BRAGG GRATINGS IN INTEGRATED PHOTONICS

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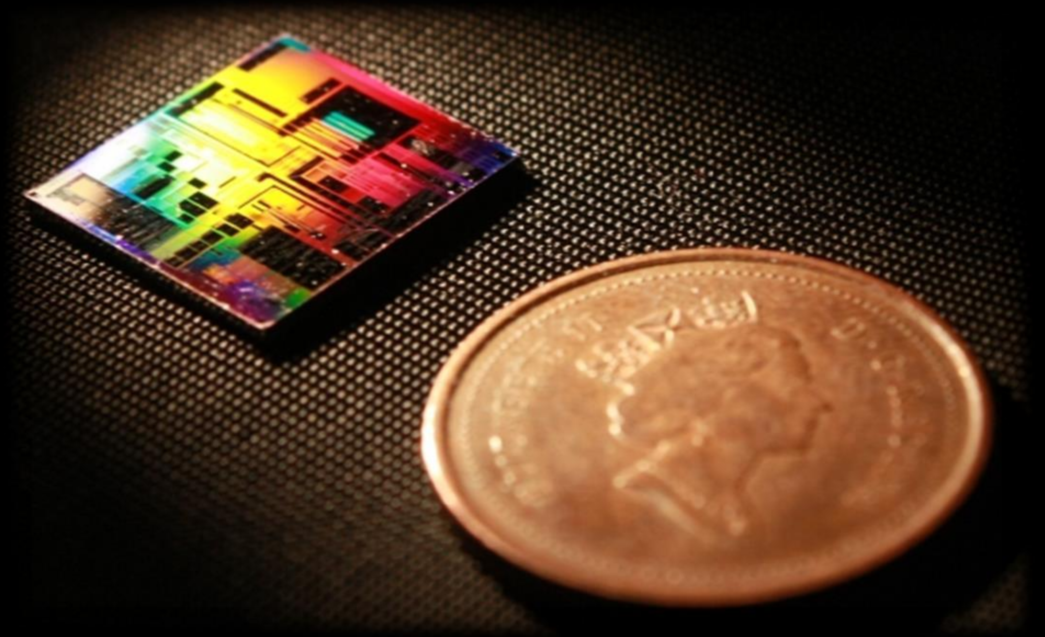
2020-11-20



OUTLINE [1.5 HOURS]

- Introduction

- Simulation:
    - Transfer Matrix Method
    - Coupled Mode Theory
    - EME Method
    - 2D/3D FDTD
    - Bloch boundary bandstructure

- Contra-directional couplers

REFERENCES

- **Bragg gratings and contra-directional couplers tutorial:**
  - https://www.youtube.com/watch?v=jr3NcJsKvTI
- **SiEPIC PDK KLayout integration of Bragg Gratings:**
  - https://www.youtube.com/watch?v=h2MOOhsuYpA
- **SiEPIC PDK KLayout integration of Contra-directional couplers:**
  - https://www.youtube.com/watch?v=aqocwLcqC0s
  - https://www.youtube.com/watch?v=-vWspXuu8I0

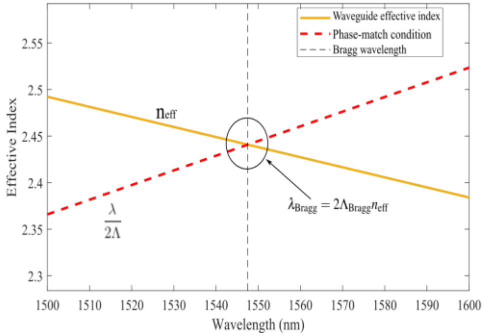
- **Bragg gratings Lumerical: EME**
  - https://support.lumerical.com/hc/en-us/articles/360042304334-Bragg-Grating-full-device-simulation-with-EME
  - https://kx.lumerical.com/t/simulating-integrated-waveguides-bragg-grating-with-mode-eme/
- **Bragg gratings Lumerical: FDTD**
  - https://support.lumerical.com/hc/en-us/articles/360042304394-Bragg-Grating-Initial-Design-with-FDTD
  - https://kx.lumerical.com/t/simulating-integrated-waveguides-bragg-grating-with-fdtd-bandstructure

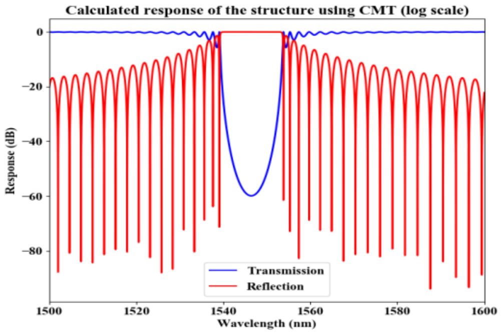
BRAGG GRATINGS

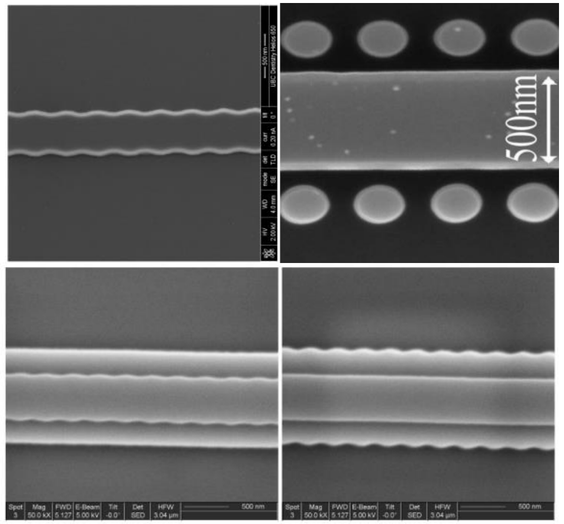
- **Periodically perturbed waveguides**
  - Side-wall modulation (rib or strip waveguides)
  - Cladding modulation
  - Vertical modulation

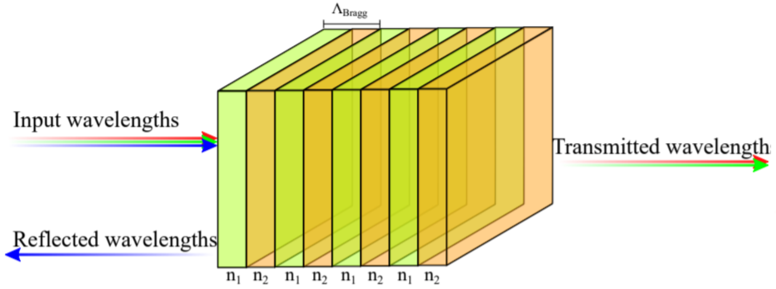
- **Applications:**
  - Dispersion compensation
  - Narrow-band filters
  - Wide-band filters

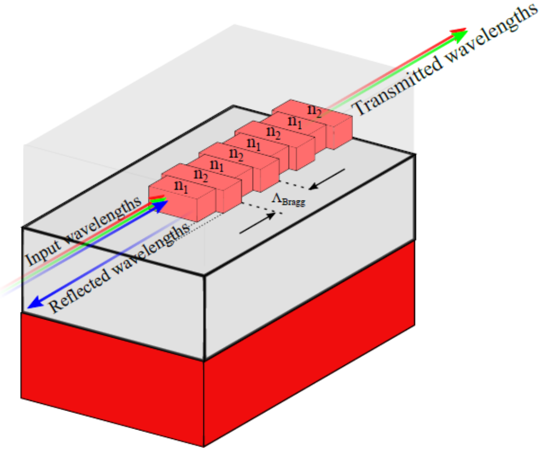
- Filtered wavelengths are reflected back to the input port.
  - **A circulator/isolator is needed!**



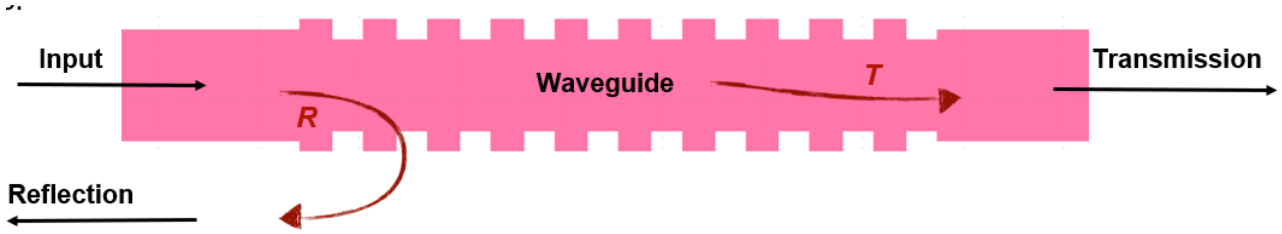






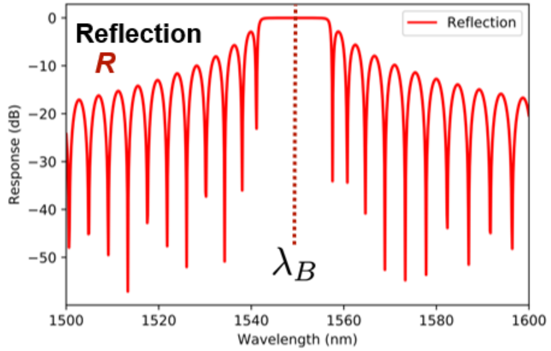


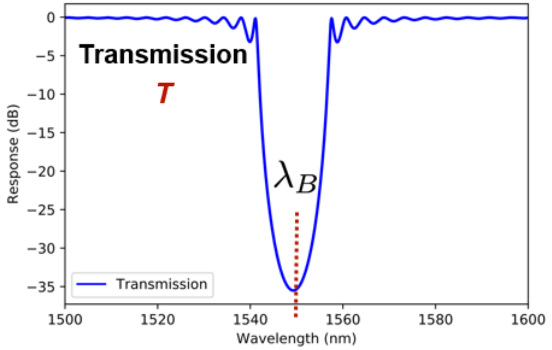
BRAGG GRATINGS



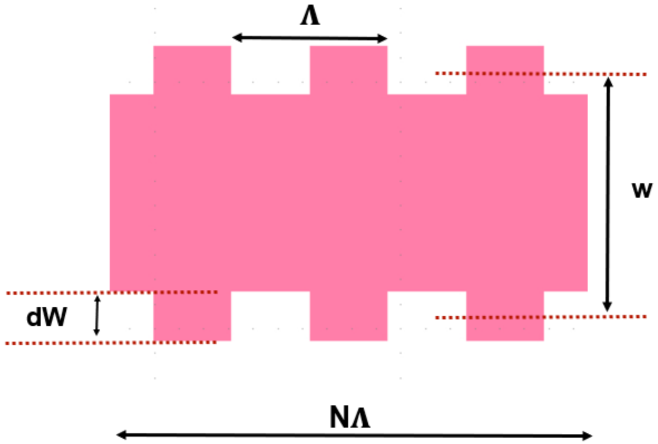
- **Reflections at each perturbation**
- **Reflections interfere constructively only within a narrow range of wavelengths: Bragg wavelength**

$$\lambda_B = 2n_{\text{eff}}\Lambda$$





- **Design Parameters:**
  - **Grating period Λ**
  - **Width of the waveguide, W**
  - **Corrugations width, dW**
  - **Number of corrugations, N**



BRAGG GRATINGS

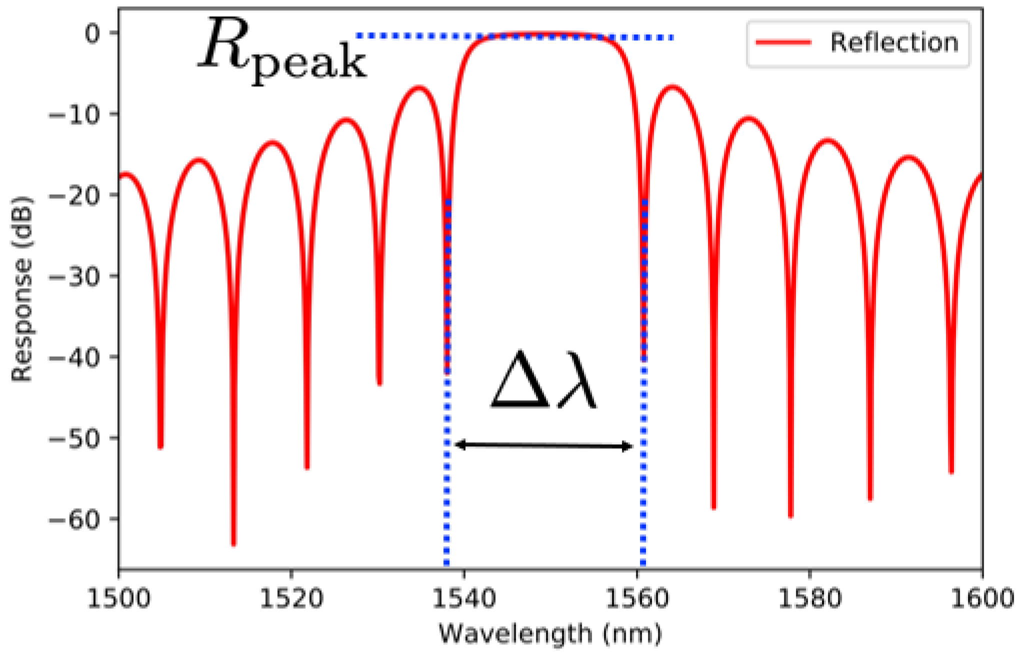
- Coupled-mode theory also predicts the peak reflectivity

$$R_{peak} = \tanh^2(\kappa L)$$

- And the bandwidth (defined here as the 1st-nulls bandwidth, not the 3-dB bandwidth)

$$\Delta\lambda = \frac{\lambda_B^2}{\pi n_g}\sqrt{\kappa^2 + (\pi/L)^2}$$

- How do we find (kappa), the coupling coefficient?
  - Experiments
  - Simulations



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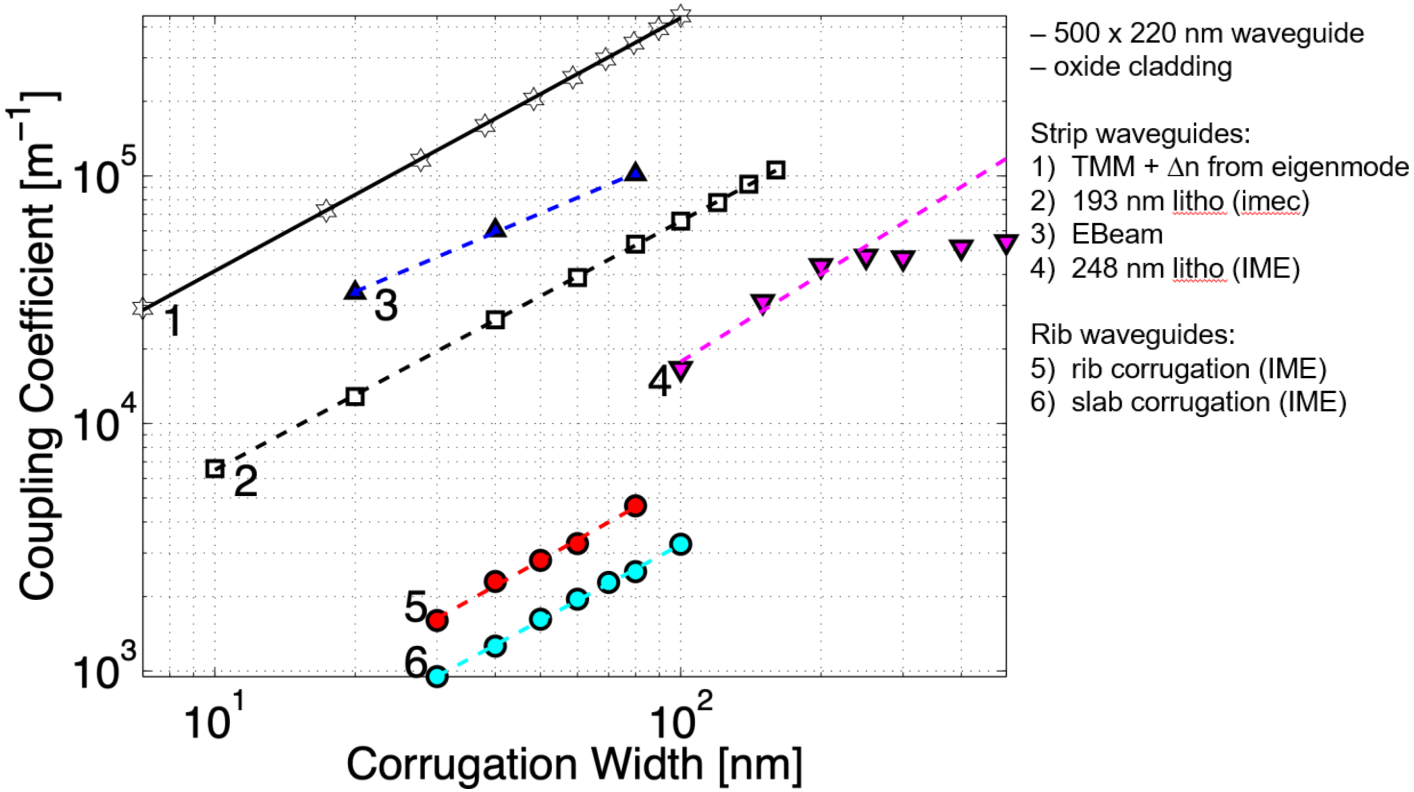
SiEPIC FAB

EXPERIMENTS

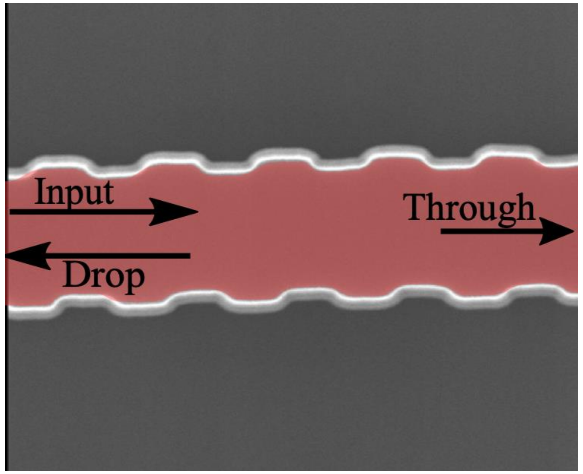
- **Experimental Data from Previous Runs**

- **Coupling coefficient correlates with bandwidth**



APPLICATIONS

- **Bragg reflector for the laser cavity**



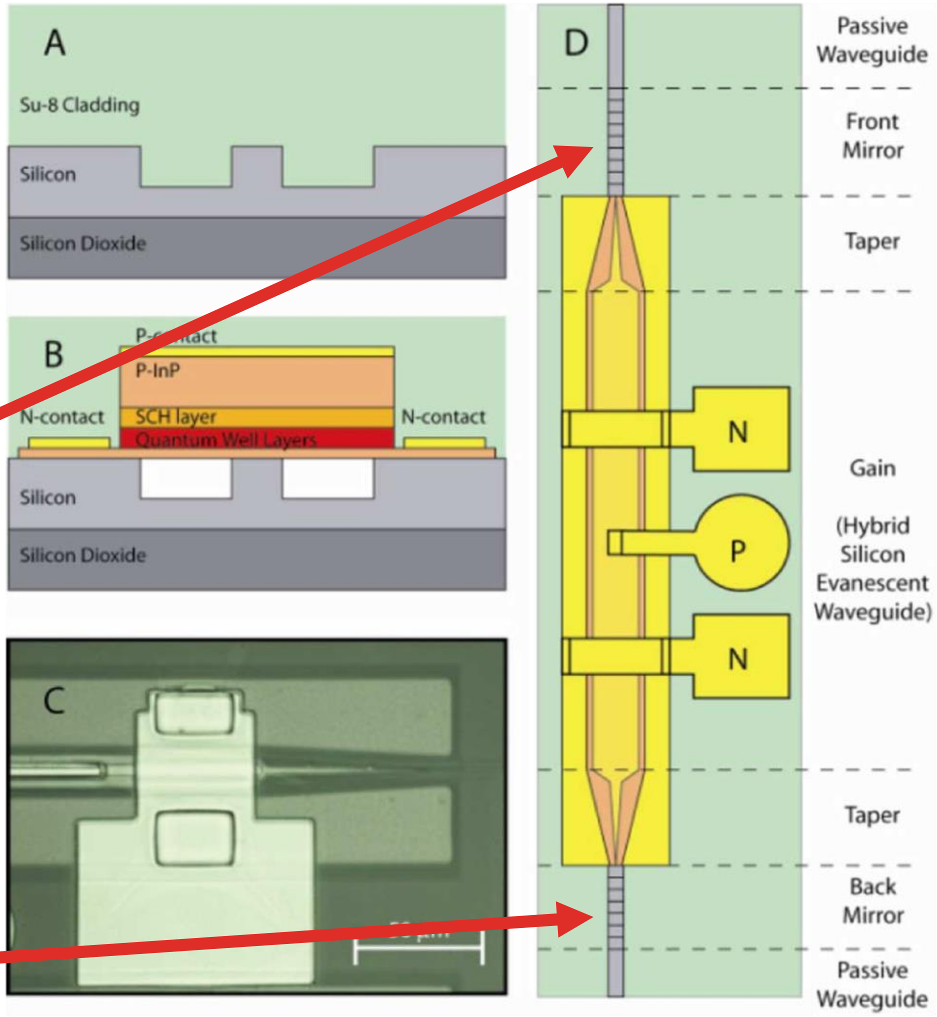


Fig. 1. (a) Passive silicon rib and (b) hybrid silicon evanescent waveguide cross section. (c) Microscope image of a hybrid to passive taper. (d) DBR-SEL top-view topographical structure.

TRANSFER MATRIX METHOD

- **Available:** https://github.com/mustafacc/SiEPIC_Photonics_Package/blob/master/SiEPIC_Photonics_Package/solvers_simulators/bragg_tmm/bragg_tmm.py

- Handy tool to quickly model phase-shifted Bragg gratings

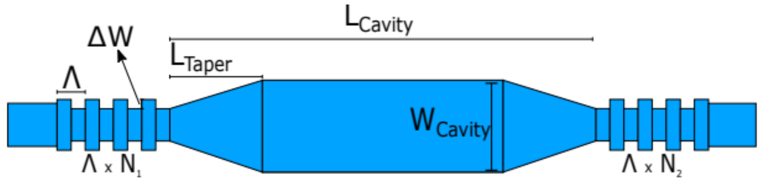
- **Inputs:**
  - Waveguides compact models (effective indices fits, n(λ))
  - Period
  - Number of corrugations
  - Perturbation size

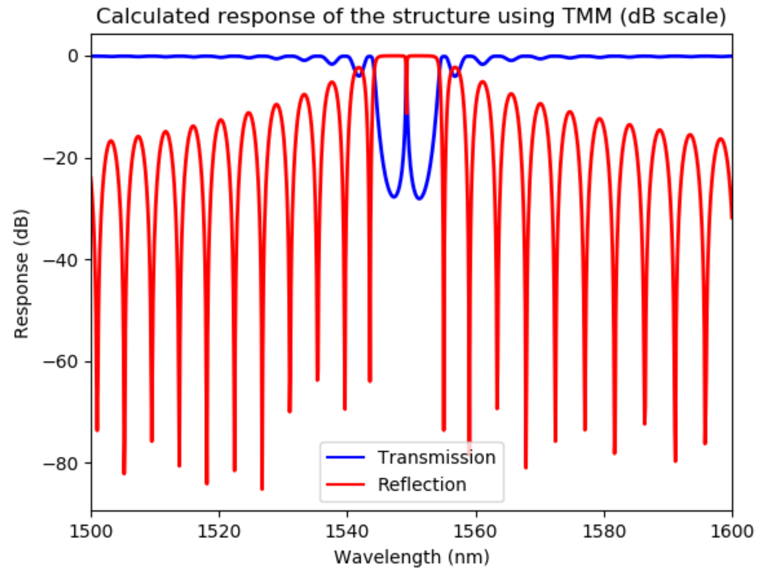
- **Advantages:**
  - Quick and simple
  - Does not scale up with the length of the device
  - Can simulate complex device profiles (apodized, chirped, etc.)

- **Disadvantages:**
  - Must have data to fit the coupling coefficient profile vs perturbation size!

TRANSFER MATRIX METHOD

- **Run bragg_tmm.py**






```python
#%% user input

# set the wavelength span for the simultion
wavelength_start = 1500e-9
wavelength_stop = 1600e-9
resolution = 0.1

# Grating waveguide compact model (cavity)
# these are polynomial fit constants from a waveguide width of 500 nm
n1_wg = 4.077182700600432
n2_wg = -0.982556173493906
n3_wg = -0.046366956781710

# Cavity waveguide compact model (cavity)
# these are polynomial fit constants from a waveguide width of 500 nm
n1_c = 4.077182700600432
n2_c = -0.982556173493906
n3_c = -0.046366956781710

# grating parameters
period = 317e-9      # period of pertrubation
n_delta = .0       # effective index pertrubation
lambda_Bragg = 1550e-9
dw = 20e-9
kappa = -1.53519e19 * dw**2+ 2.2751e12 * dw
n_delta = kappa * lambda_Bragg / 2
print(n_delta)
N_left = 200          # number of periods (left of cavity)
N_right = 200         # number of periods (right of cavity)

# Cavity Parameters
alpha_dBcm = 7      # dB per cm
alpha = np.log(10)*alpha_dBcm/10*100. # per meter

L = period/2     # length of cavity
```

TRANSFER MATRIX METHOD

- **Available:** https://github.com/mustafacc/SiEPIC_Photonics_Package/blob/master/SiEPIC_Photonics_Package/solvers_simulators/bragg_cmt/bragg_cmt.py
- Handy tool to quickly model phase-shifted Bragg gratings
- **Inputs:**
  - Waveguides compact models (effective indices fits, n(λ))
  - Period
  - Number of corrugations
  - Coupling coefficient (kappa)
- **Advantages:**
  - Accurate, less accurate for large perturbations
  - Not computationally intensive
- **Disadvantages:**
  - Must have a real value for the coupling coefficient!

COUPLED MODE THEORY

- Dependent on the waveguides' geometry and structure of the perturbation gratings (strength/shape)
- Determines the bandwidth and reflectivity of the device
- The key parameter that sets coupled-mode theory model to work.
- Accurate for small perturbations
- Easily implemented for simple
- perturbations
- Difficult to find the Fourier-expansion term (**Δε**) for unconventional perturbations shapes (ex: sinusoidal or litho. smoothed corrugations)

$$\kappa_{11} = \frac{\omega}{4}\iint \mathbf{E_1^*}(x,y)\cdot\Delta\epsilon_1(x,y)\mathbf{E_1}(x,y)dxdy$$

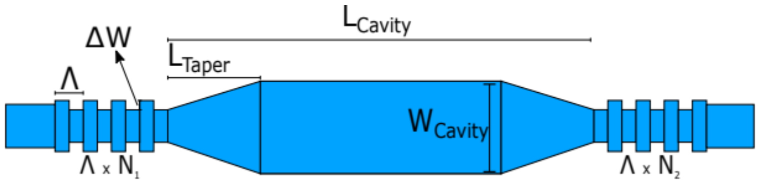
$$\kappa_{12} = \frac{\omega}{4}\iint \mathbf{E_1^*}(x,y)\cdot\Delta\epsilon_1(x,y)\mathbf{E_2}(x,y)dxdy$$

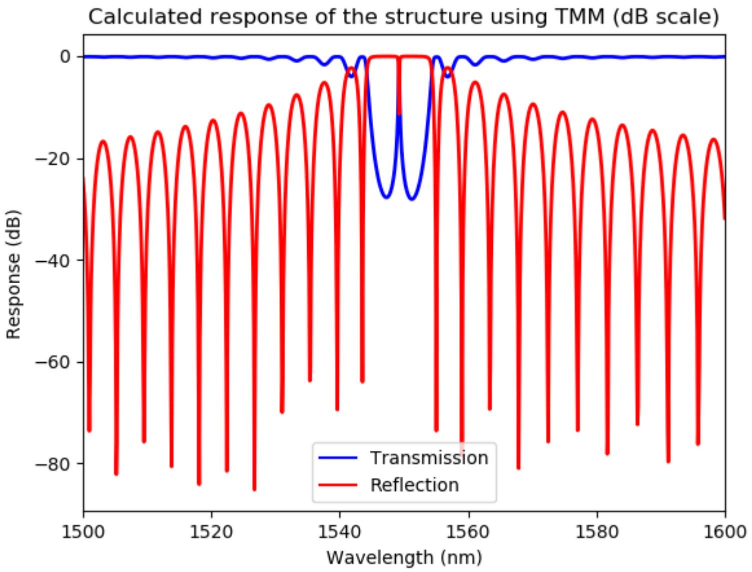
$$\kappa_{21} = \frac{\omega}{4}\iint \mathbf{E_2^*}(x,y)\cdot\Delta\epsilon_1(x,y)\mathbf{E_1}(x,y)dxdy$$

$$\kappa_{22} = \frac{\omega}{4}\iint \mathbf{E_2^*}(x,y)\cdot\Delta\epsilon_1(x,y)\mathbf{E_2}(x,y)dxdy$$

COUPLED MODE THEORY

- Run bragg_cmt.py





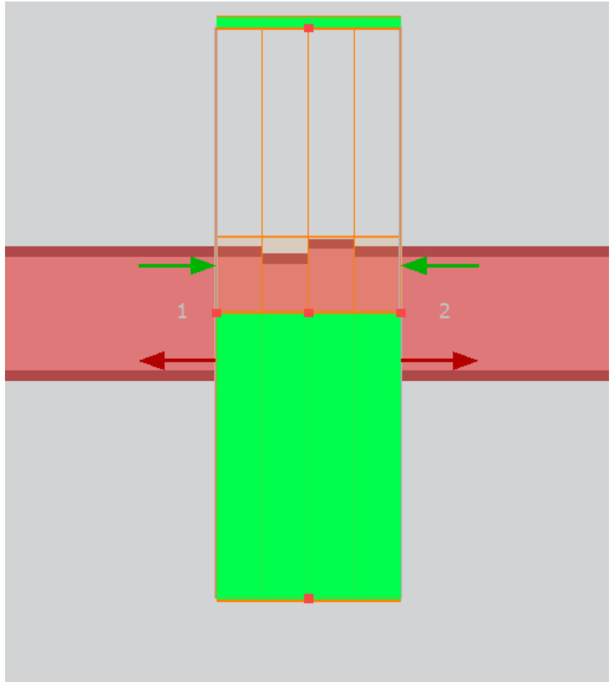

```python
#%% dependent packages
import numpy as np
import math, cmath, matplotlib
from numpy.lib.scimath import sqrt as csqrt

#%% user input
wavelength_start = 1500e-9
wavelength_stop = 1600e-9
resolution = 0.001

# Grating waveguide compact model (cavity)
# these are polynomial fit constants from a waveguide width of 500 nm
n1_g = 4.077182700600432
n2_g = -0.982556173493906
n3_g = -0.046366956781710

# Cavity waveguide compact model (cavity)
# these are polynomial fit constants from a waveguide width of 500 nm
n1_c = 4.077182700600432
n2_c = -0.982556173493906
n3_c = -0.046366956781710

# grating parameters
kappa = 45000        # coupling strength (/m)
period = 317e-9      # period of pertrubation
N_left = 200         # number of periods (left of cavity)
N_right = 200        # number of periods (right of cavity)

# Cavity Parameters
alpha = 150/4.34
L = period/2     # length of cavity
```

EME METHOD

- **Uses the EME method:**
  - Explained: https://apps.lumerical.com/pic_passive_bragg_full_device_simulation_with_eme.html
  - Video tutorial: https://www.lumerical.com/support/video/waveguide-bragg-gratings-res.html
  - https://kx.lumerical.com/t/simulating-integrated-waveguides-bragg-grating-with-mode-eme/62560

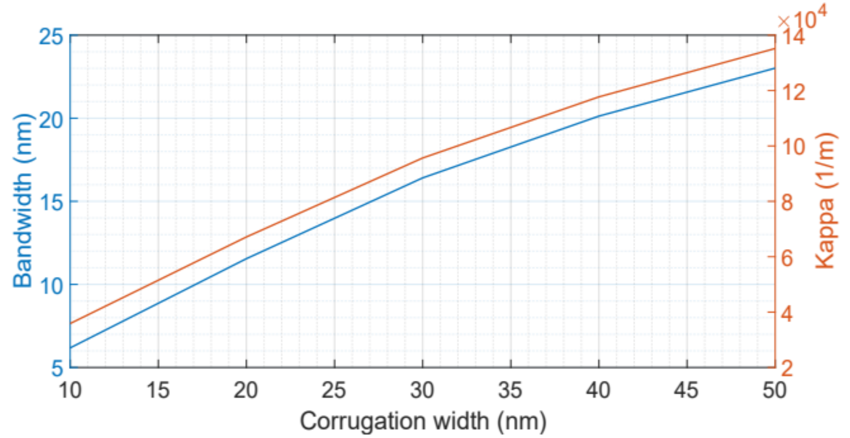
- **Advantages:**
  - Does not need information other than the physical geometry of the device
  - Relatively fast simulation time compared to FDTD

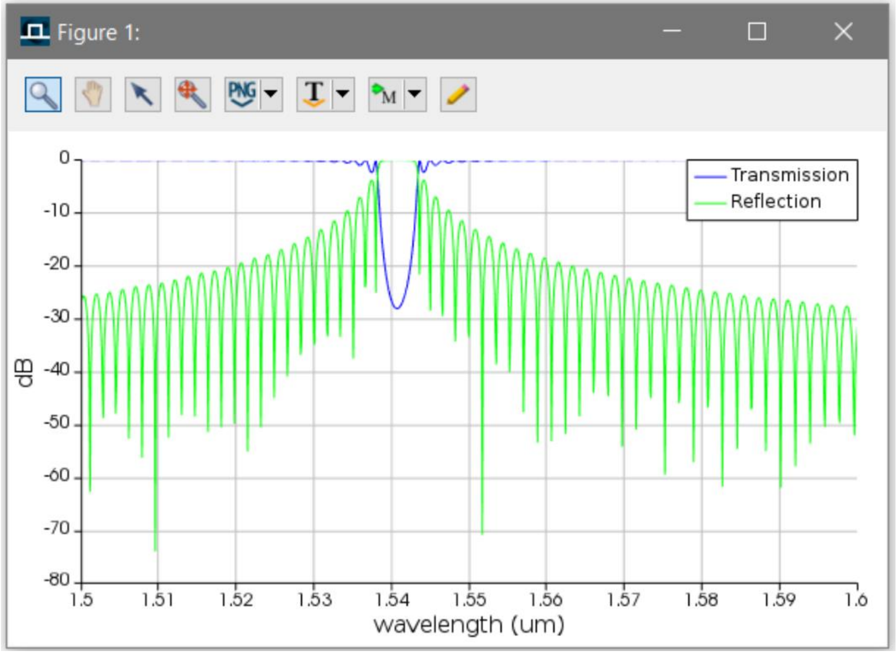
- **Disadvantages:**
  - Simulation time scales up with the complexity of the profile
  - Simulation time scales up with the number of simulation modes required to simulate the device
  - Less accurate than FDTD simulations



EME METHOD

- **How to:**
  - Run Main_EME.lfs in MODE
  - The script will plot the transmission and reflection spectra, and then extract the 3-dB bandwidth and central wavelength (for your future Kappa analysis).





EME METHOD

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  - Run Main_EME.lfs in MODE

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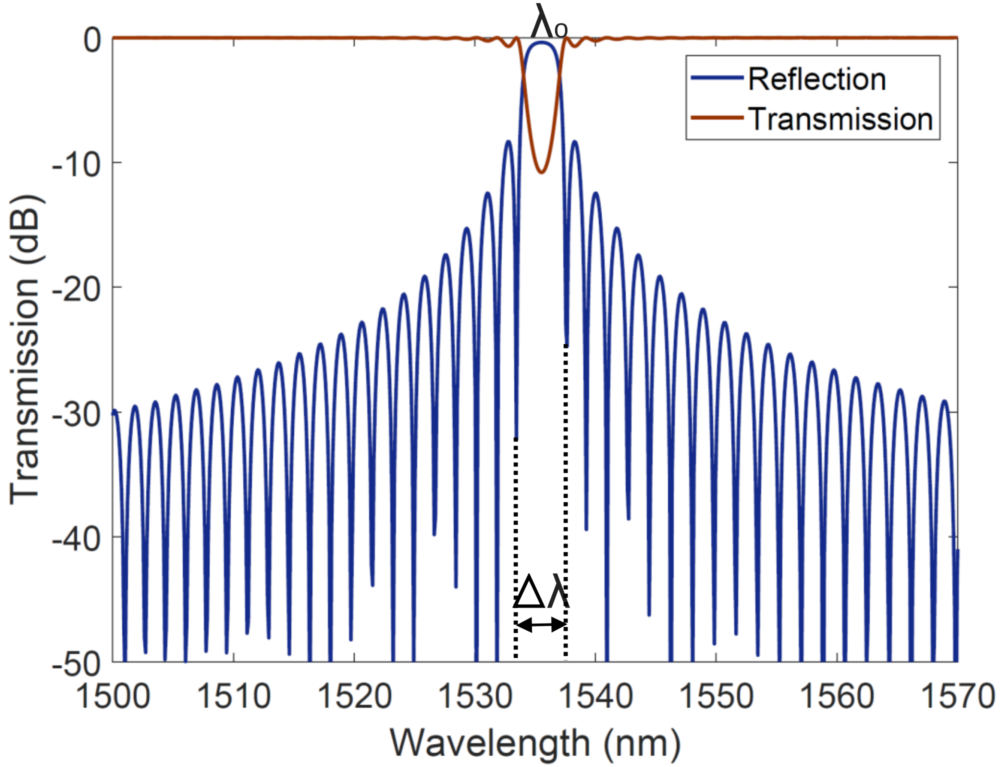
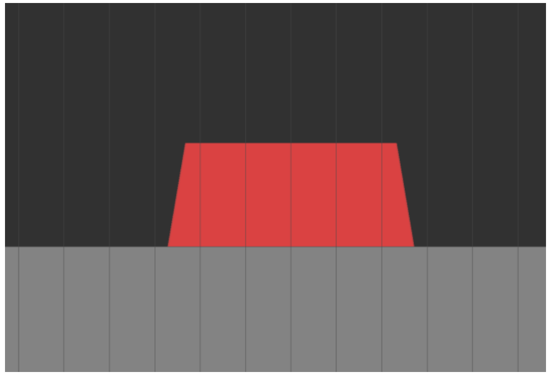
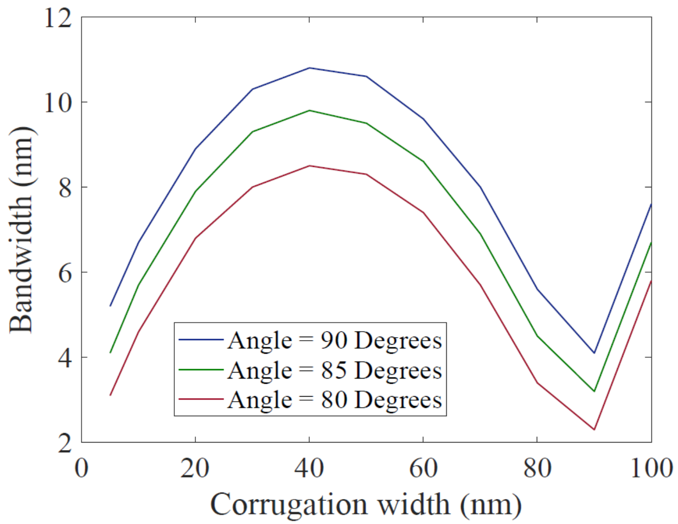
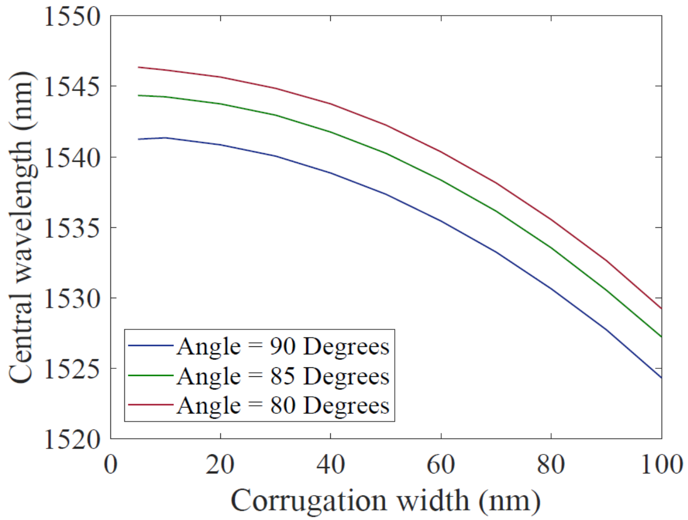


EME METHOD



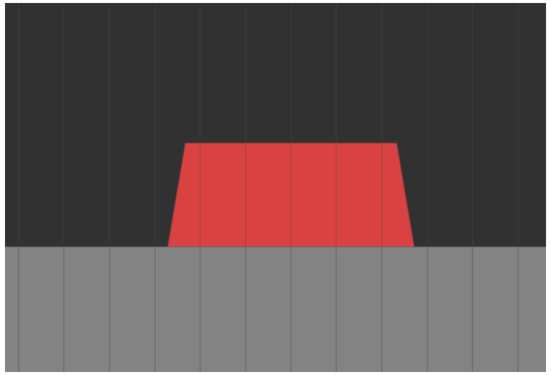
- EME simulations can be used to quickly perform parametric studies to understand the effects of specific parameters, i.e. **the effects of changing the waveguide's sidewall angle**:



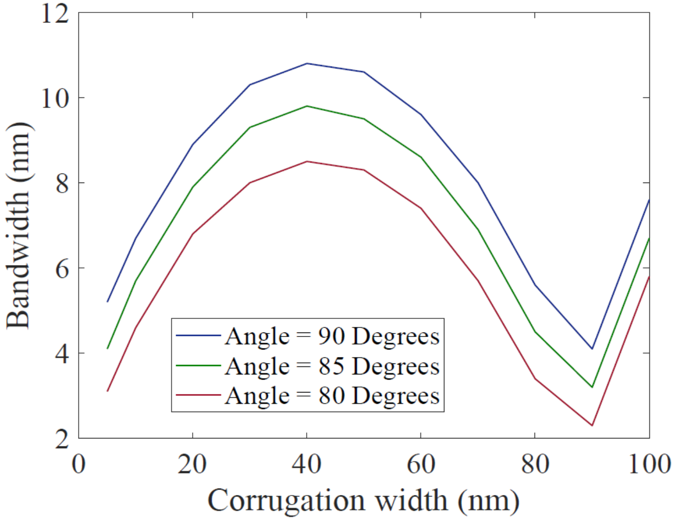


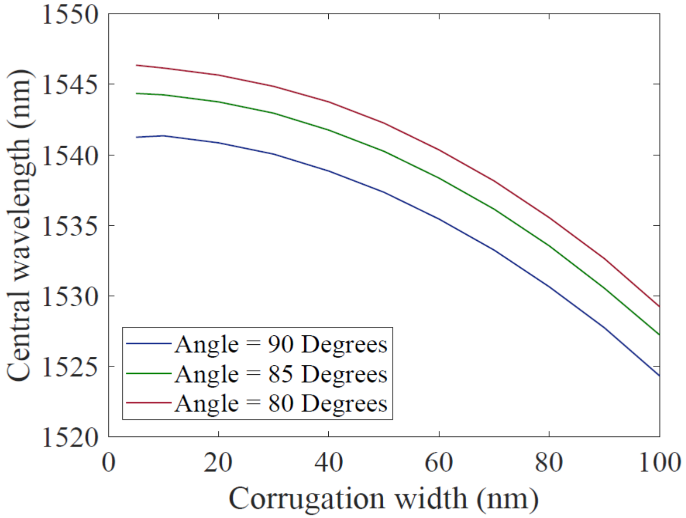
- Run applications -> dw_sweep -> **MAIN_dw_sweep.lsf**

EME METHOD



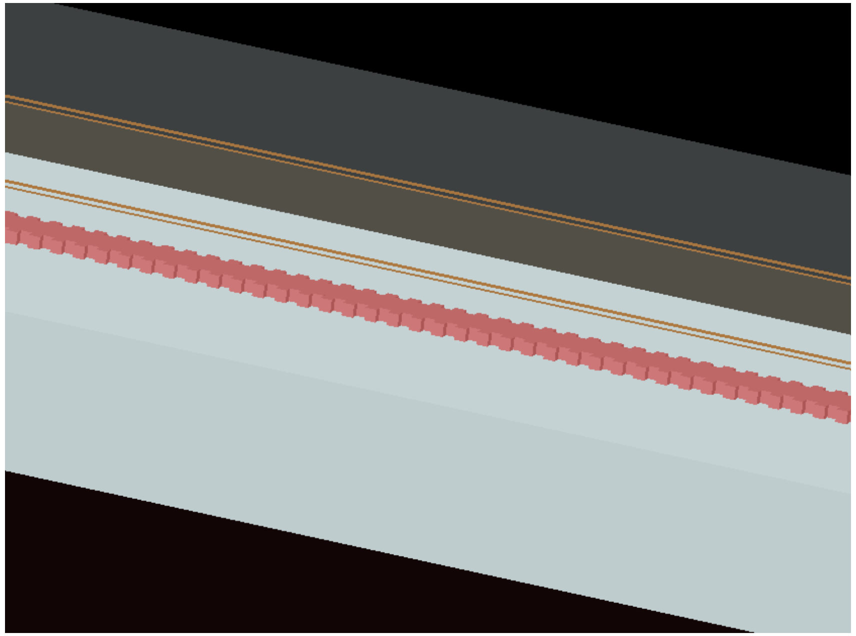
- The scripts will force specific settings to improve the simulation speed (e.g., force anti-symmetric boundary conditions when the user specifies the TE polarization) - therefore, if you care more about accuracy rather than speed, you might want to remove these settings from *Bragg_simulate.lsf*.





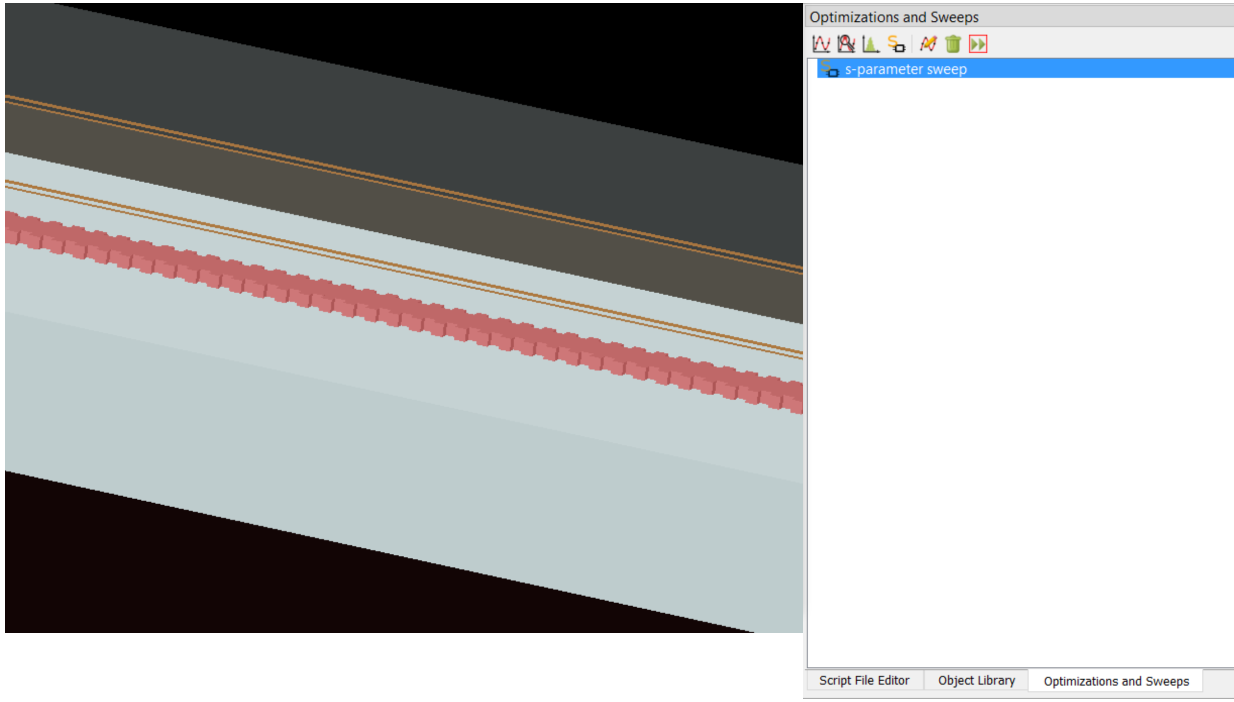
2D/3D FDTD

- **Uses FDTD solver:**
  - Simulating the full device length either in **2D FDTD or 3D FDTD**
- **Advantages:**
  - Accurate, if the simulation mesh and time were sufficiently large…
  - Can be used to simulated complex apodization provide.
- **Disadvantages:**
  - Very lengthy simulation time!



2D/3D FDTD

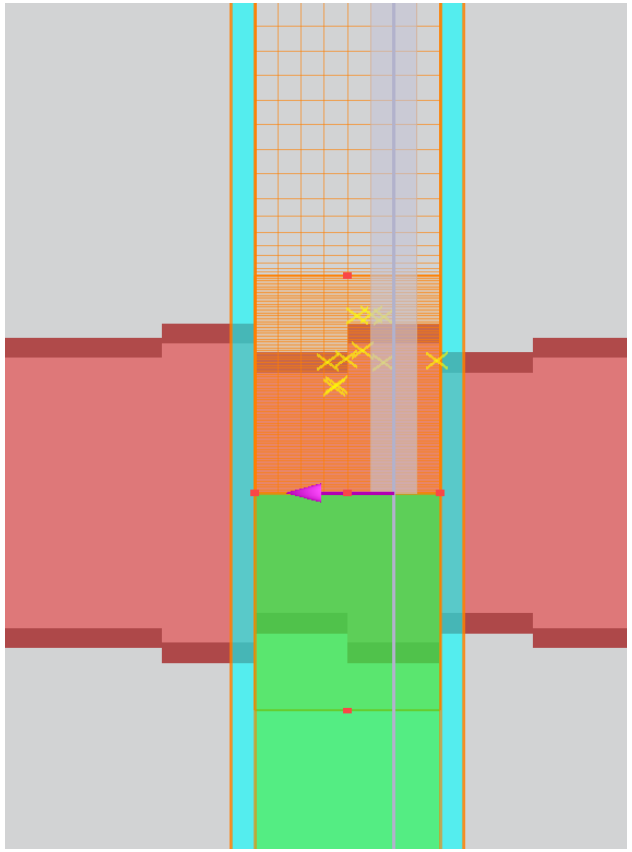
- Open new FDTD project and load sample code ***MAIN_FDTD.lsf***
- **Input parameters:**
  - Device physical parameters
  - Simulation parameters
- You can create an S-parameters sweep as well.
  - You can use ports symmetry.



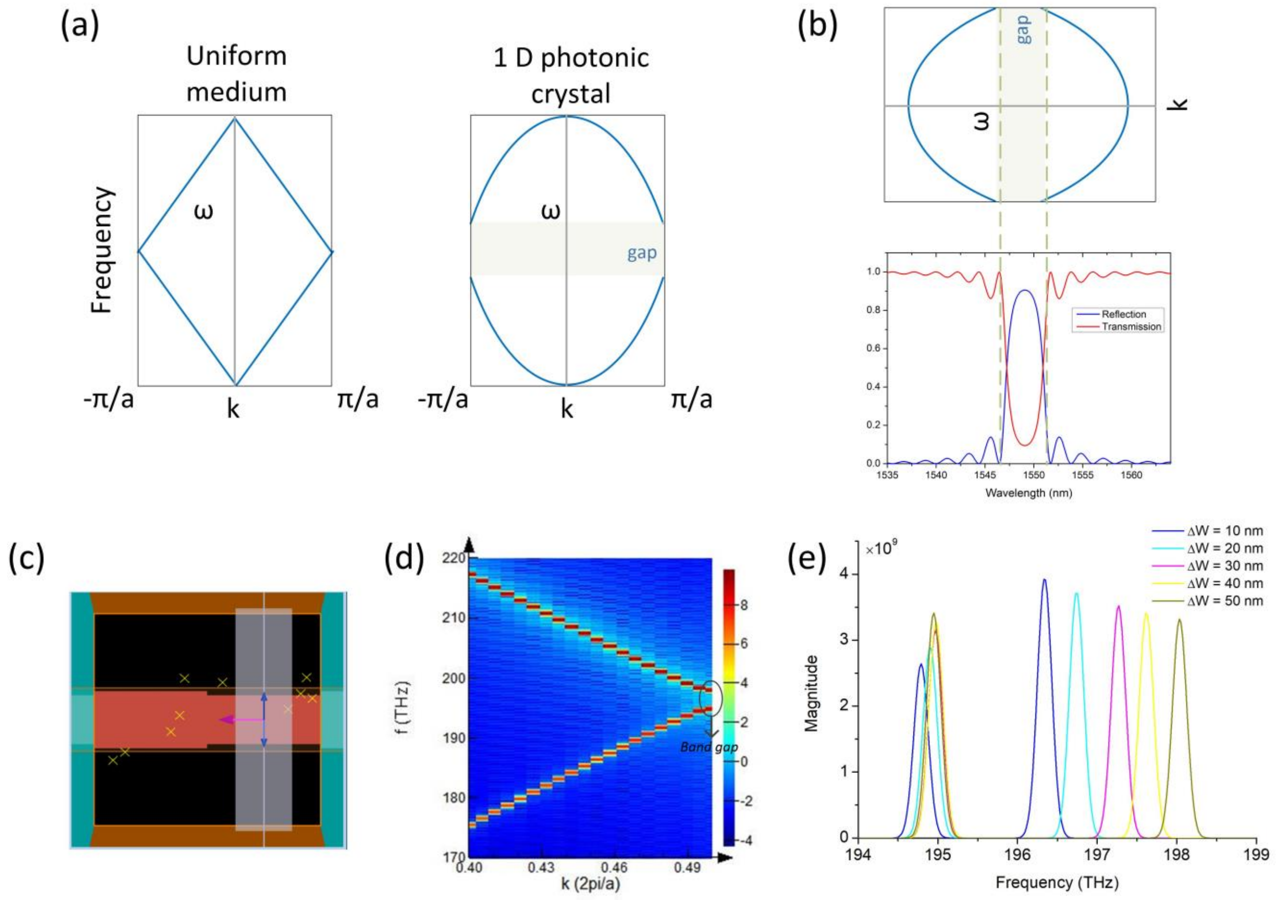
* There are rarely times you need to use 3D FDTD to simulate an entire length of a Bragg grating device. The example is added here for illustrating the inefficiency of the method relative to other methods.

FDTD BLOCH BOUNDARY

- **Uses FDTD solver:**
  - Simulating one unit cell of a grating over an infinite length.
- **Advantages:**
  - Relatively fast simulation with the most accurate results.
  - Can be used to perform various parametric sweeps.
- **Disadvantages:**
  - Cannot simulate the output spectra of advanced apodized devices (directly).
  - Does not show the output spectra of the device
- More at:
  - https://support.lumerical.com/hc/en-us/articles/360042304394-Bragg-Grating-Initial-Design-with-FDTD

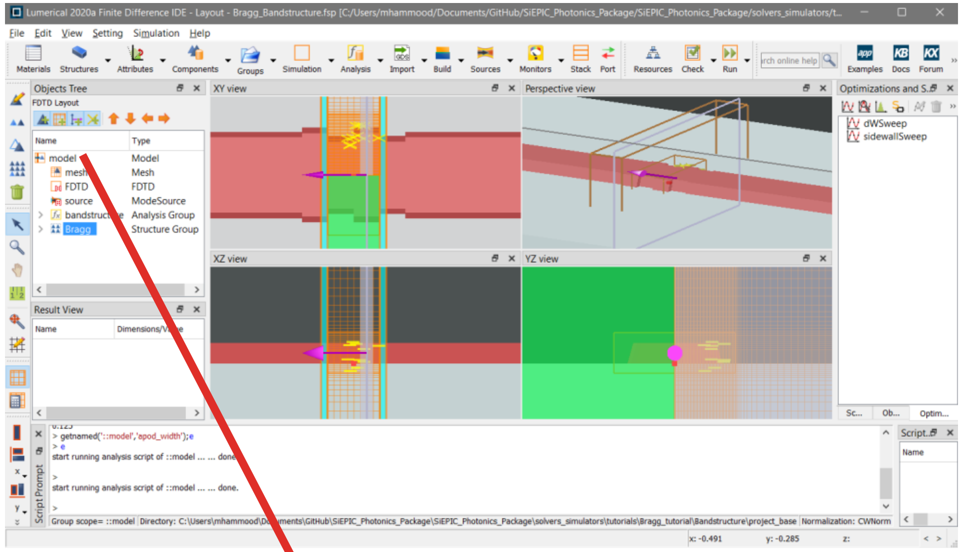


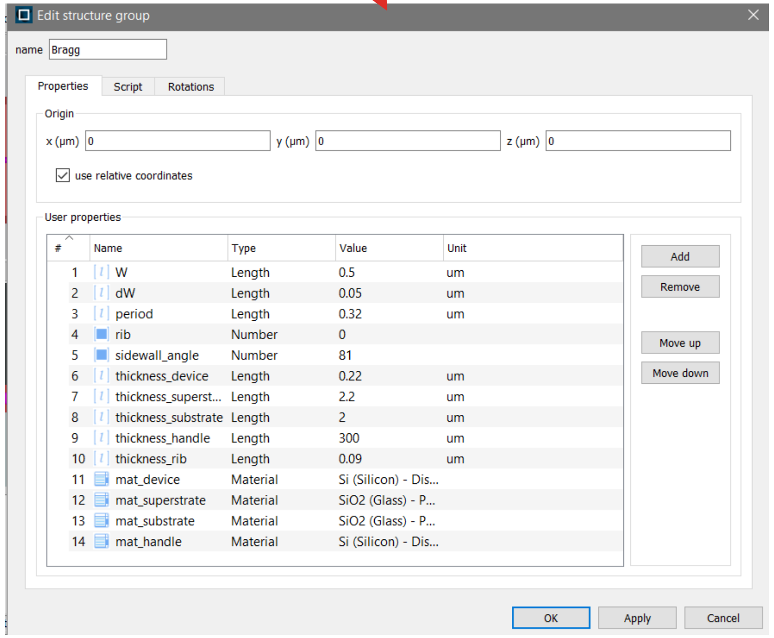
FDTD BLOCH BOUNDARY



FDTD BLOCH BOUNDARY

- Two examples provided under '**Bandstructure**'
  - **Script-based:** run 'MAIN_Bandstructure.lsf' using FDTD script window with simulation and physical parameters. This is a "GUI"-less approach that will setup the simulation for you.
  - **Project-based:** open "Bragg_bandstructure.fsp' using FDTD and configure the simulation settings under "model" and physical settings under "Bragg" objects.
    - Sample parametric sweeps were setup in this project as an example.





#	Name	Type	Value	Unit
1	W	Length	0.5	um
2	dW	Length	0.05	um
3	period	Length	0.32	um
4	rib	Number	0	
5	sidewall_angle	Number	81	
6	thickness_device	Length	0.22	um
7	thickness_superst...	Length	2.2	um
8	thickness_substrate	Length	2	um
9	thickness_handle	Length	300	um
10	thickness_rib	Length	0.09	um
11	mat_device	Material	Si (Silicon) - Dis...	
12	mat_superstrate	Material	SiO2 (Glass) - P...	
13	mat_substrate	Material	SiO2 (Glass) - P...	
14	mat_handle	Material	Si (Silicon) - Dis...	

FDTD BLOCH BOUNDARY

- **How to (method 1, script base):**
  - Download the scripts script_base.zip and open a blank FDTD project
  - From FDTD, load the script *MAIN_Bandstructure.lsf*
  - Adjust the simulation parameters to your needs (wavelength range, polarization, mesh accuracy

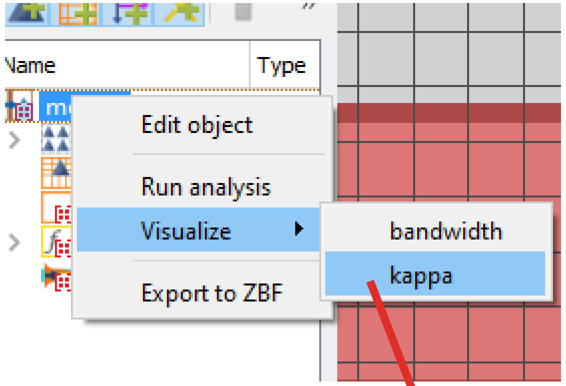
```
###############################

wl_min = 1.5e-6; # simulation wavelength start
wl_max = 1.6e-6; # simulation wavelength stop

pol = 'TE'; # simulaiton polarization

mesh_y = 5e-9;
mesh_x = 5e-9;
mesh_z = 20e-9;

sim_time = 1500e-15; #E-15 is femto...
mesh = 2;
```

FDTD BLOCH BOUNDARY

- **How to (method 1, script base):**
  - Adjust the device geometry, material, and process stack settings to your needs. Currently the default settings are set for SOI in mind, but it can be changed to any platform.

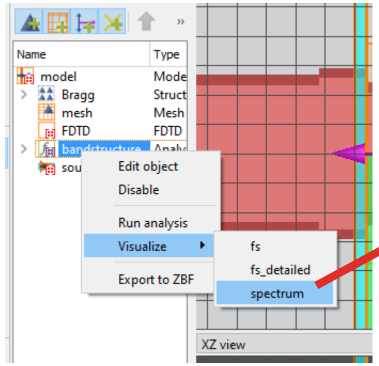
```
W = 500e-9; # uncorrugated waveguide width
dW = 50e-9; # waveguide corrugation
period = 320e-9; # corrugations period
rib = false; # enable or disable rib layered waveguide type (do not enable with TM mode)
sidewall_angle = 81;

thickness_device = 220e-9; # waveguide full thickness
thickness_rib = 90e-9; # waveguide rib layer thickness
thickness_superstrate = 2e-6; # superstrate thikness
thickness_substrate = 2e-6; # substrate thickness
thickness_handle = 300e-6; # handle substrate thickness

mat_device = 'Si (Silicon) - Dispersive & Lossless'; # device material
mat_superstrate = 'SiO2 (Glass) - Palik'; # superstrate material
mat_substrate = 'SiO2 (Glass) - Palik'; # substrate material
mat_handle = 'Si (Silicon) - Dispersive & Lossless'; # handle substrate material
```

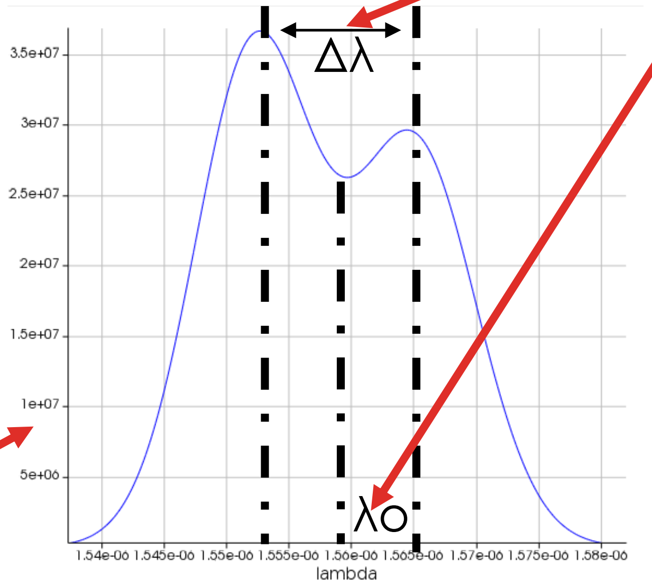
FDTD BLOCH BOUNDARY



$$\kappa = \frac{\pi n_g \Delta\lambda}{\lambda_0^2}$$

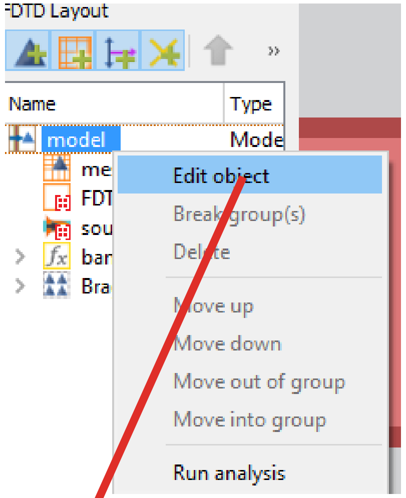
- **How to (method 1, script base):**
  - Run the script - given the current settings, it should run in under ~3 minutes.
  - The script will extract the nulls bandwidth and central wavelength of the Bragg grating, which you can use to extract the Kappa (coupling coefficient) to be used in a coupled-mode theory model.
  - You can visualize the results





FDTD BLOCH BOUNDARY

- **How to (method 2, project base):**
  - Download the scripts project_base.zip and open Bragg_bandstructure.fsp this is an already setup simulation project.
  - Right click on Model and edit the simulation settings and parameters to your requirements:

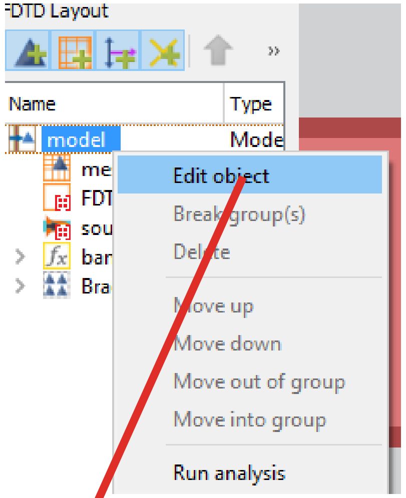


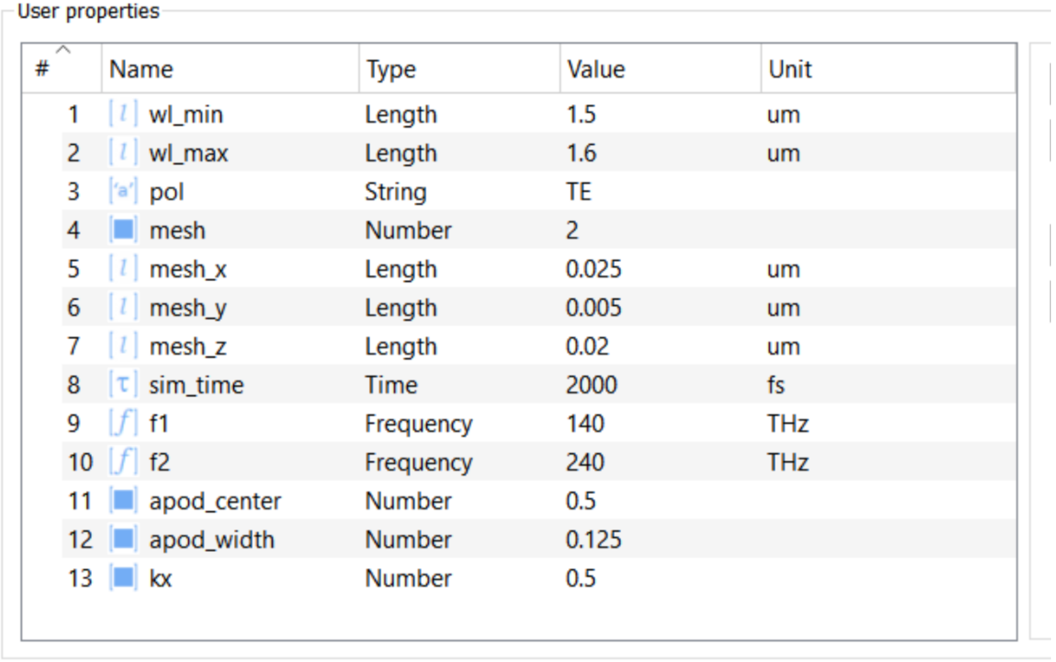
User properties

#	Name	Type	Value	Unit
1	wl_min	Length	1.5	um
2	wl_max	Length	1.6	um
3	pol	String	TE	
4	mesh	Number	2	
5	mesh_x	Length	0.025	um
6	mesh_y	Length	0.005	um
7	mesh_z	Length	0.02	um
8	sim_time	Time	2000	fs
9	f1	Frequency	140	THz
10	f2	Frequency	240	THz
11	apod_center	Number	0.5	
12	apod_width	Number	0.125	
13	kx	Number	0.5	

FDTD BLOCH BOUNDARY

- **How to (method 2, project base):**
  - Right click on Bragg structure group and edit the device geometry, material, and process stack.

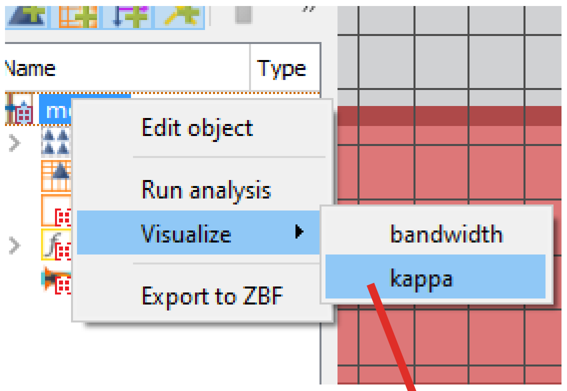



User properties

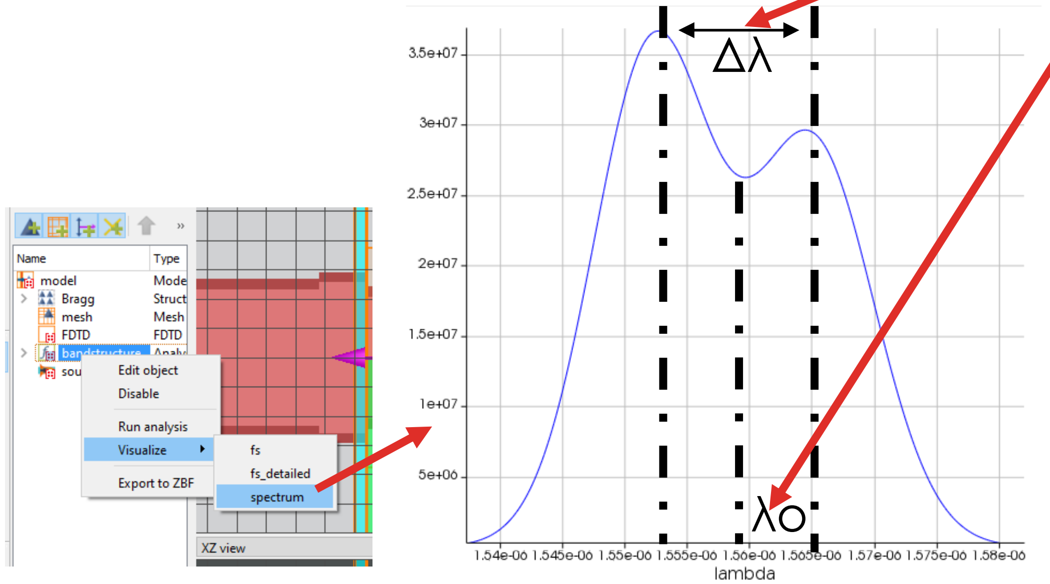
#	Name	Type	Value	Unit
1	wl_min	Length	1.5	um
2	wl_max	Length	1.6	um
3	pol	String	TE	
4	mesh	Number	2	
5	mesh_x	Length	0.025	um
6	mesh_y	Length	0.005	um
7	mesh_z	Length	0.02	um
8	sim_time	Time	2000	fs
9	f1	Frequency	140	THz
10	f2	Frequency	240	THz
11	apod_center	Number	0.5	
12	apod_width	Number	0.125	
13	kx	Number	0.5	

FDTD BLOCH BOUNDARY

- **How to (method 2, project base):**
  - Run the simulation and let it run. Once the simulation is done you can right click on model and run the analysis to extract the coupling coefficient, bandwidth, and central wavelength of the Bragg grating.

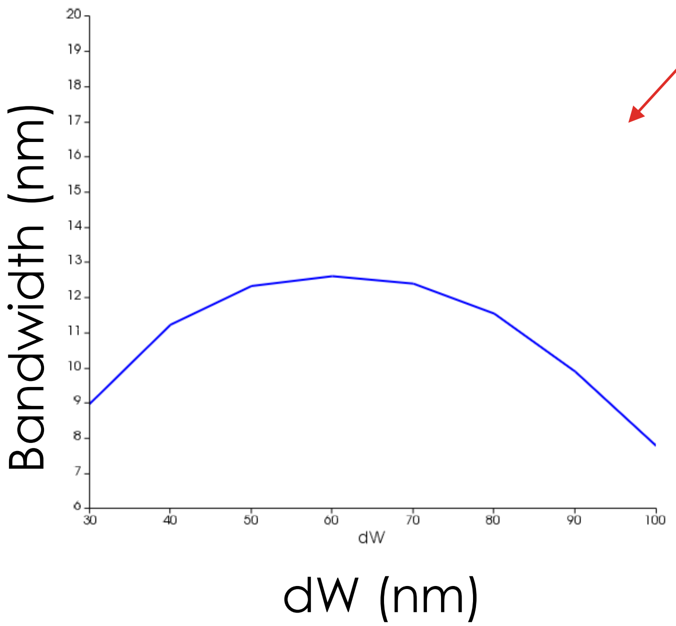


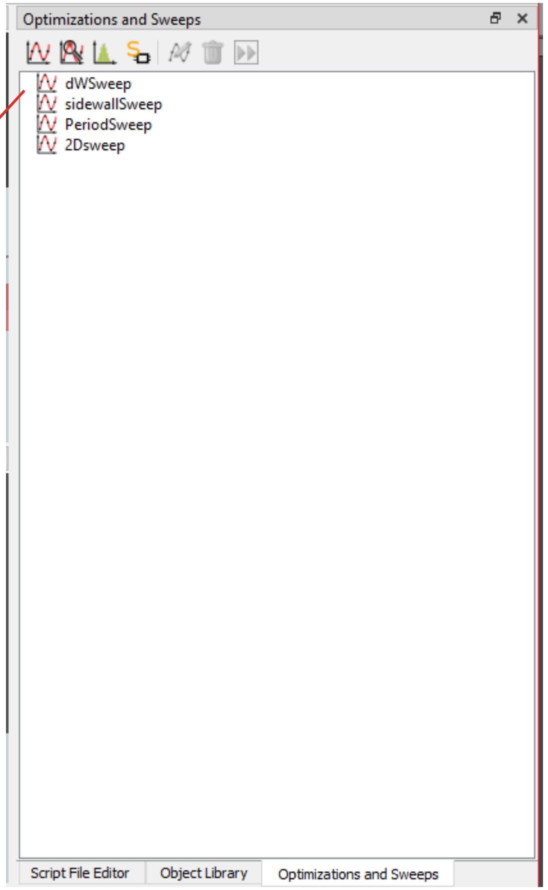
$$\kappa = \frac{\pi n_g \Delta\lambda}{\lambda_0^2}$$



FDTD BLOCH BOUNDARY

- **How to (method 2, project base):**
  - I provided sample parametric sweeps in the optimization and sweeps tab that will help you understand the effects of each of the following parameters:
    - Perturbation width
    - Sidewall angle
    - Bragg Period





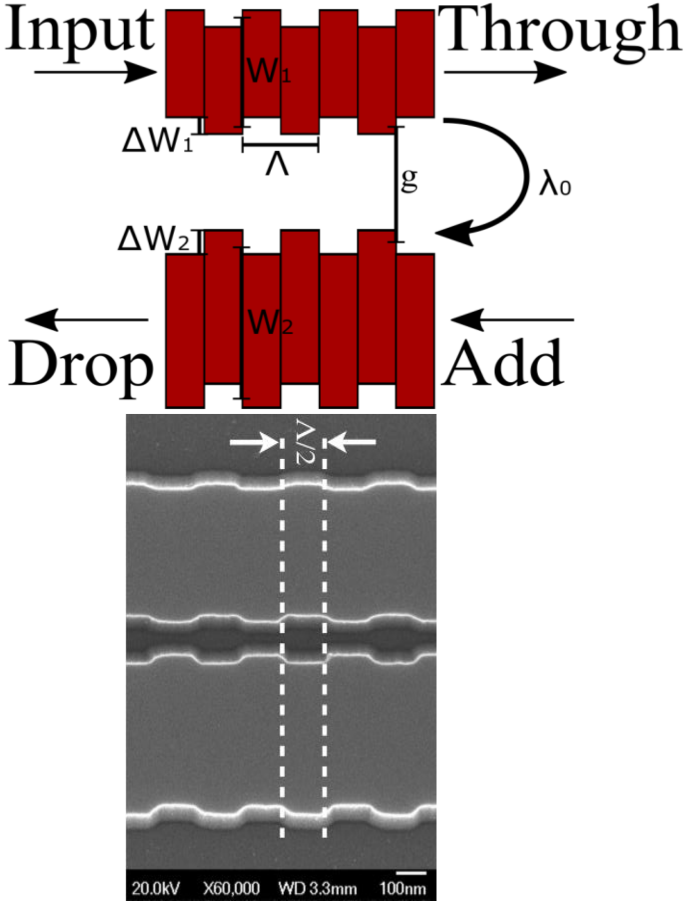
CONTRA-DIRECTIONAL COUPLERS

- **Design parameters:**
  - Waveguides widths, corrugations width, waveguides gap, corrugations period apodization profile

- Selected design parameters determine the **figures of merit**:
  - Bandwidth, central wavelength, band ripple/flatness, crosstalk

- Demonstrated on both E-Beam Deep-Ultraviolet (DUV) lithography **[3]**.

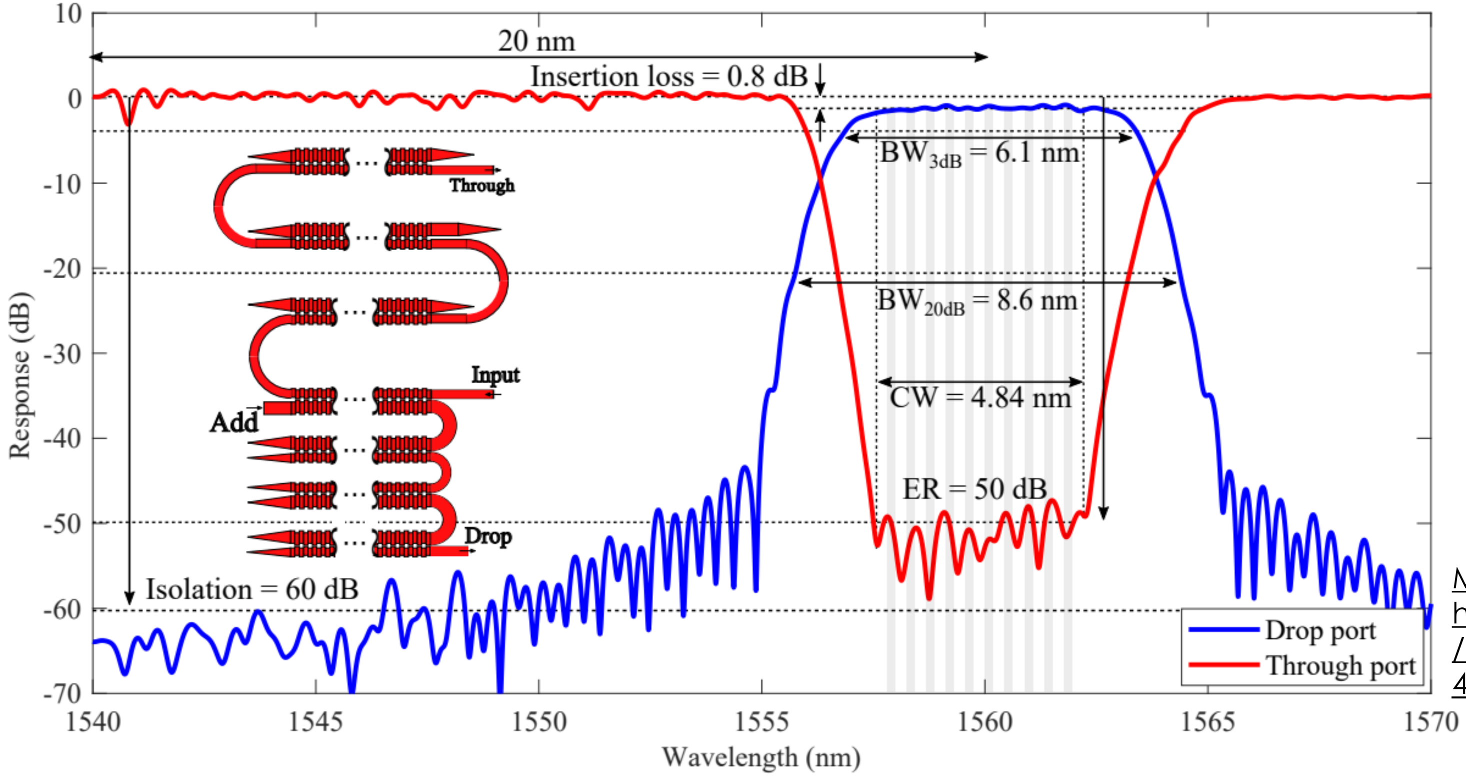
- Demonstrated on both C-Band and O-Band.



[3] W. Shi, X. Wang, W. Zhang, L. Chrostowski, and N. A. F. Jaeger, "Contradirectional couplers in silicon-on-insulator rib waveguides," *Optics Letters*, vol. 36, no. 20, p. 3999, May 2011.

CONTRA-DIRECTIONAL COUPLERS

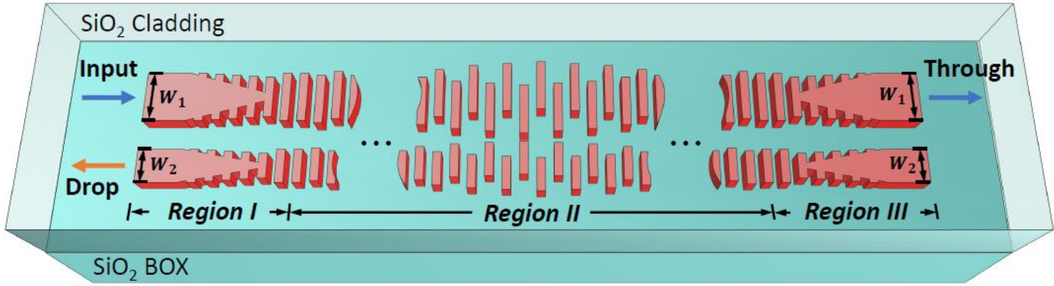
- Similarly, we can apply the same concept to the **Through-port** and achieve ultra-high extinction ratio filters



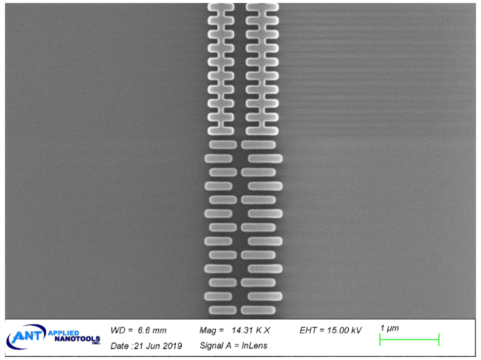
M. Hammood, 2019
https://ieeexplore.ieee.org/abstract/document/8936494/

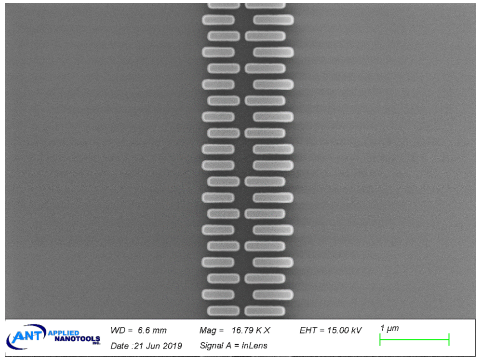
CONTRA-DIRECTIONAL COUPLERS

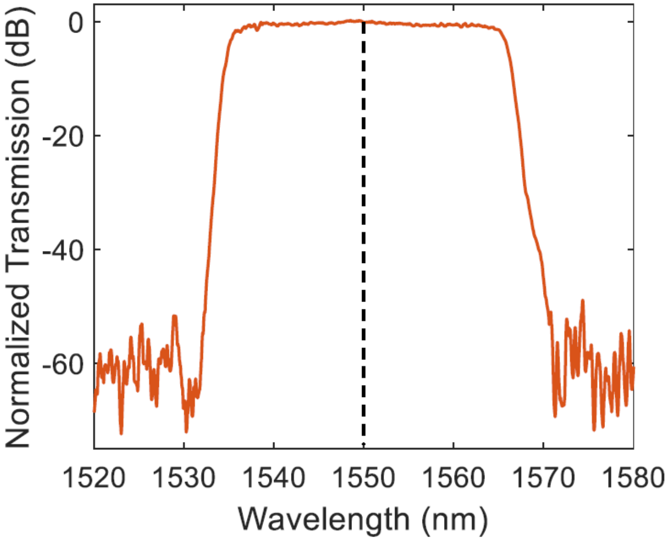
- Use sub-wavelength waveguides in a contra-DC configuration
- Low mode-confinement significantly increases the coupling coefficient
  - Significantly shorter devices
  - Wider bandwidths
- **Insertion loss:** 0.86 dB
- **Bandwidth:** up-to 33 nm
- **Isolation:** >55 dB (stacked – 3 stage)



H. Yun et al, OL 2020 -
10.1364/OL.44.004929







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REFERENCES