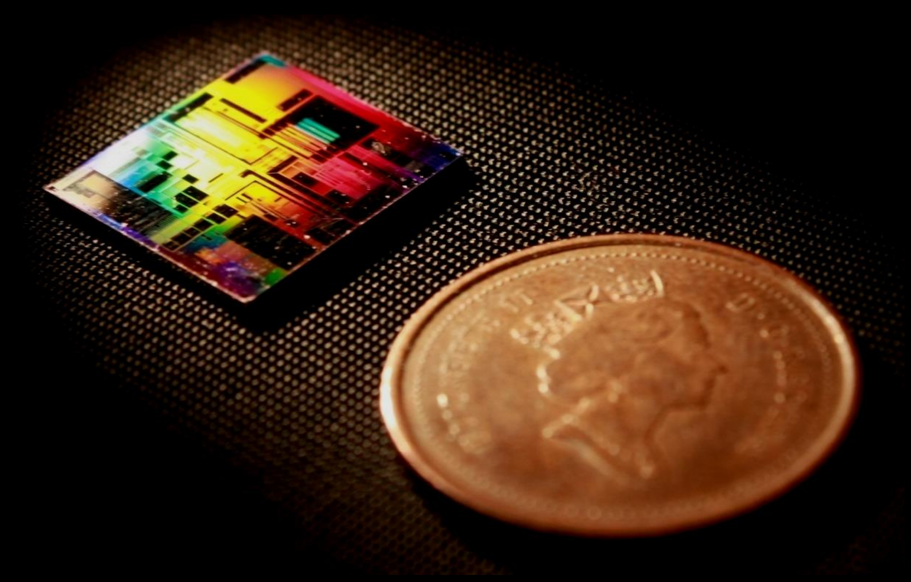
Understanding The Contra-Directional Couplers Models

2019 SiEPIC Passives Workshop, Vancouver, Canada



Mustafa Hammood,

The University of British Columbia

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

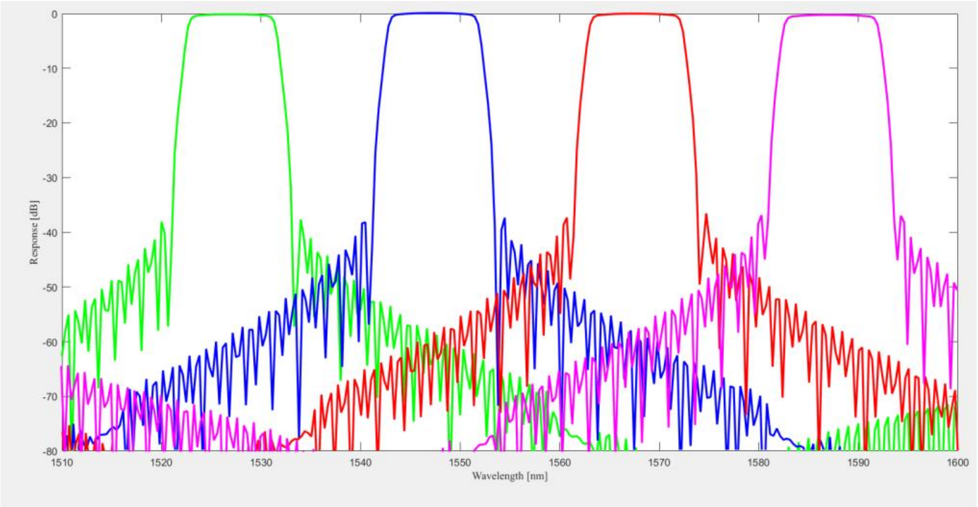
MiNa Microsystems and Nanotechnology Group
Photonics Research Group

SI-EPIC PROGRAM

Electrical and Computer Engineering

CWDM on SOI

- Athermal filters with large bandwidth, tolerant to laser's wavelength drift, suitable for short-reach data communication
- Fabrication variations are one of the major limitations on SOI-based photonics, realizing such systems on the SOI platform is important
- Approaches on SOI include: Echelle gratings, Arrayed Waveguide Gratings (AWGs) **[1]**, Mach-Zehnder lattice filters **[2]**, and **contra-directional couplers** (contra-DCs)

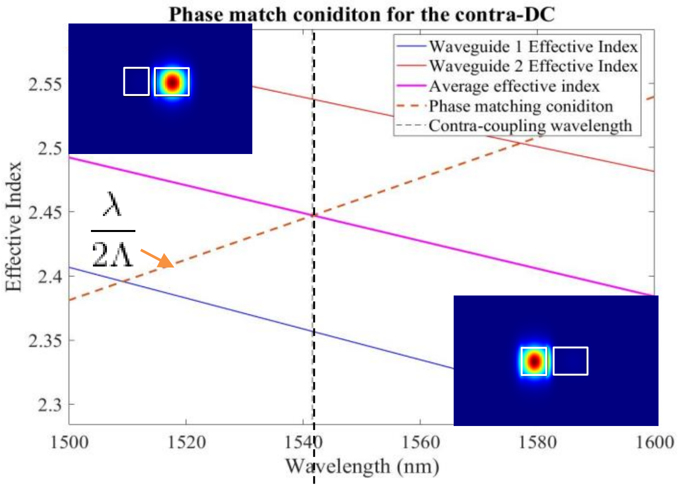


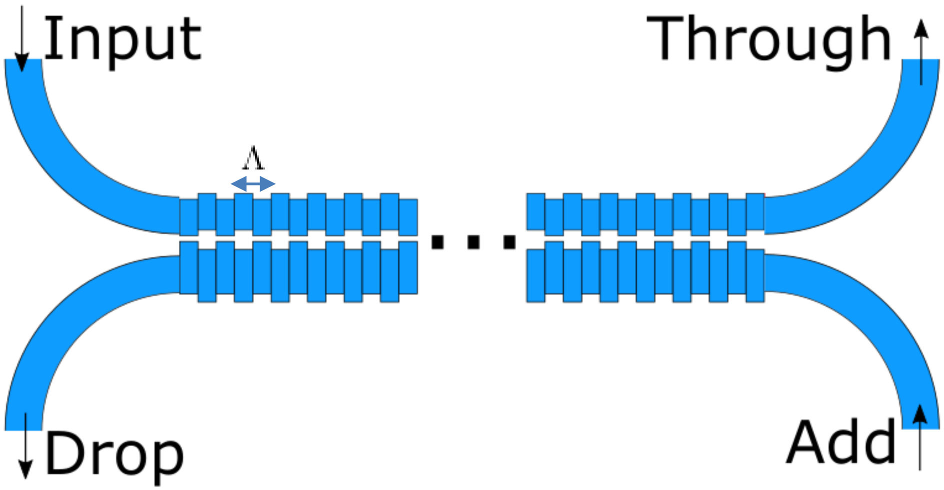
[1] S. Pathak, E. Lambert, P. Dumon, D. V. Thourhout, and W. Bogaerts, "Compact SOI-based AWG with flattened spectral response using a MMI," *8th IEEE International Conference on Group IV Photonics*, 2011.

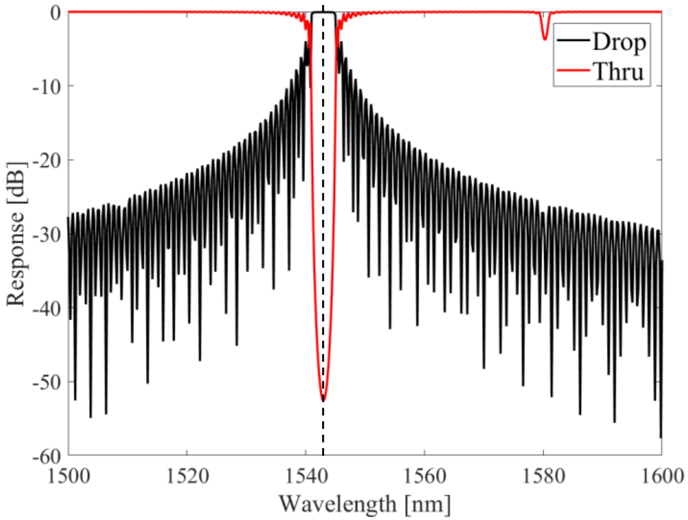
[2] "Polarization-insensitive silicon nitride Mach-Zehnder lattice wavelength demultiplexers for CWDM in the O-band" Mikkelsen JC et al. 10.1364/OE.26.030076

Contra-directional couplers overview

- **2-Waveguide system, 4-port Device:**
  - Input, through, add, drop
- side-walls corrugated, asymmetric waveguides
- Light at the phase matched wavelengths couples backwards (contra)





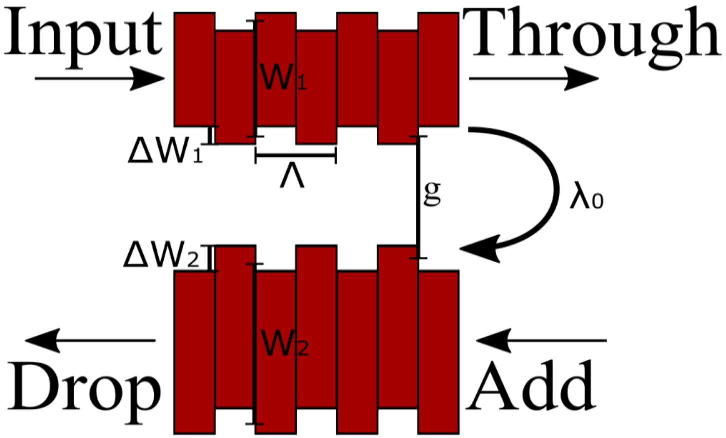


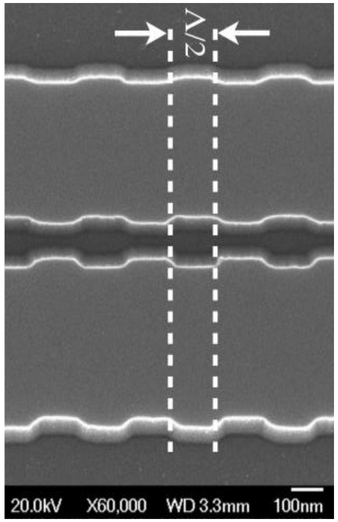
Contra-directional couplers design

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

- Selected design parameters determine the **figures of merit**:
  Bandwidth, central wavelength, band ripple/flatness, sidelobes levels, insertion loss

- Demonstrated on both E-Beam lithography and 248/193 nm deep-UV lithography **[3]**





[2]

[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 applications

- CWDM (de) multiplexers **[3]**
- Free-spectral-range (FSR)-free DWDM (de) multiplexers **[4,5]**
- FSR-free WDM modulators **[6]**
- MDM (de) multiplexers **[7]**

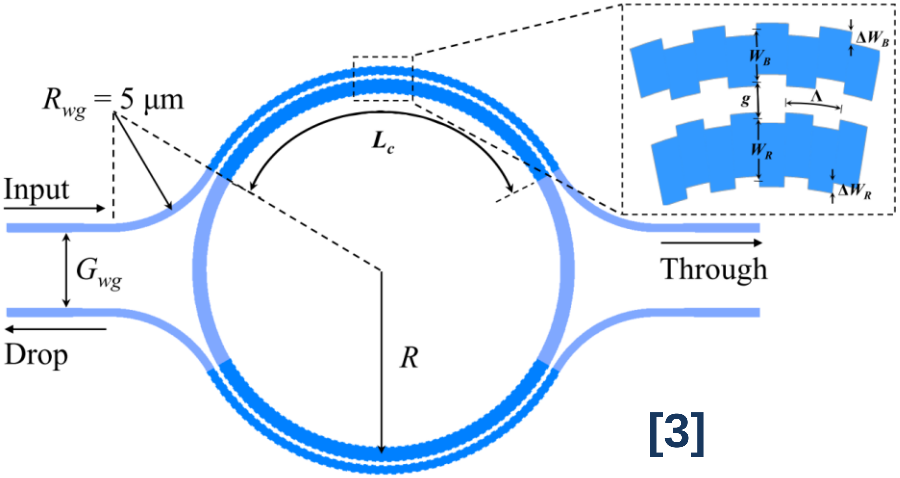
[3] W. Shi, X. Wang, W. Zhang, L. Chrostowski, and N. A. F. Jaeger, "Contradirectional couplers in silicon-on-insulator rib waveguides," *Optics Letters*, vol. 36, no. 20, p. 3999, May 2011.

[4] N. Eid, R. Boeck, H. Jayatilleka, L. Chrostowski, W. Shi, and N. A. F. Jaeger, "A silicon-on-insulator microring resonator filter with bent contradirectional couplers," *2016 IEEE Photonics Conference (IPC)*, 2016.

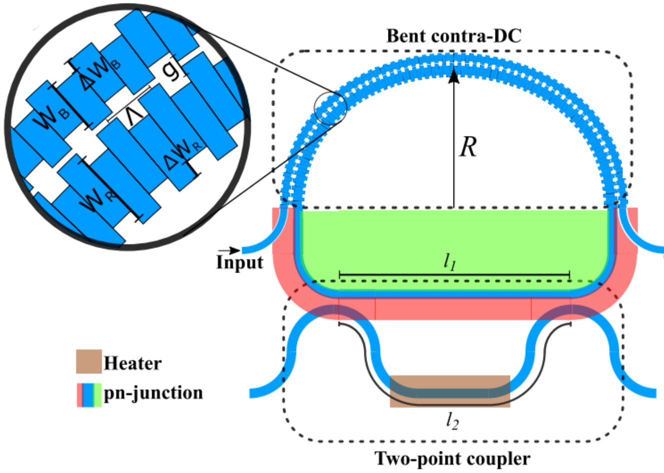
[5] N. Eid, R. Boeck, H. Jayatilleka, L. Chrostowski, W. Shi, and N. A. F. Jaeger, "FSR-free silicon-on-insulator microring resonator based filter with bent contra-directional couplers," *Optics Express*, vol. 24, no. 25, p. 29009, Jul. 2016.

[6] A. Mistry, M. Hammood, H. Shoman, L. Chrostowski, N. A. F. Jaeger, "FSR-free microring modulator," 15th IEEE International Conference on Group IV Photonics, 2018.

[7] X. Zhao, Y. Wang, Q. Huang, and J. Xia, "Two-mode contra-directional coupler based on superposed grating," *Optics Express*, vol. 25, no. 3, p. 2654, Jan. 2017.



[3]



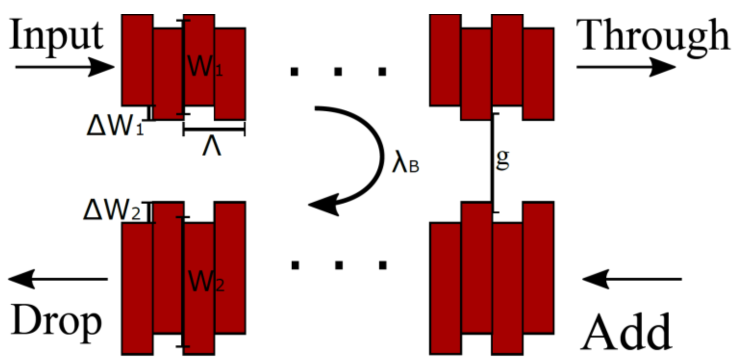
[6]

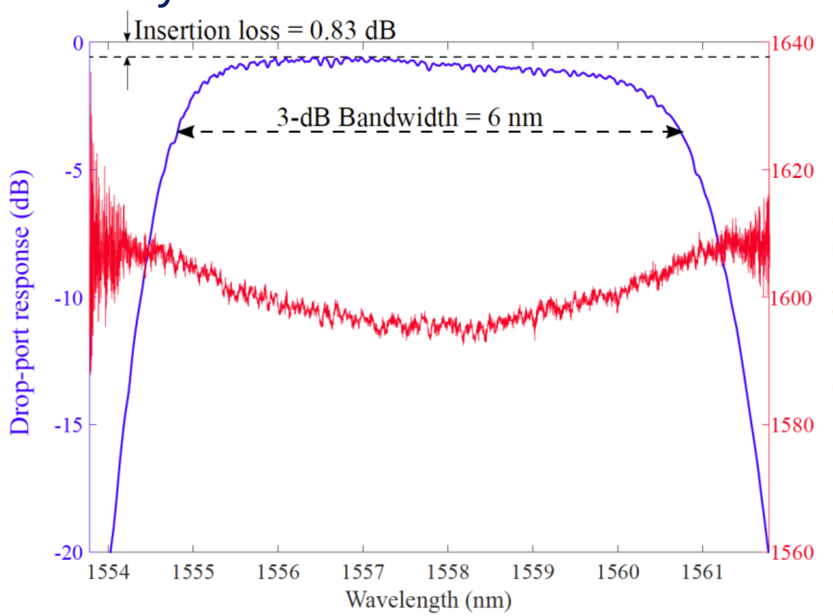
Modelling and Simulation Approaches

- **Full-length 3D FDTD Simulation**
  - Slowest: Time and resources consuming, high risk of divergence
  - Accurate simulation, if your simulation converges…
- **EME Propagation Simulation**
  - Fast (er?)
  - Difficult to simulate non-uniform grating profiles (not impossible)
  - Difficult to simulate unconventional perturbations (i.e. sinusoidal)
  - Accurate within contra-coupling wavelengths
- **Analytical: Coupled-mode Theory + Transfer Matrix Method**
  - Fastest
  - Most accurate, can model every profile, and every band (self+contra)
  - Requires prior knowledge of device parameters:
    - Waveguides system modes
    - <u>Coupling coefficients / **Kappa**</u>

What is: Coupling Coefficient / Kappa?

- 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.





How to find Kappa? Analytically

- Can be modelled analytically using:
  - 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)

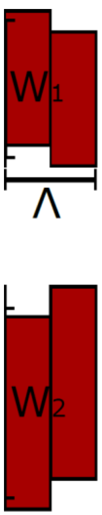
$$\kappa_{11} = \frac{\omega}{4}\iint \mathbf{E}_1^*(x,y)\cdot\Delta\epsilon_1(x,y)\mathbf{E}_1(x,y)dxdy$$

$$\kappa_{12} = \frac{\omega}{4}\iint \mathbf{E}_1^*(x,y)\cdot\Delta\epsilon_1(x,y)\mathbf{E}_2(x,y)dxdy$$

(a) (c) (b)

$$\kappa_{21} = \frac{\omega}{4}\iint \mathbf{E}_2^*(x,y)\cdot\Delta\epsilon_1(x,y)\mathbf{E}_1(x,y)dxdy$$

$$\kappa_{22} = \frac{\omega}{4}\iint \mathbf{E}_2^*(x,y)\cdot\Delta\epsilon_1(x,y)\mathbf{E}_2(x,y)dxdy$$



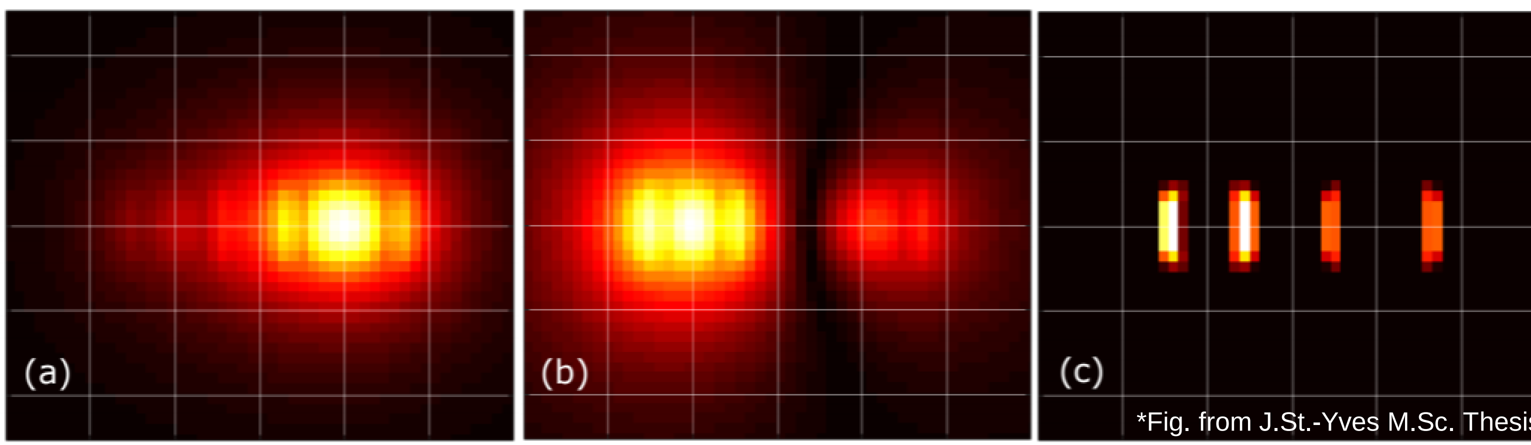


*Fig. from J.St.-Yves M.Sc. Thesis

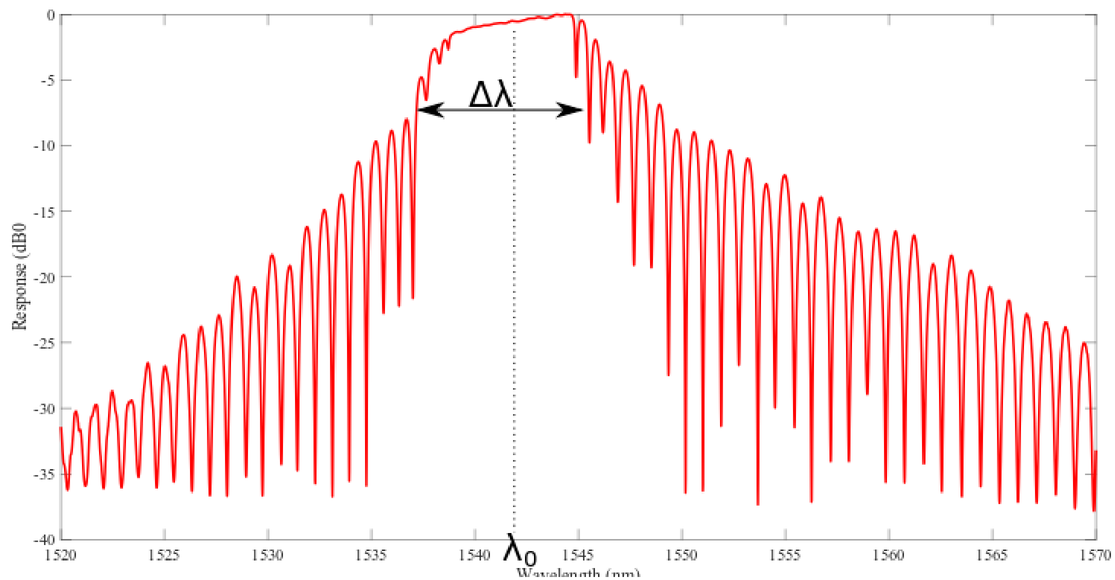
How to find Kappa? Experimentally, extracted from a response

- Can be extracted from a device response/modelled experimentally using:

- Given any device response (either experimental/simulation) we can find Kappa, **assuming a waveguide system (to find ng).**

- Several means to extract from experimental data:
    - FWMM Method (Robi 2017)*
    - Nulls method*

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



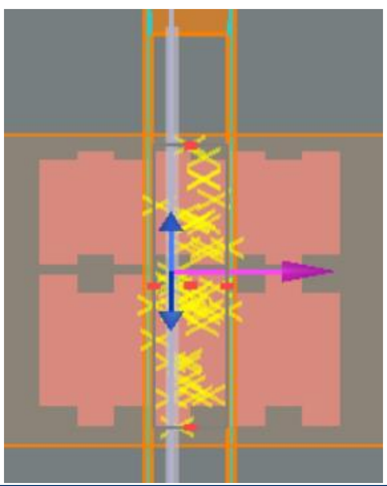
* Not always applicable

How to find Kappa? Simulation using Bloch boundary band-structure

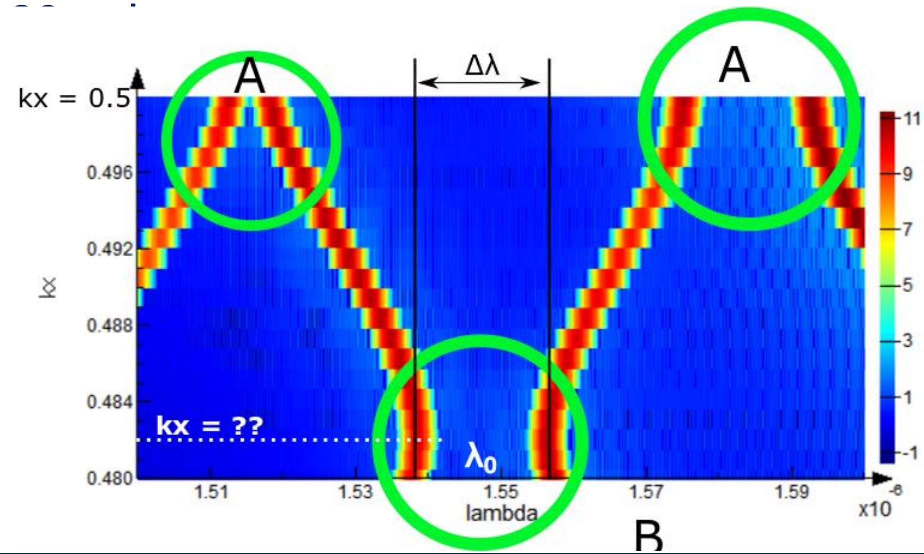
- Using an infinite length, Bloch boundary band-structure simulation, we can calculate the bandwidth and wavelength of the **system's forbidden bands**

  - Self-Bragg bands at Kx = 0.5 – labelled (A)
  - Contra bands at **unknown Kx** – labelled (B)

Uncertainty of contra wavevector (Kx) means we have to sweep a large range to find where the contra-coupling forbidden band occurs. This is time and resource consuming. Below plot is generated from

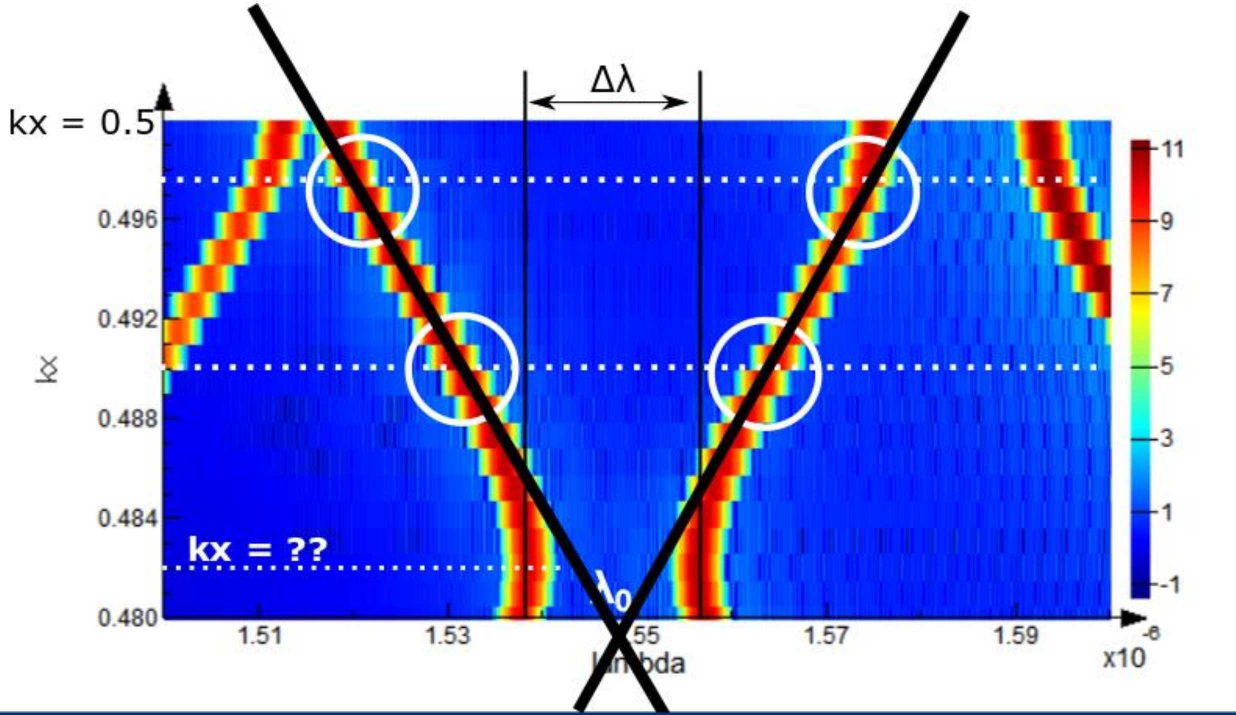


$$\kappa = \pi n_g \Delta\lambda / \lambda_0^{\,2}$$



How to find Kappa? Simulation using Bloch boundary band-structure

- Can we do better, simulation time and resources wise? Interpolate the system's forbidden bands?
- Can 2 simulations at two wave-vectors to predict the location of the contra-bandgap?



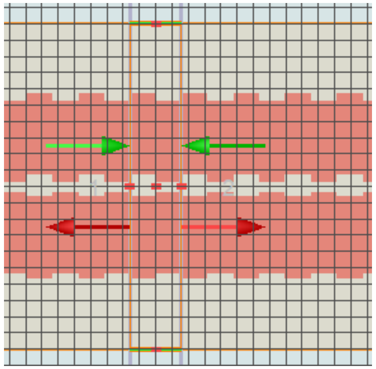
Test case:

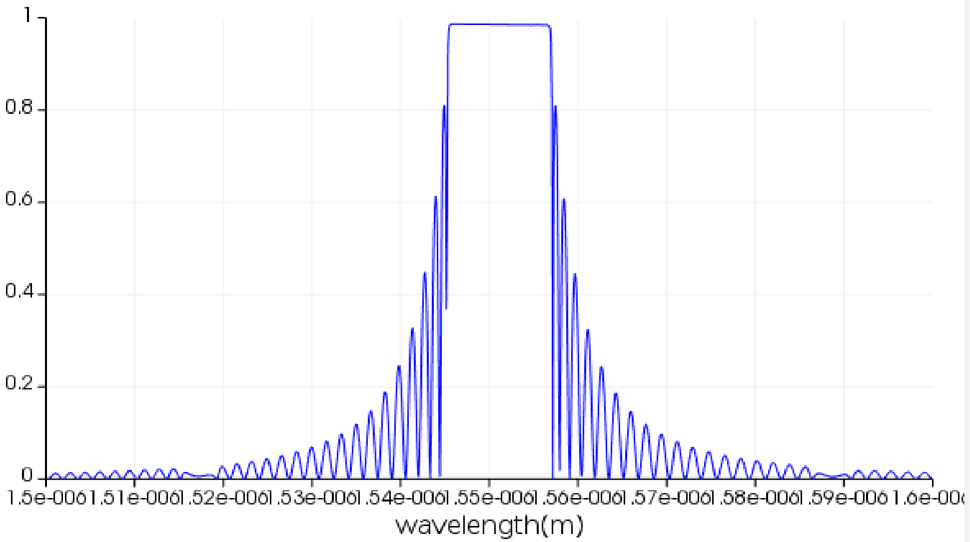
	Kx	Bandwidth (nm)
Actual	0.4796	5.32
Predicted	0.4794	5.88

Error **<10%**

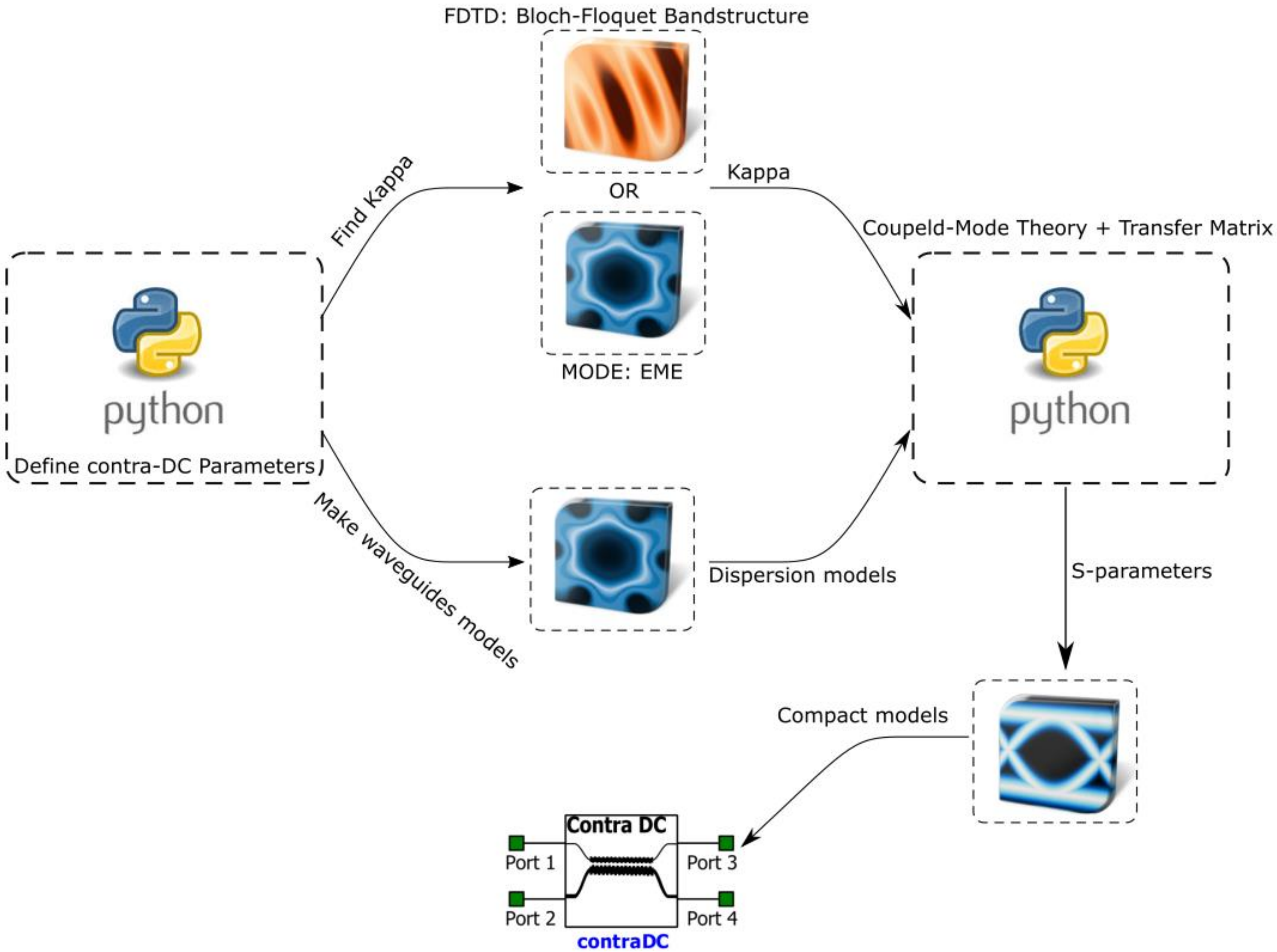
How to find Kappa? Even faster? MODE EME Simulation!

- Simulate a single periodic contra-DC cell in EME
- Generate the uniform profile response
- Extract kappa from the response using the nulls method
- Feed the kappa into coupled-mode theory, transfer matrix apodized model





Contra-Directional Couplers Simulator Flow

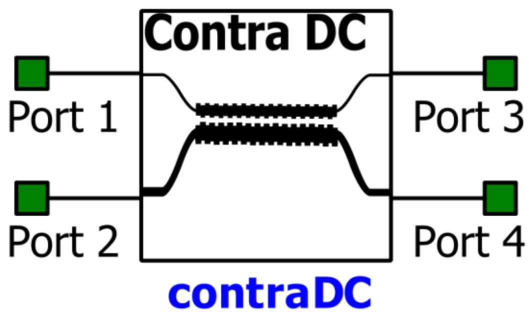


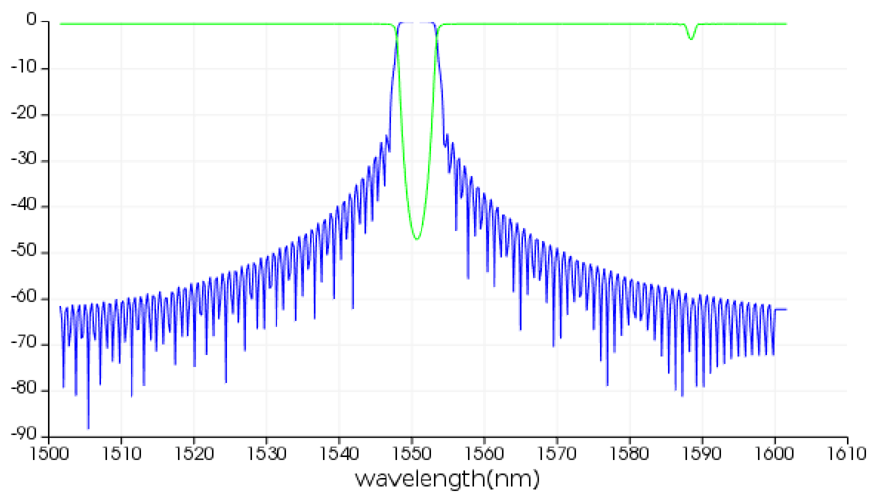
What’s new in this approach?

- Fully automated flow in Python – no need for a MATLAB engine for coupled-mode theory or the setup of any 3rd party tools (other than Lumerical)
- Generates an S-parameter file (.dat) for circuit simulations
- Dual polarizations: TE-TM, compact model includes two-modes support
- Two new approaches to find the bandgap and Kappa – reduce FDTD simulation time from more than 5 hours to an improved, to less than a minutes. This was the simulation flow bottleneck.
- Accurately predicts and simulates the waveguide’s self-reflection
- Higher level of abstraction

How to? Define physical parameters and simulation parameters

- Feed in the design parameters
  - Let the script run!



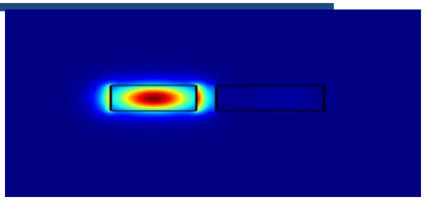


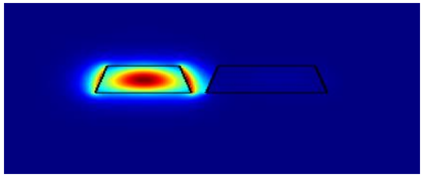

```
class contra_DC():
    def __init__(self, *args):
        # physical geometry parameters
        self.w1 = 560e-9
        self.w2 = 440e-9
        self.dW1 = 24e-9
        self.dW2 = 24e-9
        self.gap = 100e-9
        self.period = 318e-9
        self.N = 1000

        self.thick_si = 220e-9

        self.slab = False
        self.thick_slab = 90e-9

        self.sinusoidal = False

        self.apodization = 10

        #behavioral parameters (leave as default
        self.pol = 'TE' # TE or TM
        self.alpha = 3
        self.kappa_contra = 30000
        self.kappa_self1 = 300
        self.kappa_self2 = 300
#%% simulation parameters class constructor
class simulation():
    def __init__(self, *args):
        # make sure range is large enouh to capture
        self.lambda_start = 1480e-9
        self.lambda_end = 1600e-9
        self.resolution = 501

        self.deviceTemp = 300
        self.chipTemp = 300
```

Optional

Further improvements can be done on…

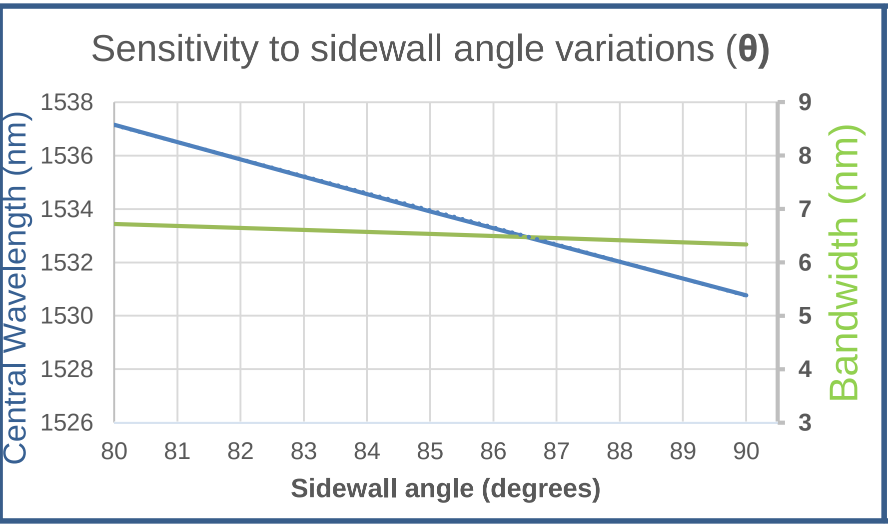
- Parameterized sidewall angle
- Model sensitivity to process variations and corner analysis
  - Conclusion: bandwidth is somewhat stable, central wavelength not quite.
- **Segmented kappa:** Wavelength-dependent coupling coefficient

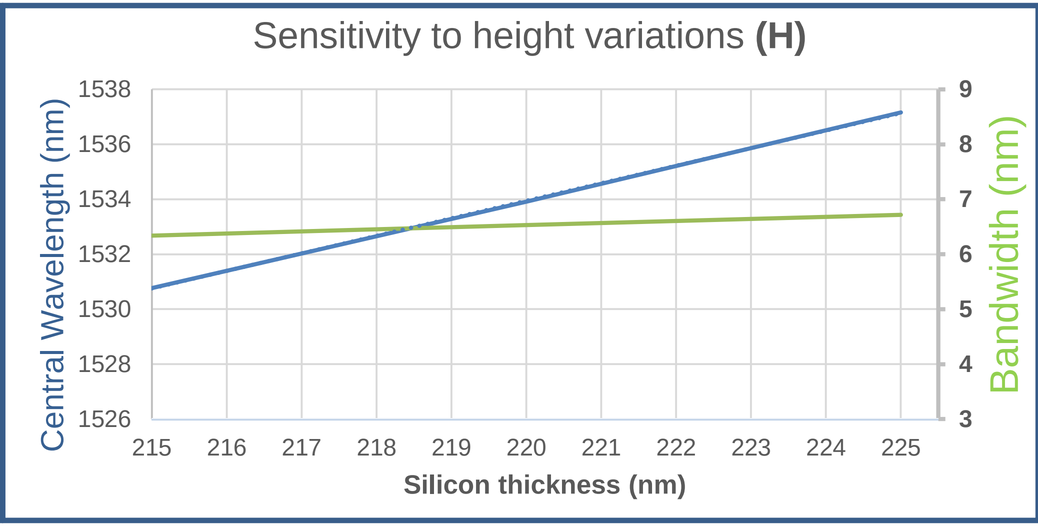




$\boldsymbol{\delta(\lambda_0)/\,\delta(\theta)}$ = 0.63 nm/degree

$\boldsymbol{\delta(\lambda_0)/\,\delta(H)}$ = 0.7 nm/nm





Acknowledgements

- Natural Sciences and Engineering Research Council (**NSERC**) of Canada and **Keysight Technologies** for their financial support. Fabrication was done by **Applied Nanotools**, Alberta, Canada through the **SiEPICfab** consortium.

KEYSIGHT TECHNOLOGIES

NSERC CRSNG

SiEPICfab

APPLIED NANOTOOLS INC.

Contributors

- Wei Shi
- Mustafa Hammood
- Jonathan St-Yves
- Simon Belanger
- Dominique Charron
- Han Yun
- Xu Wang
- Ajay Mistry
- Stephen Lin

Activity:

- Design a 4-Channel CWDM filter, Add-drop (de) MUX in INTERCONNECT.
- Design for ~C-Band.
- Use ITU CWDM grid specs:
  - Channel bandwidth +/- 6.5 nm (13 nm)
  - Channel grid (spacing) 20 nm
- Think of system architecture
  - Which waveguide to inject light from? Narrow? Wide?
  - What is the order to place the contra-DCs in?
- Refer to Intel Si-Photonics 100G CWDM4 and 400G CWDM8 Transceivers:
  - **100G CWDM4**: https://www.intel.ca/content/www/ca/en/architecture-and-technology/silicon-photonics/optical-transceiver-100g-cwdm4-qsfp28-brief.html
  - **400G CWDM8**: No public specs yet, only demos: https://www.tomshardware.com/news/intel-silicon-photonics-transceiver-400g,39028.html