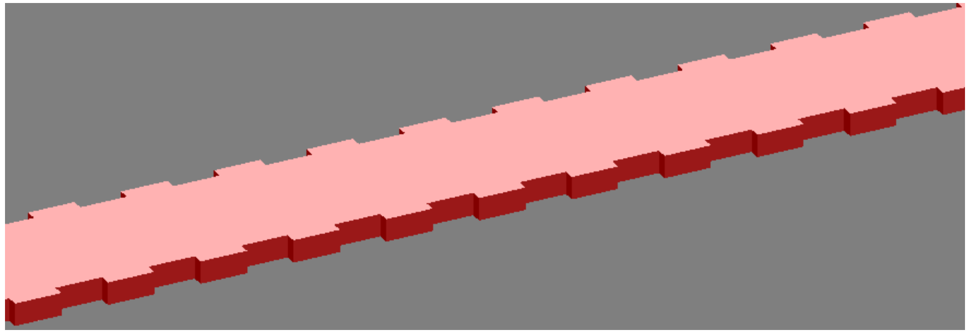
Waveguide Bragg Gratings

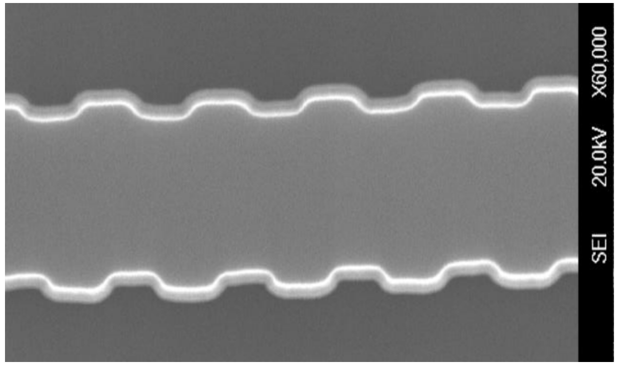
© LUMERICAL SOLUTIONS INC

What is a Waveguide Bragg Grating?

1D photonic bandgap structure

- Straight waveguide with a periodic perturbation
- Wavelength specific dielectric mirror
  - ~100% reflection over a range of frequencies
  - ~100% transmission otherwise



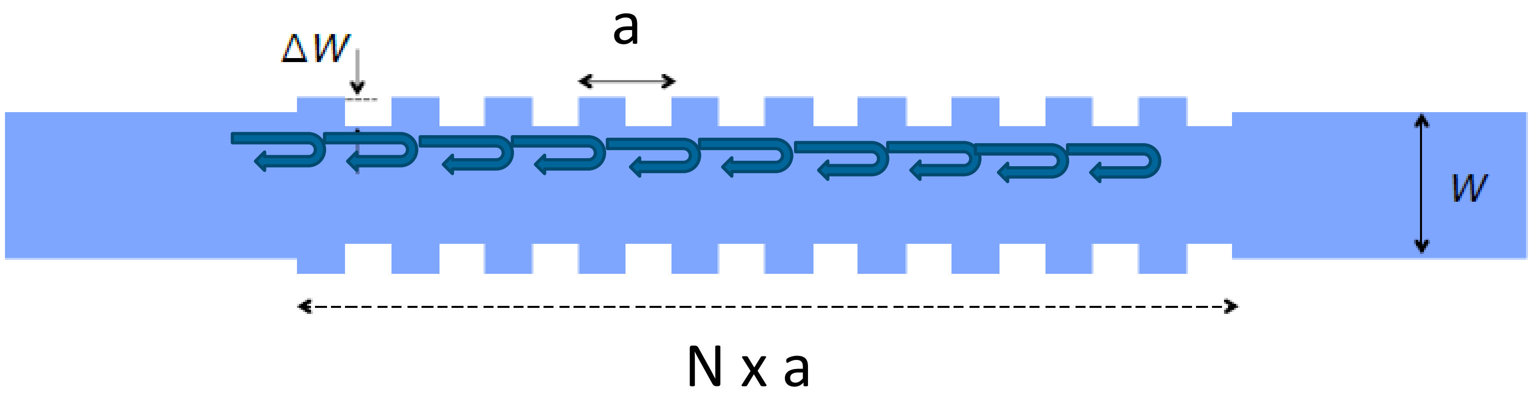


© LUMERICAL SOLUTIONS INC

Basic design of a waveguide mirror

Find condition for constructive interference of reflections

- Wavelenght in the waveguide: $\lambda=\lambda_0/n_{eff}$
- Reflected waves will be in phase if $2*a = m*\lambda$
- Bragg condition for first-order grating (m=1): $\lambda_0=2*a*n_{eff}$

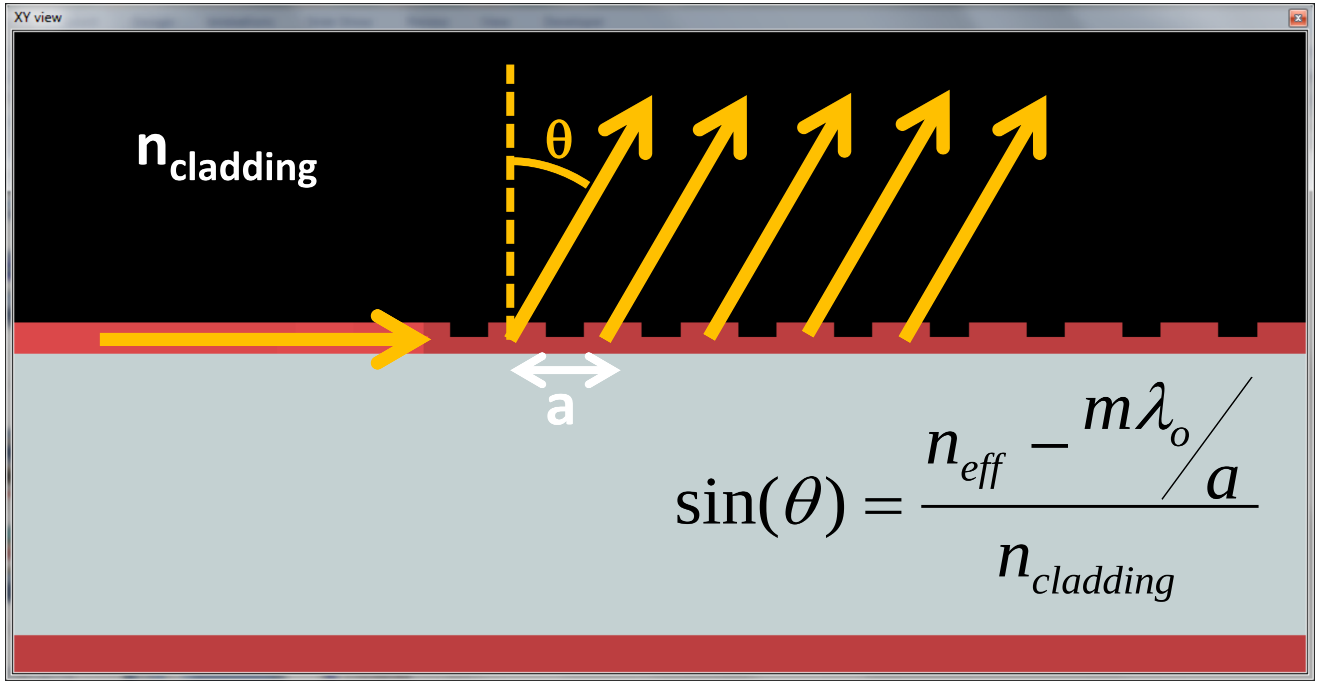


© LUMERICAL SOLUTIONS INC

Basic design of a waveguide mirror

It is also possible to scatter light out of the structure

- Another constructive interference condition
- Used to design grating couplers

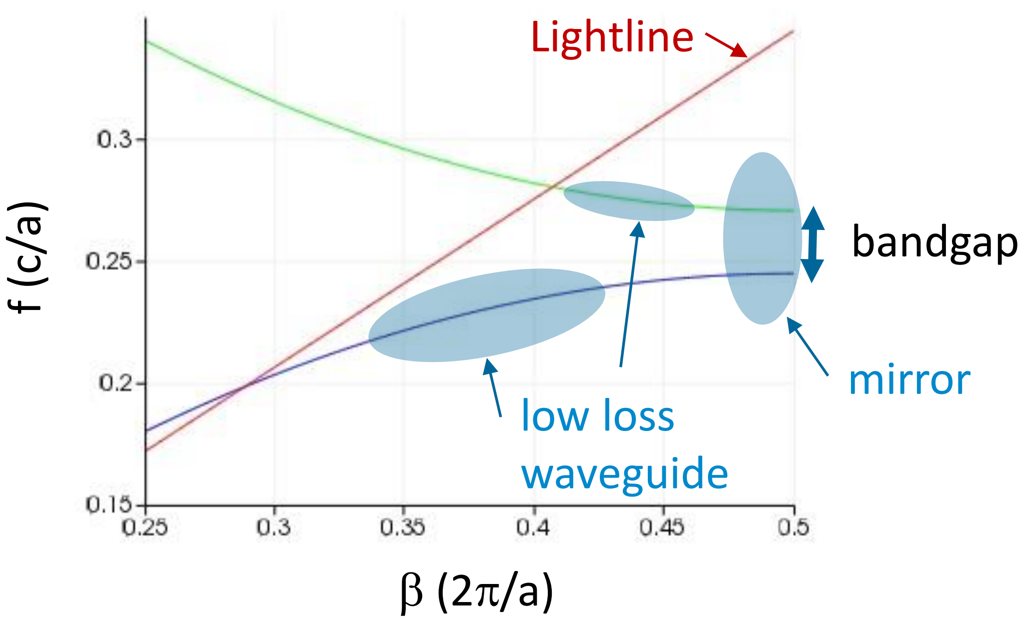


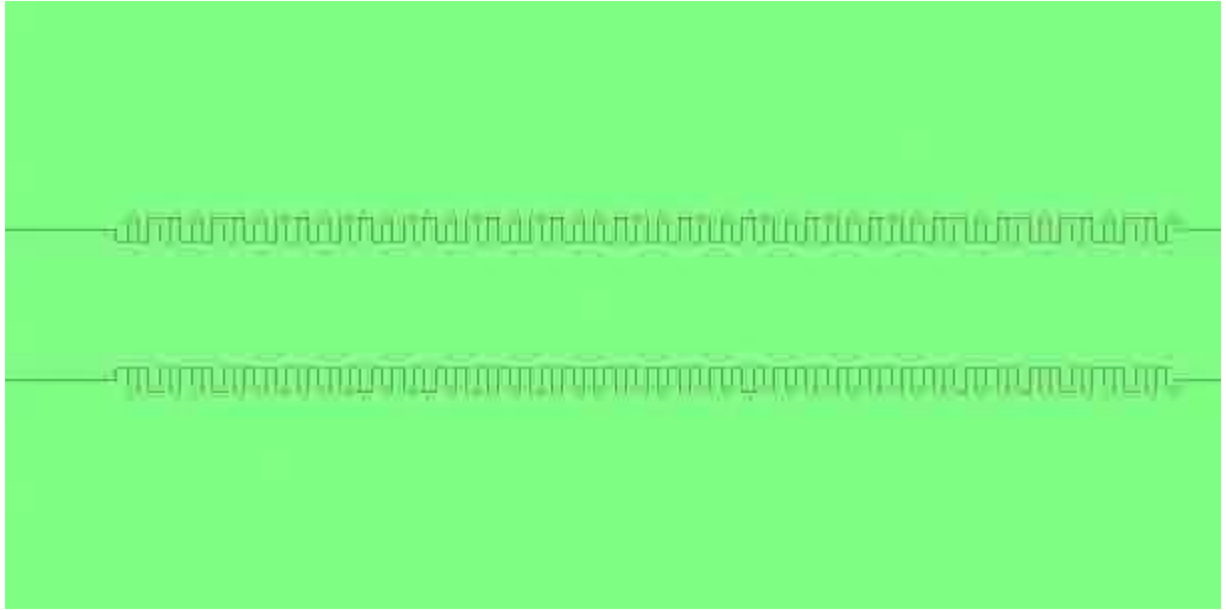
© LUMERICAL SOLUTIONS INC

lumerical

Band structure analysis

Below the light line, the Bragg grating can selectively transmit or reflect light along the waveguide

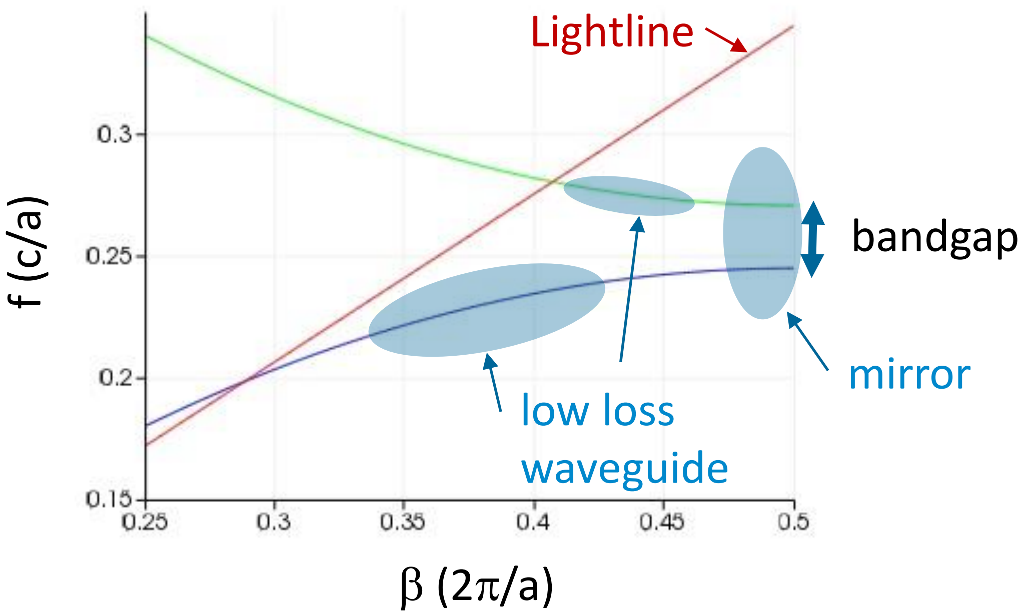


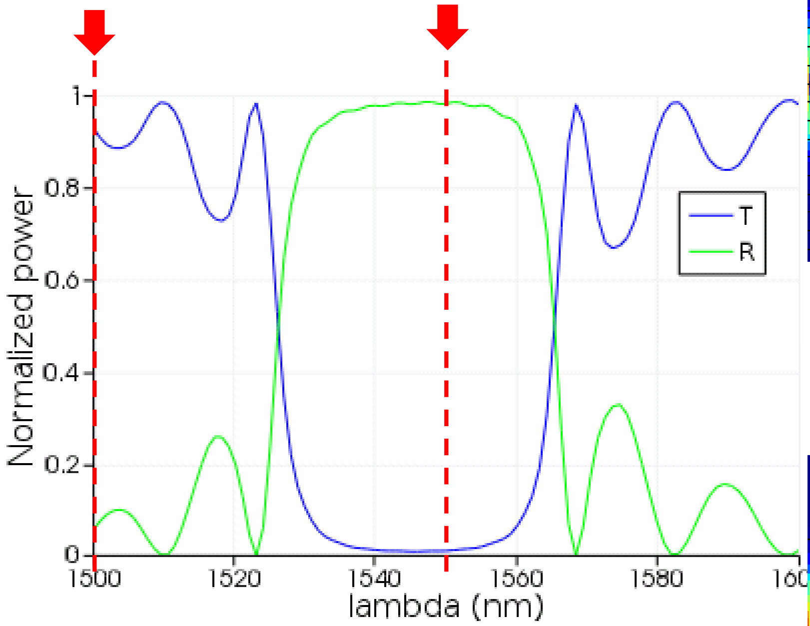


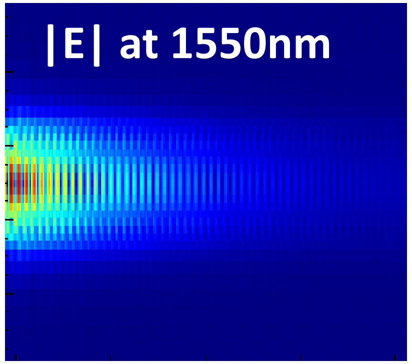
© LUMERICAL SOLUTIONS INC

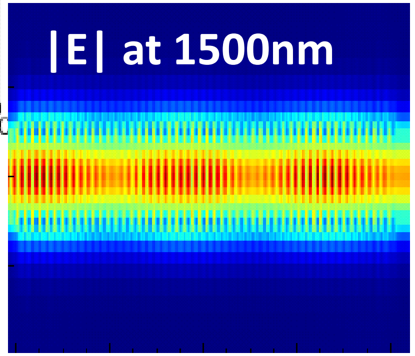
Band structure analysis

Below the light line, the Bragg grating can selectively transmit or reflect light along the waveguide





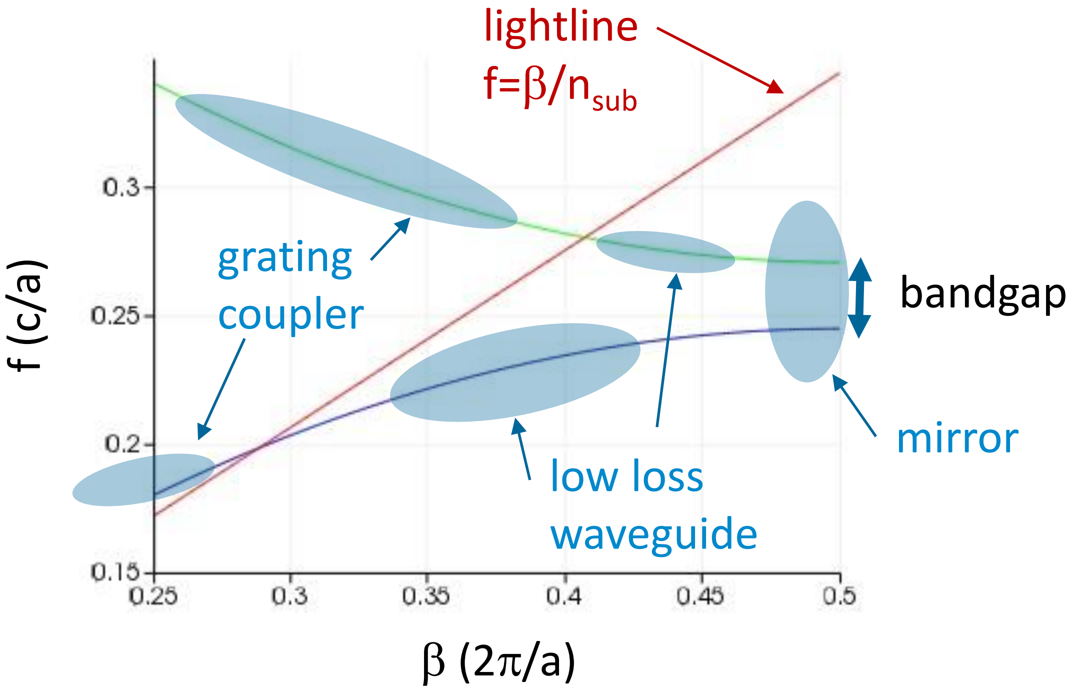


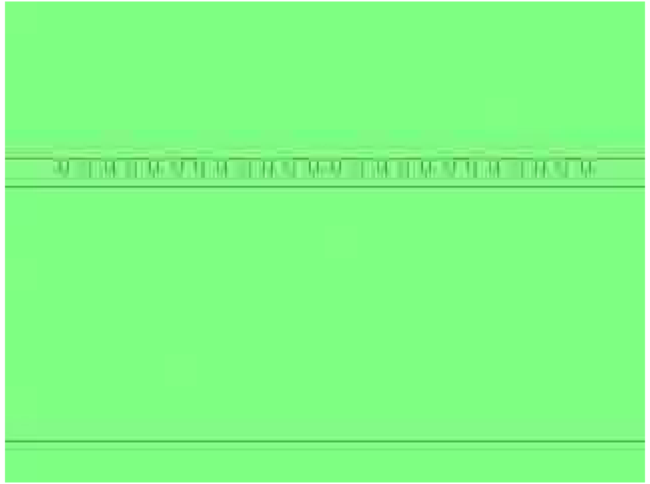


© LUMERICAL SOLUTIONS INC
lumerical

Band structure analysis

Above the light line, we can scatter light out of the structure: grating coupler





© LUMERICAL SOLUTIONS INC

lumerical

Simulation Challenges and Solutions

Challenges

- FDTD
  - Simulation size: full device is usually many periods long
- EME
  - Modes can be very discontinuous
  - Many wavelengths required to resolve spectrum: one simulation per wavelength in frequency-domain solvers
- Geometry effects
  - Lithography effects
  - Corrugation depth and misalignment

Initial design with FDTD

- Simulate unit cell with Bloch-periodic boundary conditions
- Calculate center wavelength and bandwidth

Full simulation with EME

- Quickly simulate many periods
- Check convergence by increasing number of modes
- To resolve the spectrum scan grating period length instead of wavelength

- Lithography corrected structure
- Sweeps over corrugation depth and misalignment

Circuit simulations with **INTERCONNECT**

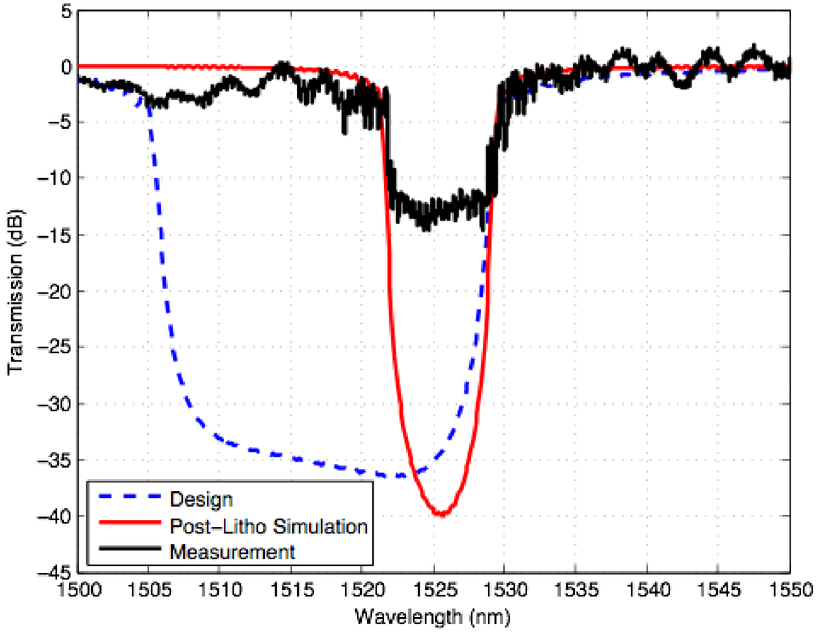
© LUMERICAL SOLUTIONS INC
lumerical

Photolithography Effects

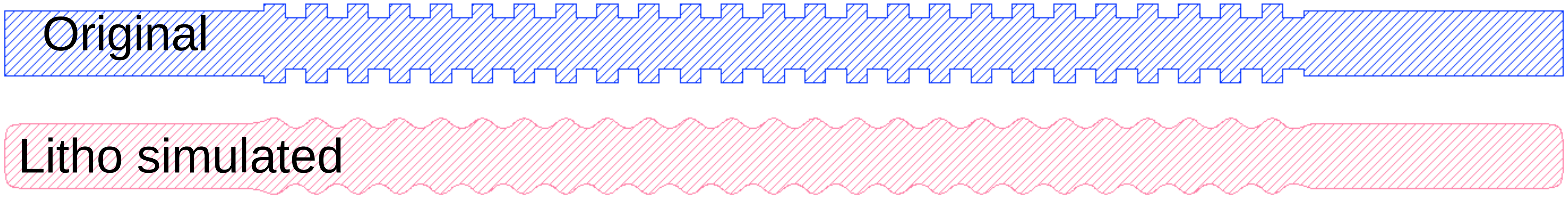
Waveguide Bragg grating designed with 40 nm square corrugations

FDTD simulations of photolithography simulated design matches experimental Bragg bandwidth

- Lithography simulation with Mentor Graphics' Calibre



Xu Wang, et al., "Lithography Simulation for the Fabrication of Silicon Photonic Devices with Deep-Ultraviolet Lithography", IEEE GFP, 2012



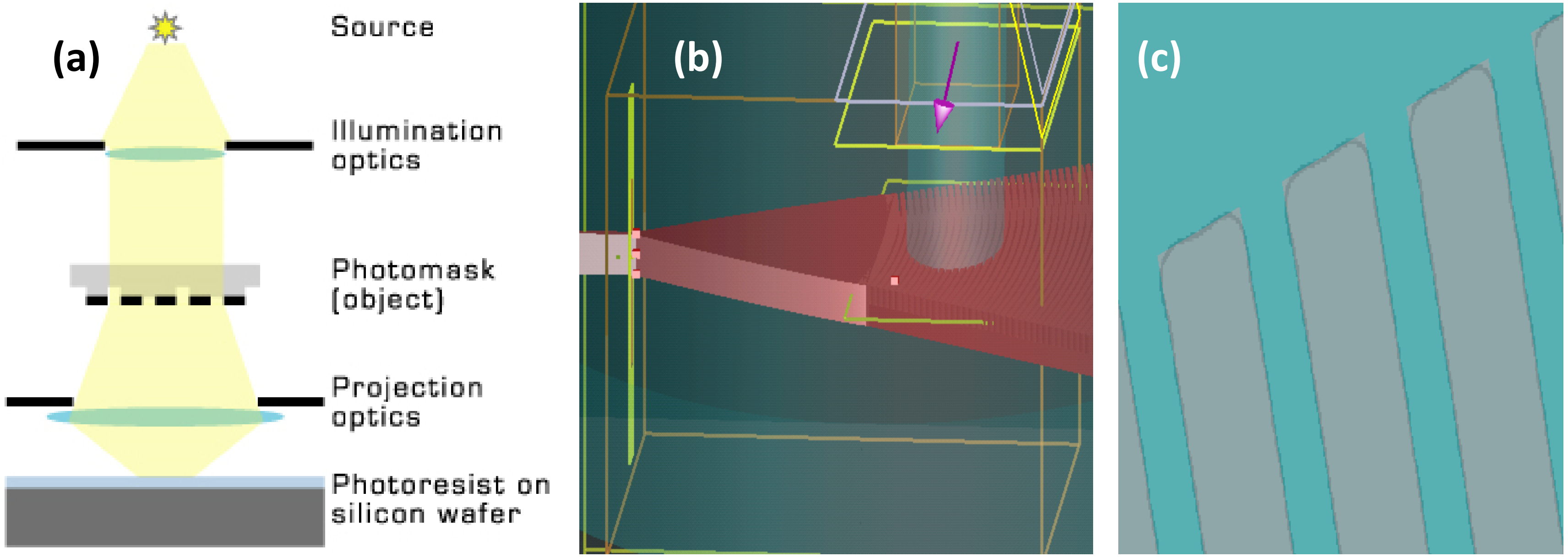
© LUMERICAL SOLUTIONS INC

lumerical

Photolithography simulation

Fraunhoffer diffraction at mask

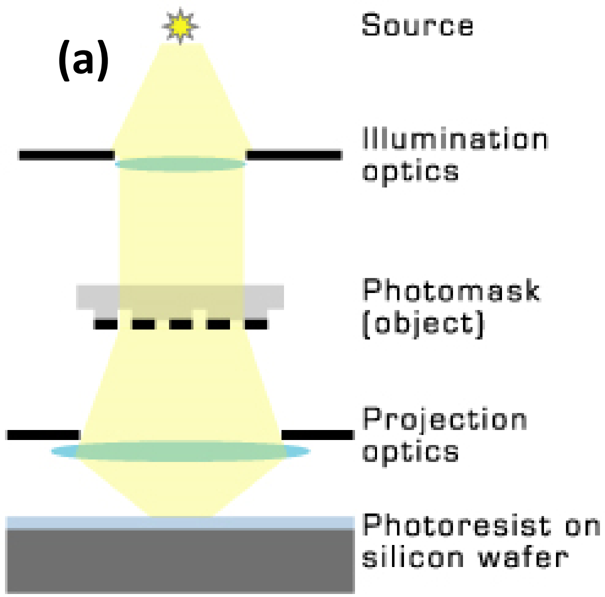
- Infinitely thin metal (ignored plasmonic or polarization effects)
- Simple resist model (defined by a threshold level)

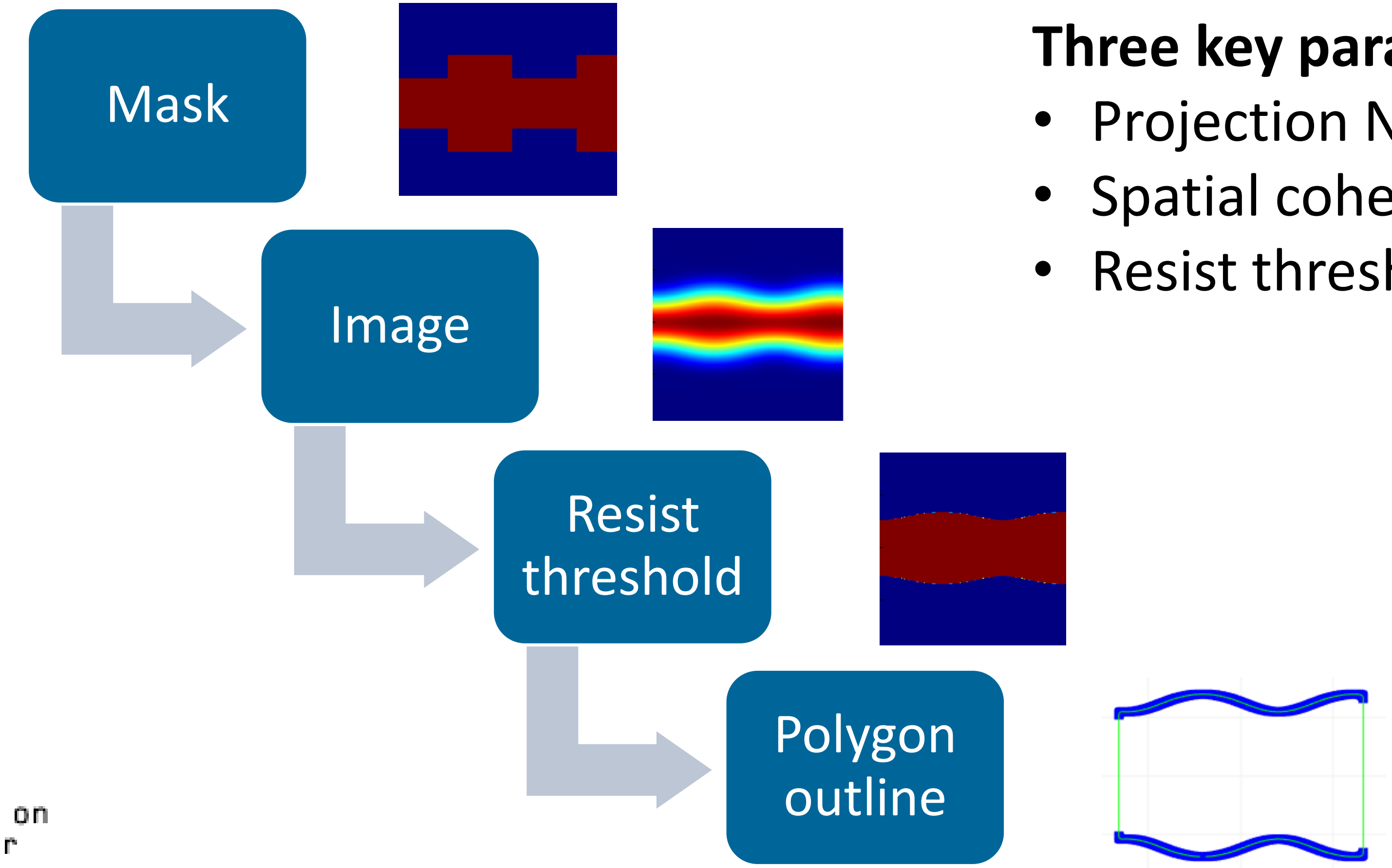


J. Pond, et al., "Design and optimization of photolithography friendly photonic components", Proc. SPIE, vol. 9751, 3/2016.

© LUMERICAL SOLUTIONS INC

Photolithography simulation





Three key parameters:

- Projection NA
- Spatial coherence factor
- Resist threshold

© LUMERICAL SOLUTIONS INC

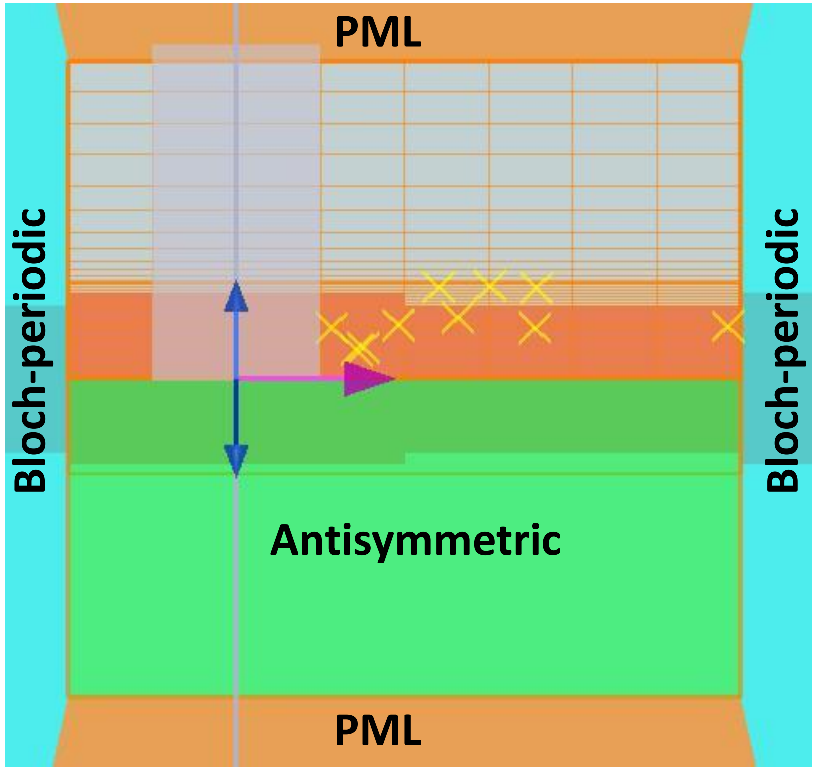
Initial design with FDTD

© LUMERICAL SOLUTIONS INC

Band structure calculation

Simulate unit cell of Waveguide Bragg grating in FDTD

- Mode source (other sources also possible)
- Bloch-periodic boundary conditions
  - Set appropriate Bloch wavevector $-\pi/a < k_x < \pi/a$
  - Band gap usually at $k_x = \pi/a$
- Calculate spectrum from time monitors



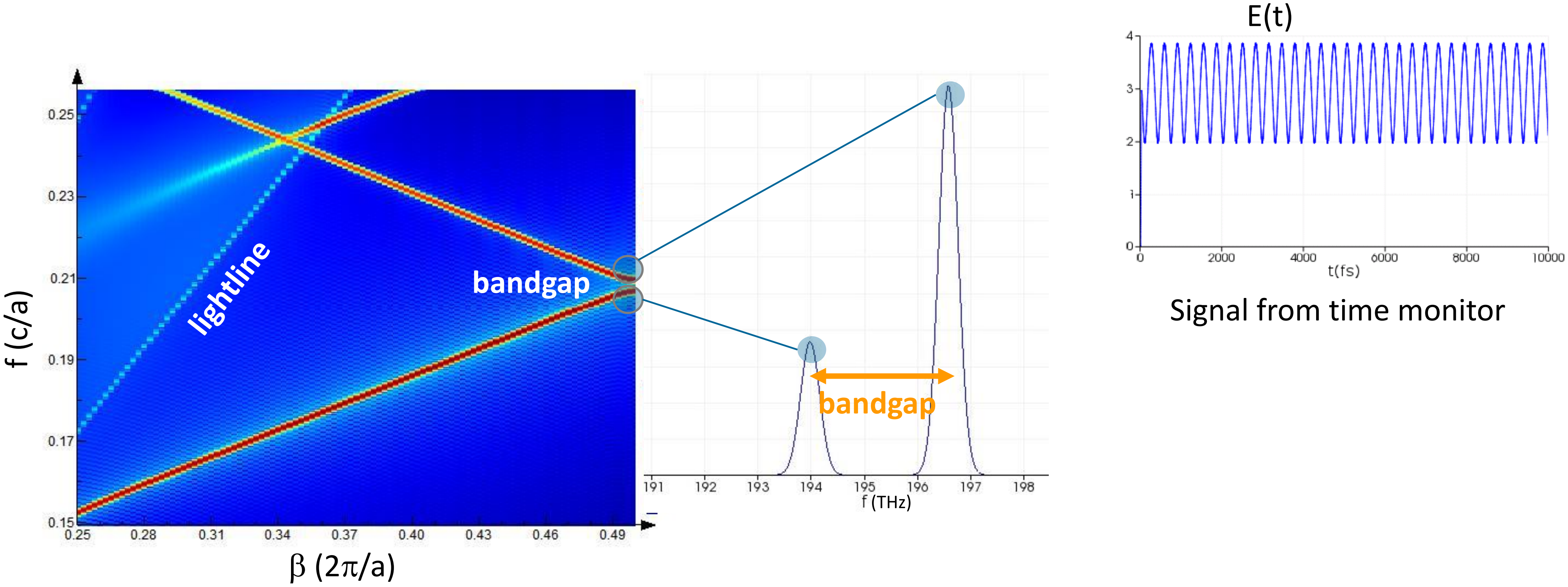
DEMO!

KB example: https://kb.lumerical.com/en/index.html?pic_passive_bragg_initial_design_with_fdtd.html

© LUMERICAL SOLUTIONS INC

Band structure analysis

Sweep over k_x to get full band structure



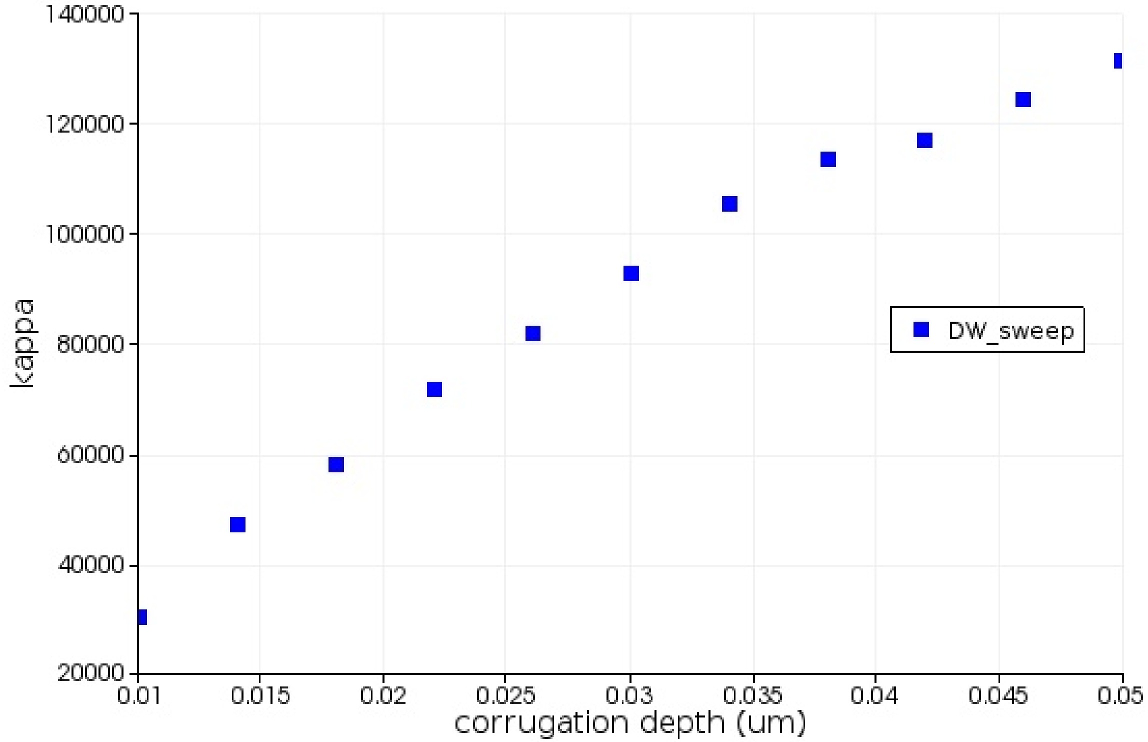
Signal from time monitor

© LUMERICAL SOLUTIONS INC

Effect of corrugation depth

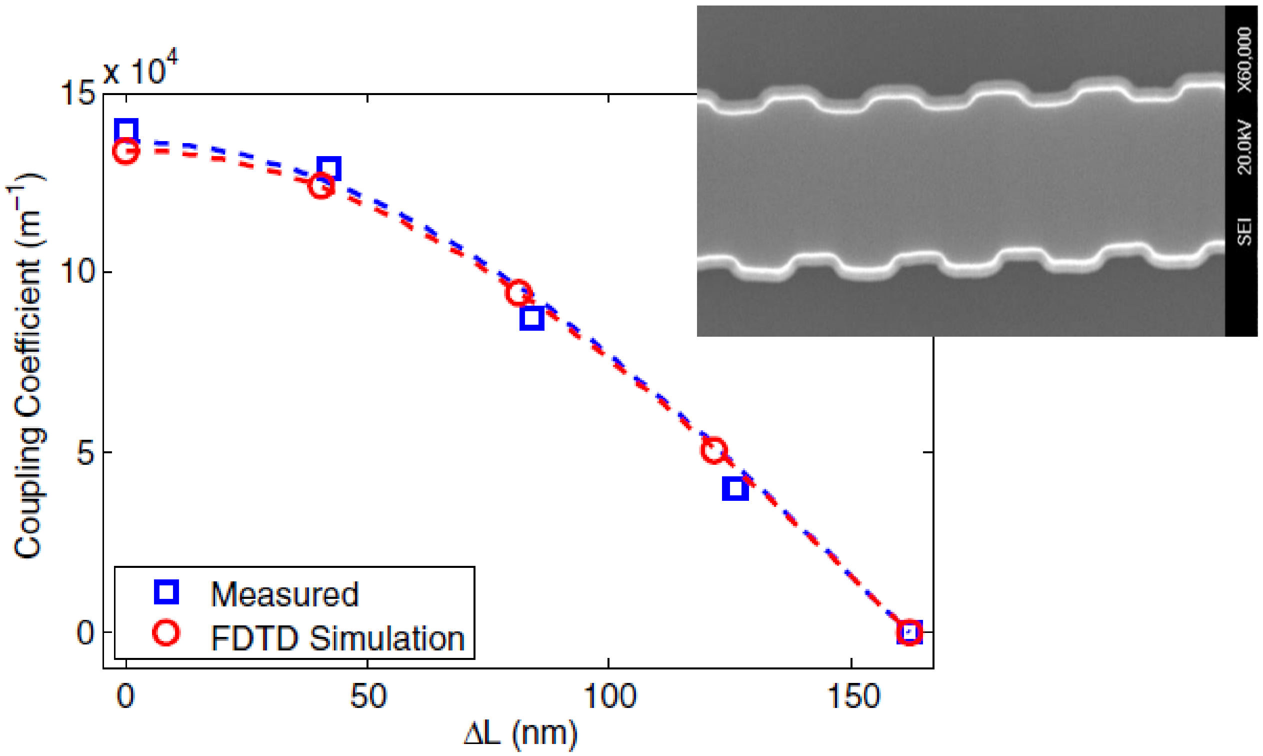
Sweep over grating depth

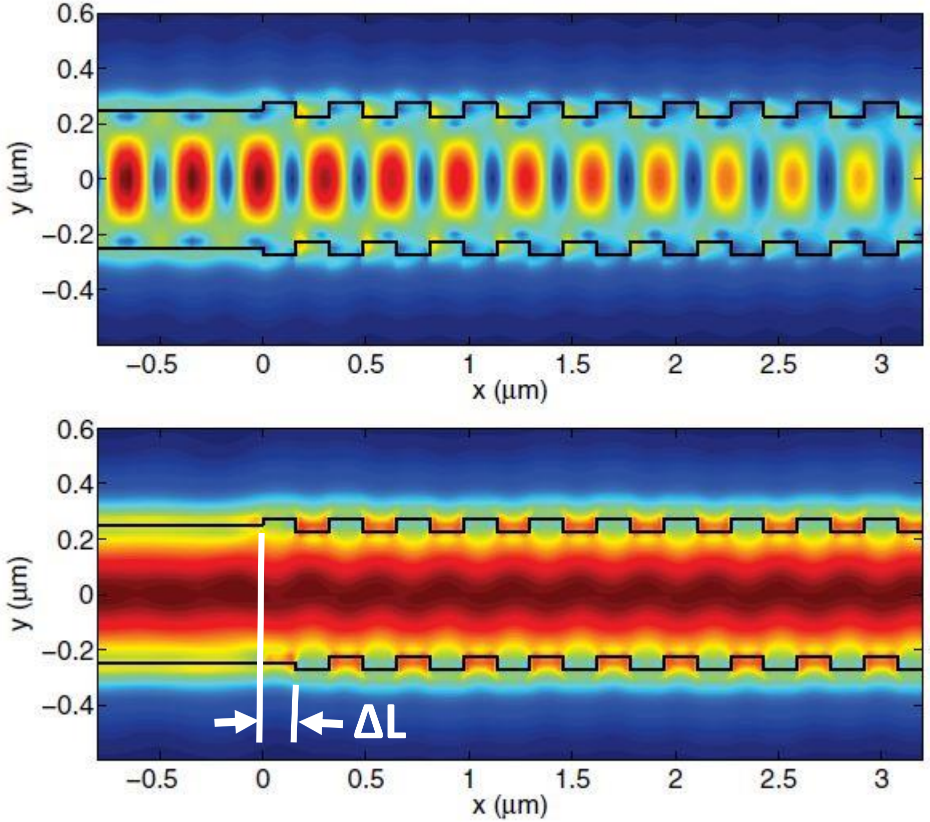
- Coupling coefficient: $\kappa = \dfrac{\pi n_g \Delta\lambda}{{\lambda_0}^2}$
  - $\Delta\lambda$ → bandwidth
  - λ_0 → center wavelength
  - n_g → group index at λ_0



© LUMERICAL SOLUTIONS INC
lumerical

Effect of misalignment



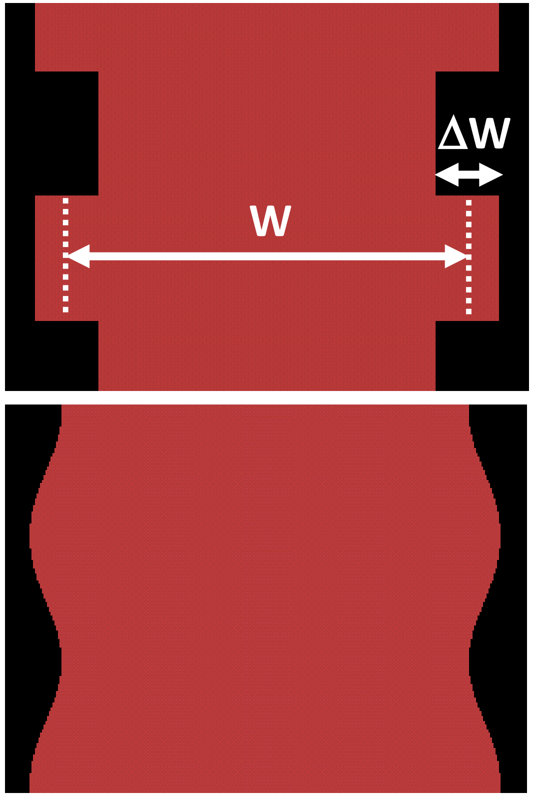


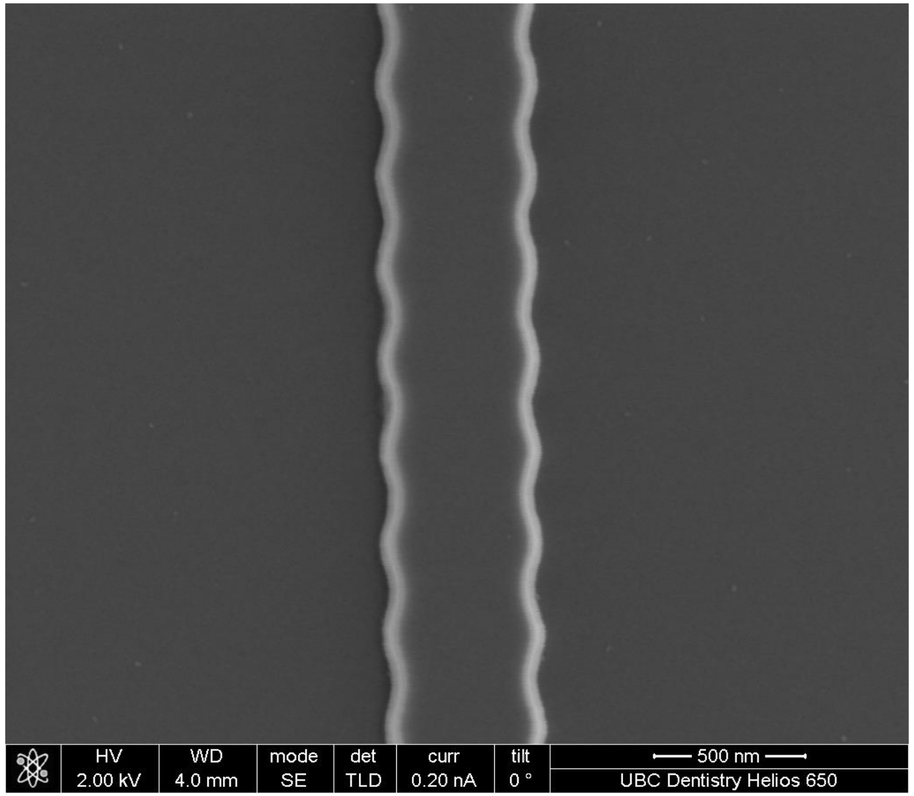
Xu Wang, et al., "Precise control of the coupling coefficient through destructive interference in silicon waveguide Bragg gratings", Optics Letters, vol. 39, issue 19, pp. 5519-5522, 10/2014.

© LUMERICAL SOLUTIONS INC

Effects of photolithography

Use script for photolithography simulation





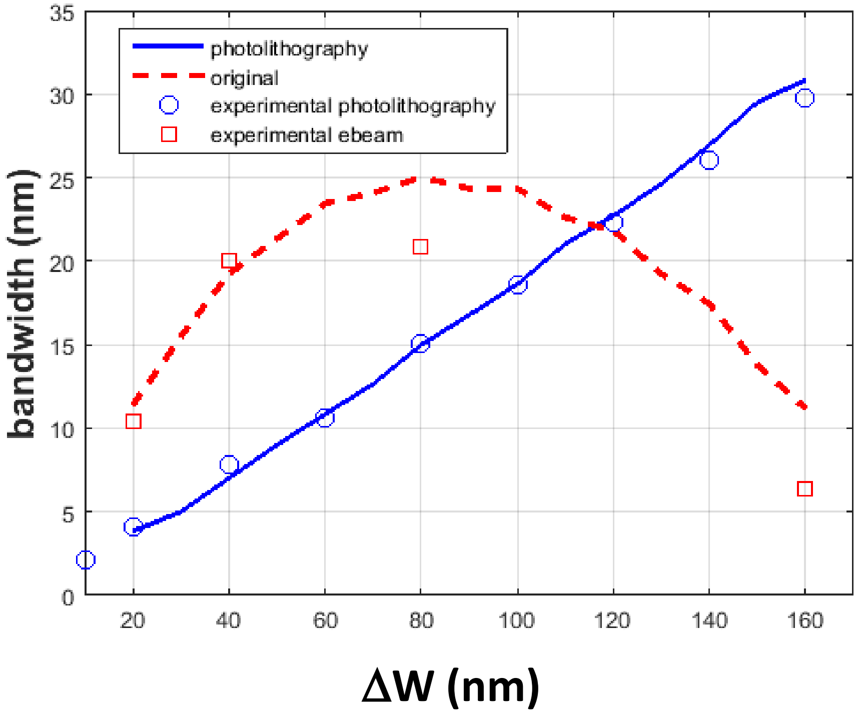
DEMO!

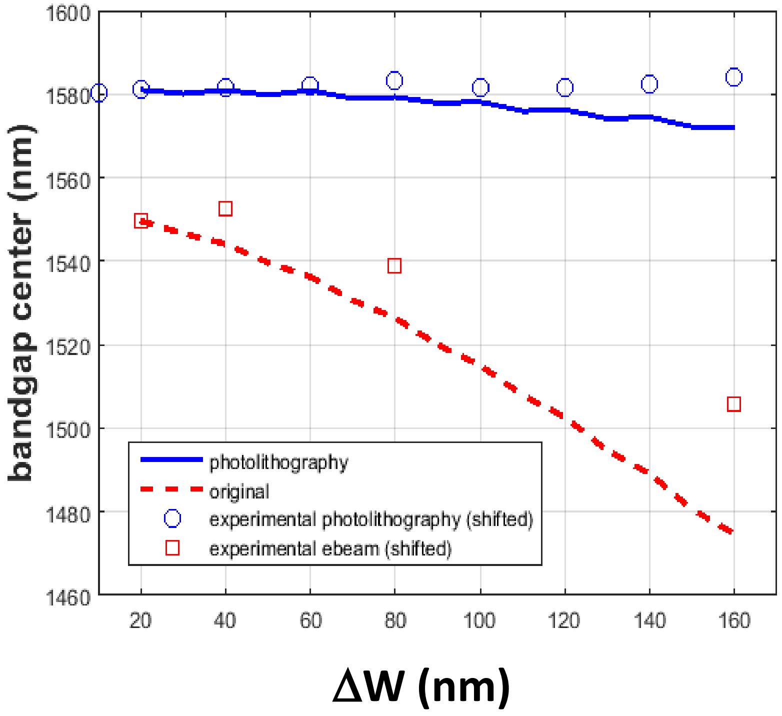
J. Pond, et al., "Design and optimization of photolithography friendly photonic components", Proc. SPIE, vol. 9751, 3/2016.

© LUMERICAL SOLUTIONS INC

Effects of photolithography

Excellent agreement between simulation and experimental results:





J. Pond, et al., "Design and optimization of photolithography friendly photonic components", Proc. SPIE, vol. 9751, 3/2016.

© LUMERICAL SOLUTIONS INC

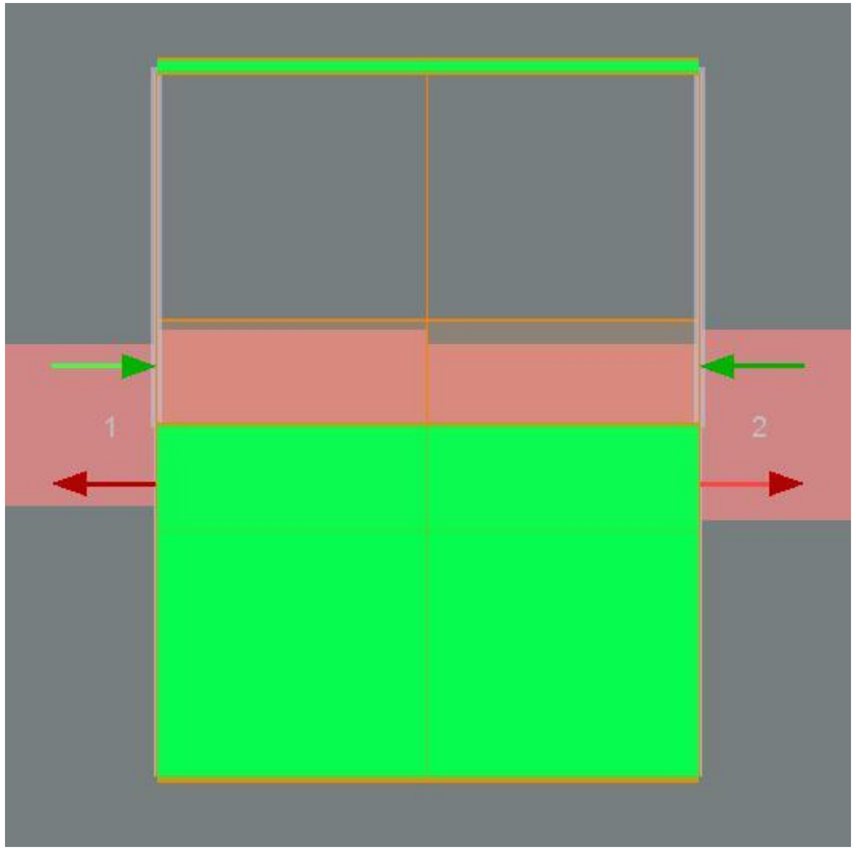
Simulation of Full Device using EME

© LUMERICAL SOLUTIONS INC

WBG: Simulation Setup in EME

Without lithography effects

- Two cell groups (one per waveguide thickness)
- One cell per group
- Start with 10 modes in every cell
- Set the number of periods in EME settings



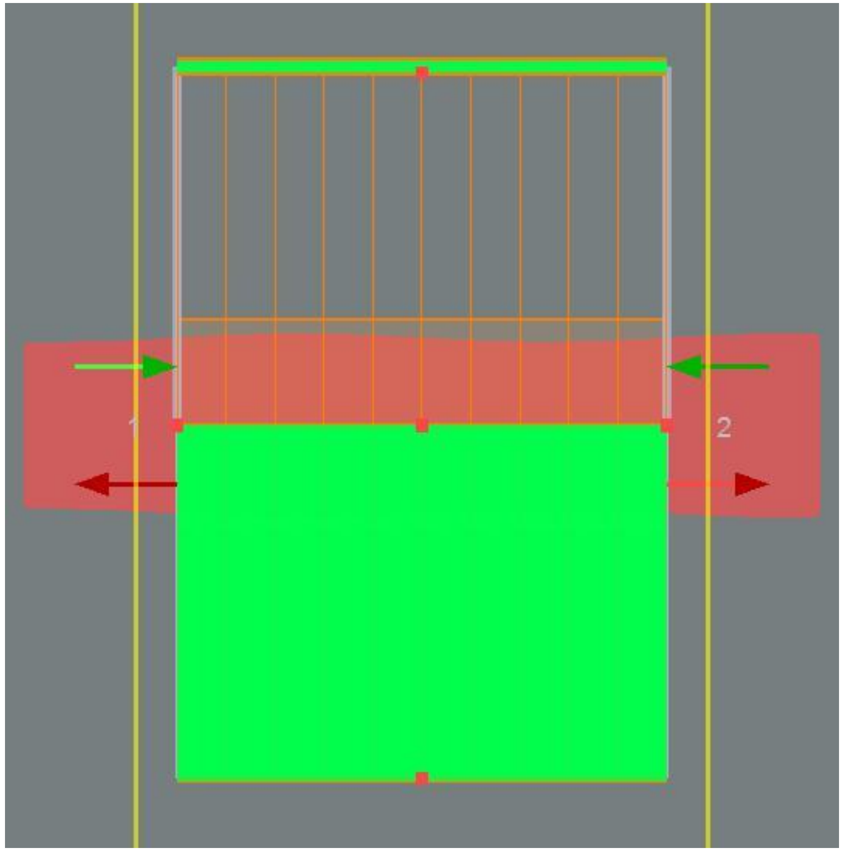
© LUMERICAL SOLUTIONS INC

lumerical

WBG: Simulation Setup in EME

With lithography effects

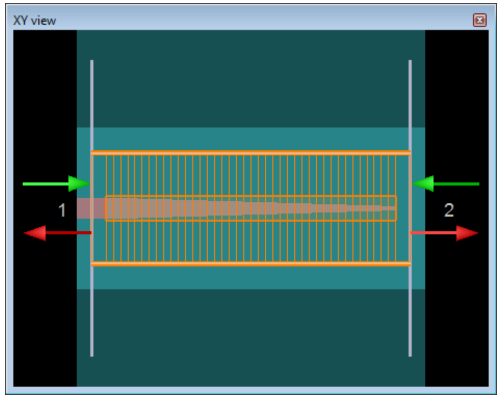
- One cell group for the entire unit cell
- Start with 10 cells to resolve curvature
- Make sure the mesh is fine enough
- Start with 10 modes in every cell
- Set the number of periods in EME settings



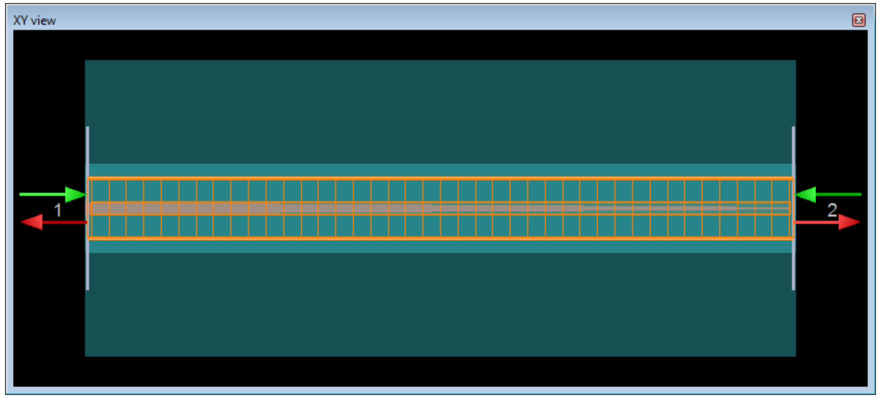
© LUMERICAL SOLUTIONS INC

Full Spectrum Simulation

The propagation length and number of periods can be modified **without having to recalculate any modes**, and the result can be calculated instantly



10um taper



100um taper

© LUMERICAL SOLUTIONS INC

WBG: Full Spectrum Simulation

Brute force method

- Run one simulation per wavelength

Efficient approach

- Solve device for one reference wavelength
- Stretch or compress each cell to create an equivalent wavelength change and calculate results at all desired wavelengths

Length scale factor: $\alpha = 1 + \frac{n_g}{n_{eff}}\left(\frac{\lambda_{ref}}{\lambda} - 1\right)$

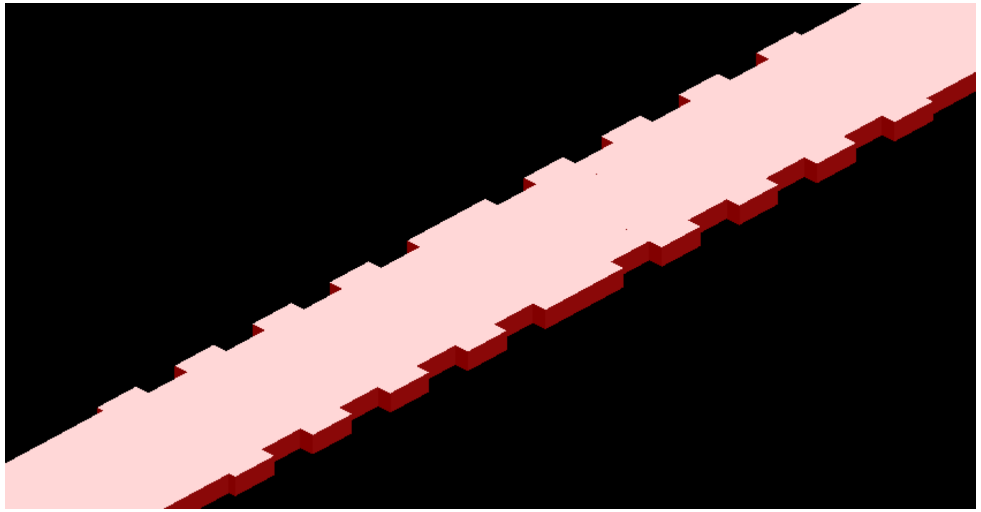
DEMO!

© LUMERICAL SOLUTIONS INC

Phase-Shifted Bragg Gratings

Introduce a phase shift in the middle of the grating to create a sharp resonant peak within the stop band

- Sharp filter for integrated optical circuits
- Sensor applications



P. Prabhathan, et al., “Compact SOI nanowire refractive index sensor using phase shifted Bragg grating", Optics Express, Vol. 17, No. 17, 2009

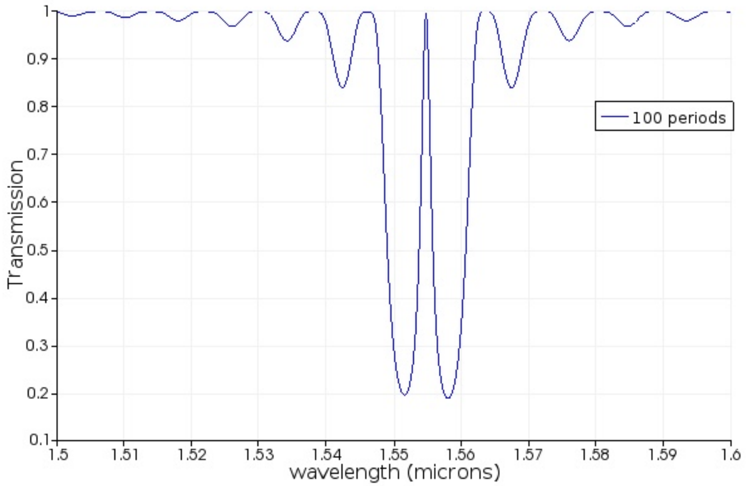
© LUMERICAL SOLUTIONS INC

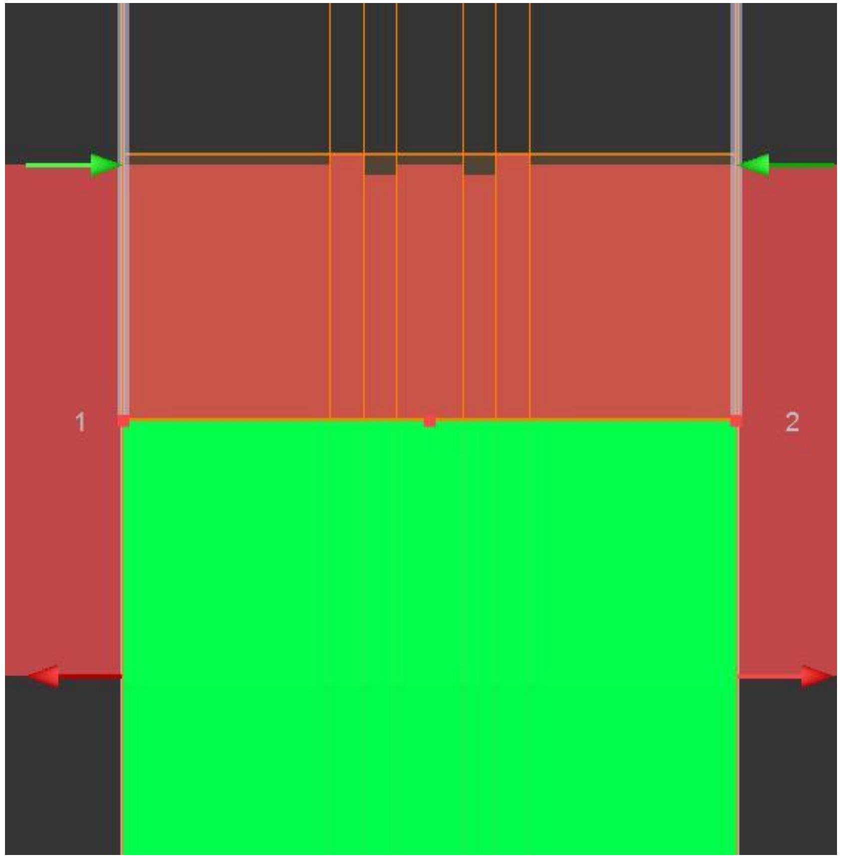
lumerical

Full Spectrum Simulation

Use same efficient approach as for WBG to get full spectrum

- Period = 320nm
- Number of periods = 100
- Cavity length = 320nm
- Corrugation length = 20nm

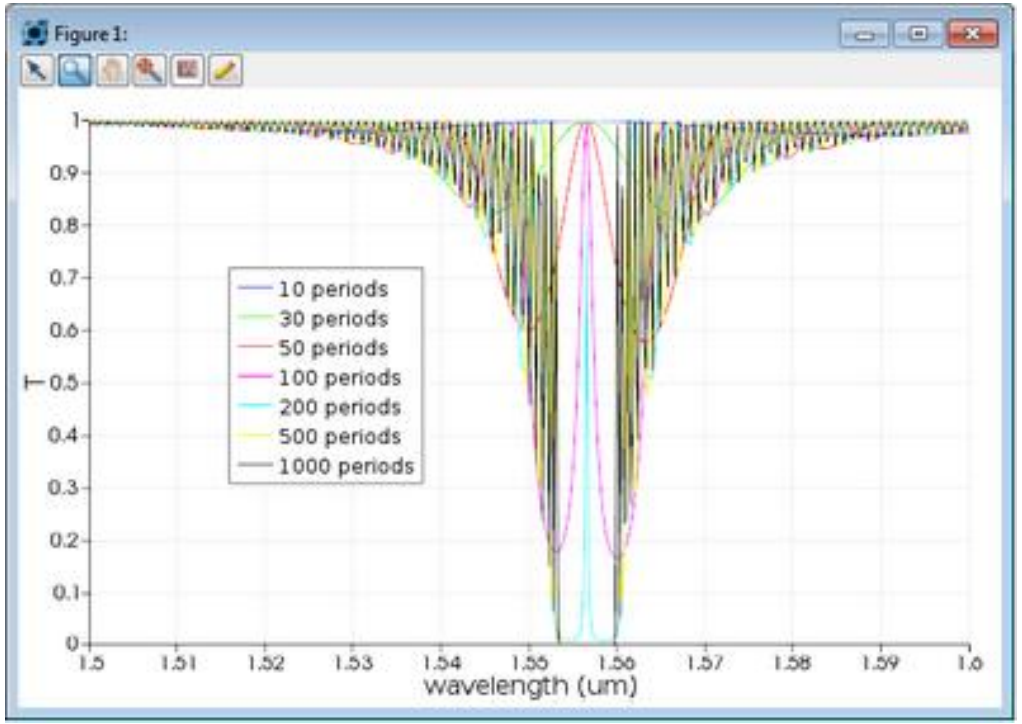




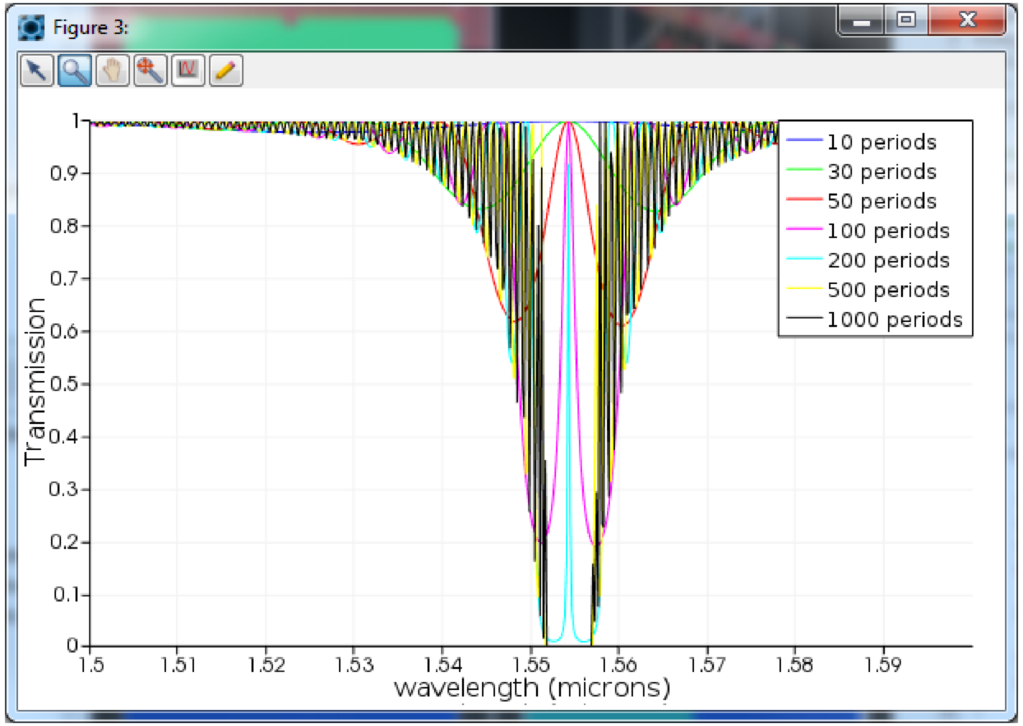
© LUMERICAL SOLUTIONS INC

Full Spectrum Simulation

Brute force approach (101 wavelength points)



Fast approach (501 wavelength points)



KB example: https://kb.lumerical.com/en/index.html?pic_passive_bragg_phase_shifted.html

© LUMERICAL SOLUTIONS INC

Optimizing with EME

Efficiently optimize devices requiring

- Length scanning such as tapers
- Modifying the number of periods

There are often tricks to avoid the disadvantage of EME when scanning wavelength

© LUMERICAL SOLUTIONS INC

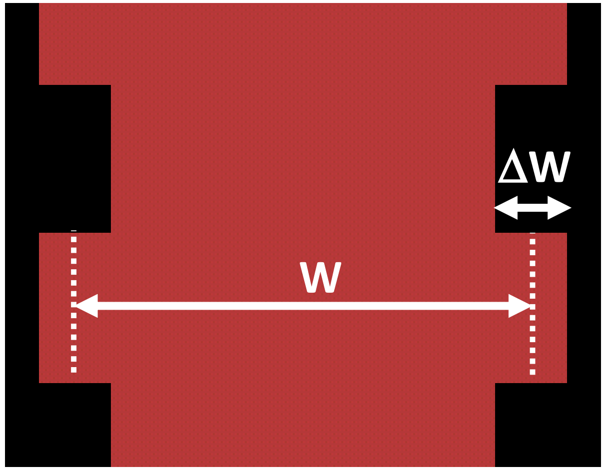
Circuit Simulations with INTERCONNECT

© LUMERICAL SOLUTIONS INC

What do we want?

A table that maps our design parameters to bandwidth and operating wavelength

- We can create compact models for PDKs
- Large scale circuit design and simulation becomes easy



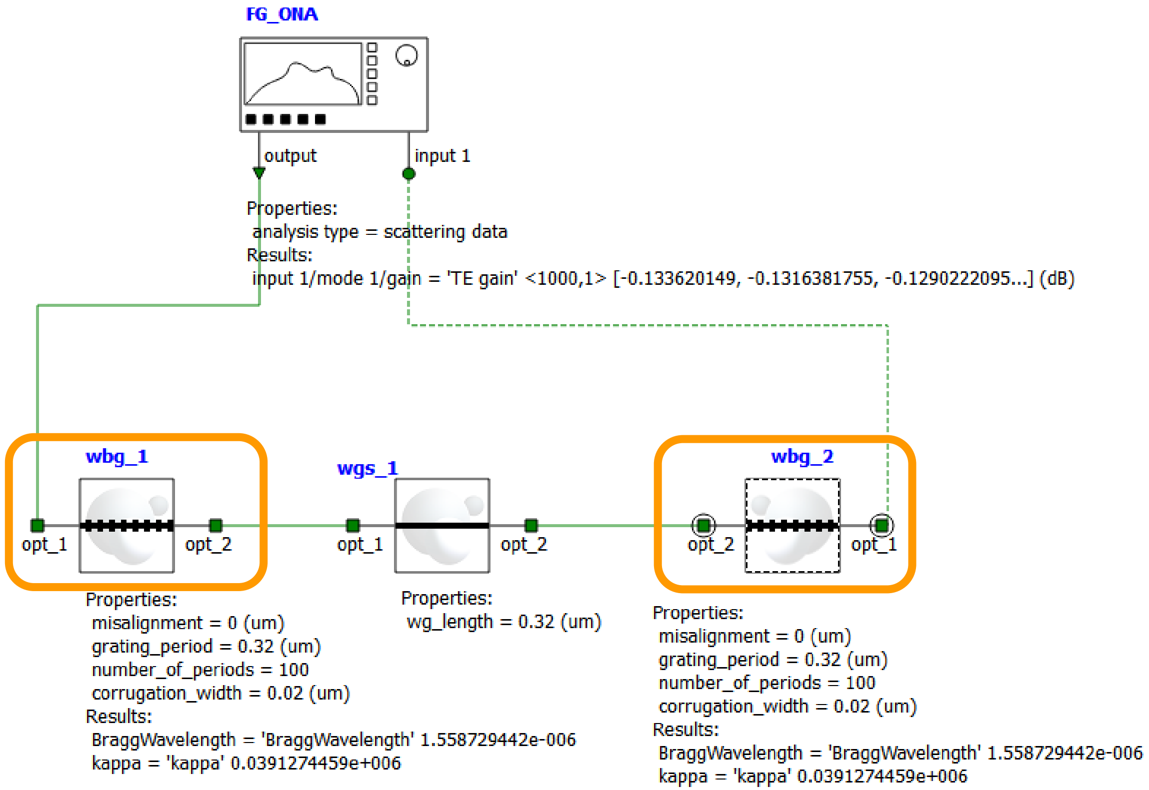
W	ΔW	Bandgap	Operating wavelength
500 nm	40 nm	10 nm	1550 nm
500 nm	50 nm	12 nm	1550 nm
…	…	…	…

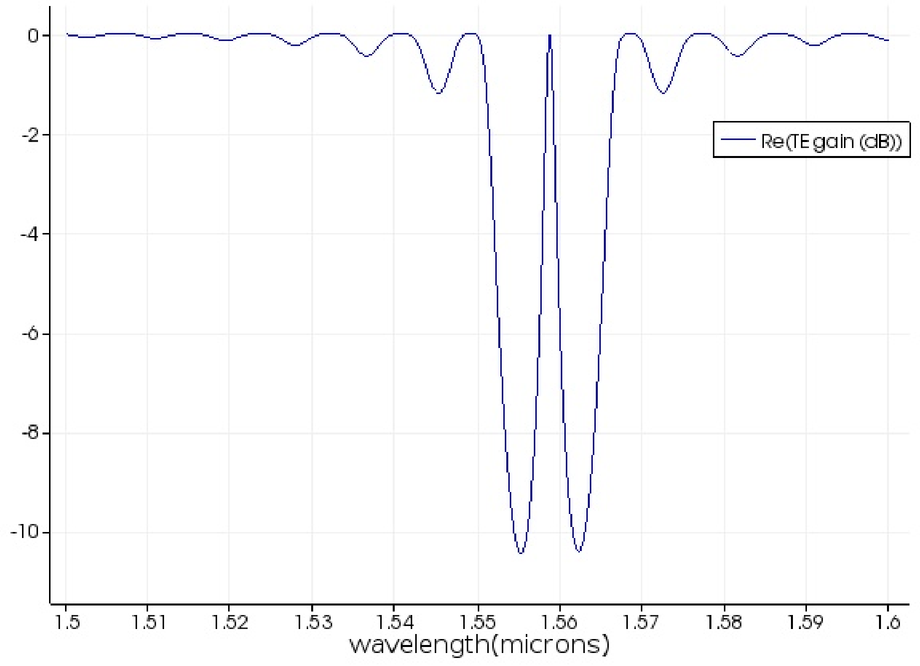
© LUMERICAL SOLUTIONS INC

WBG Compact model

WBG PCell (will be available in **Lumerical CML**)

- Quickly simulate phase shifted Bragg grating



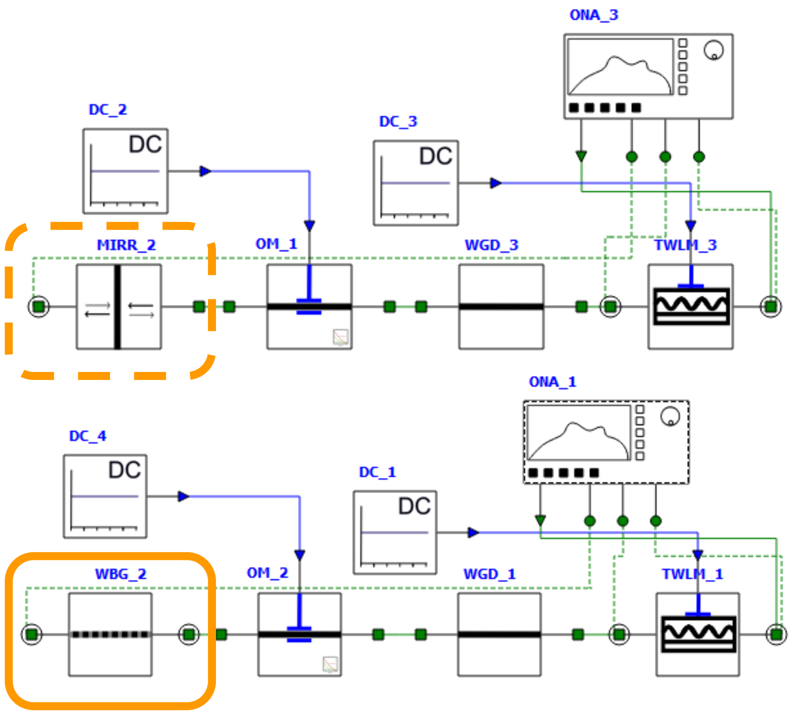


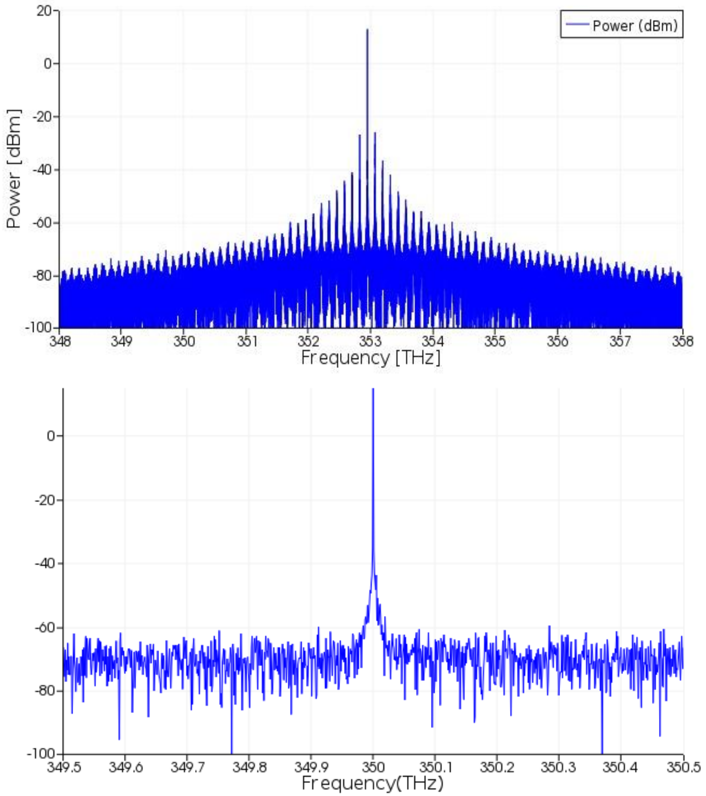
DEMO!

© LUMERICAL SOLUTIONS INC

WBG in Hybrid Lasers

WBG selective reflectivity →single-mode operation in a laser





More info: https://www.lumerical.com/support/video/modeling_lasers.html

© LUMERICAL SOLUTIONS INC

Summary

Waveguide Bragg gratings can be

- Waveguides
- Frequency selective mirrors
- Grating couplers

Simulation with

- FDTD – bandstructure of infinite device
- EME – finite device, finite device with defect
- INTERCONNECT – calibrated traveling wave model

Many applications

- Filters
- Laser mirrors
- Sensors
- …

© LUMERICAL SOLUTIONS INC

www.lumerical.com

Connect with Lumerical

Contact Us

Questions? kx.lumerical.com

Sales Inquiries: sales@lumerical.com

Evaluate Lumerical tools free for 30 days www.lumerical.com

© LUMERICAL SOLUTIONS INC

lumerical