Waveguide Bragg Gratings and Resonators
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 Products

## Optical Simulation
- **FDTD Solutions**
  - **NANOPHOTONIC SOLVER (2D/3D)**

## Electrical Simulation
- **DEVICE**
  - **CHARGE TRANSPORT SOLVER (2D/3D)**

## Thermal Simulation
- **DEVICE**
  - **HEAT TRANSPORT SOLVER (2D/3D)**

## Circuit Simulation
- **INTERCONNECT**
  - **PHOTONIC INTEGRATED CIRCUIT SIMULATOR**

### Interoperability
- Cadence Virtuoso
- Mentor Graphics Pyxis
- PhoeniX OptoDesigner

### Model Libraries
- Compact Model
- Generation and Management

## Component Design

## System Design
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
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
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
Waveguide Bragg Gratings
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
Basic design of a waveguide mirror

Find condition for constructive interference of reflections

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

\[
\sin(\theta) = \frac{n_{\text{eff}} - m\lambda_o}{a} \frac{1}{n_{\text{cladding}}}
\]
Band structure analysis

Below the light line, the Bragg grating can selectively transmit or reflect light along the waveguide.
Band structure analysis

Below the light line, the Bragg grating can selectively transmit or reflect light along the waveguide.
Band structure analysis

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

Photolithography simulation

Fraunhoffer diffraction at mask

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

Photolithography simulation

Three key parameters:
- Projection NA
- Spatial coherence factor
- Resist threshold

![Diagram](https://example.com/diagram.png)
Initial design with FDTD
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!**

Band structure analysis

Sweep over $k_x$ to get full band structure

Signal from time monitor
Effect of corrugation depth

Sweep over grating depth

- Coupling coefficient: \( \kappa = \frac{\pi n_g \Delta \lambda}{\lambda_0^2} \)
  - \( \Delta \lambda \rightarrow \) bandwidth
  - \( \lambda_0 \rightarrow \) center wavelength
  - \( n_g \rightarrow \) group index at \( \lambda_0 \)
Effect of misalignment

Effects of photolithography

Use script for photolithography simulation

Effects of photolithography

Excellent agreement between simulation and experimental results:

Simulation of Full Device using EME
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
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
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.
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

\[ \alpha = 1 + \frac{n_g}{n_{eff}} \left( \frac{\lambda_{ref}}{\lambda} - 1 \right) \]

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

DEMO!
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

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
Full Spectrum Simulation

Brute force approach (101 wavelength points)

Fast approach (501 wavelength points)

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
Circuit Simulations with INTERCONNECT
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

<table>
<thead>
<tr>
<th>W</th>
<th>ΔW</th>
<th>Bandgap</th>
<th>Operating wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 nm</td>
<td>40 nm</td>
<td>10 nm</td>
<td>1550 nm</td>
</tr>
<tr>
<td>500 nm</td>
<td>50 nm</td>
<td>12 nm</td>
<td>1550 nm</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
WBG Compact model

WBG PCell (will be available in **Lumerical CML**)
- Quickly simulate phase shifted Bragg grating
WBG in Hybrid Lasers

WBG selective reflectivity $\rightarrow$ single-mode operation in a laser

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
- ...
Contact Us

Questions? kx.lumerical.com
Sales Inquiries: sales@lumerical.com
Evaluate Lumerical tools free for 30 days  www.lumerical.com