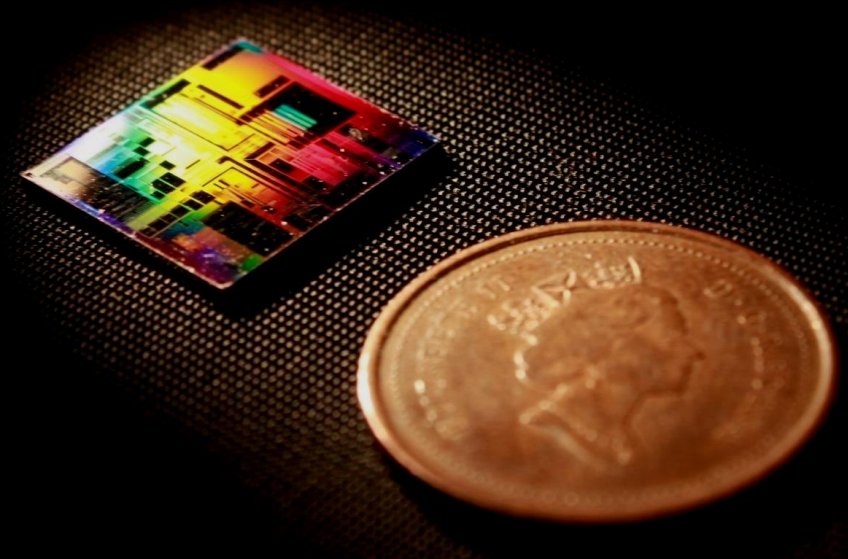


Understanding The Contra-Directional Couplers Models

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a place of mind
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MiNa Microsystems and
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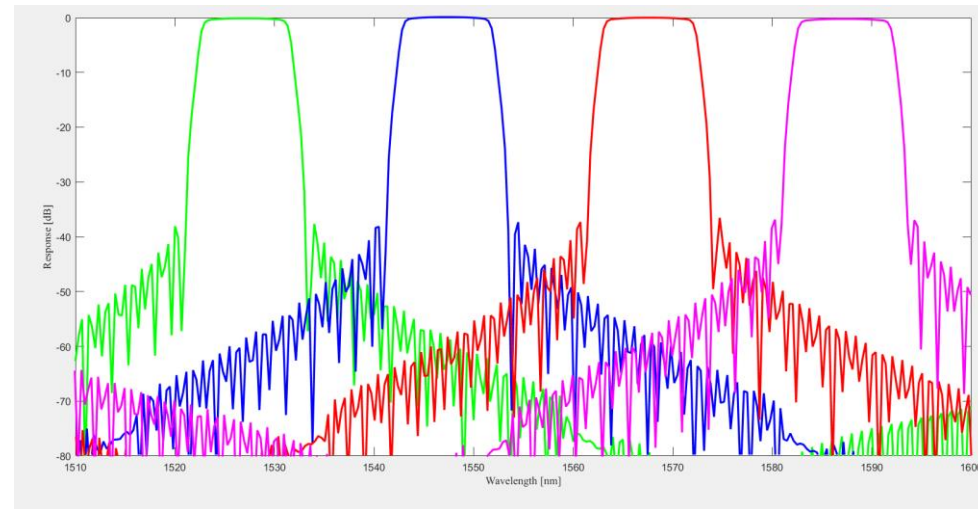
**SI-EPIC
PROGRAM**



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)

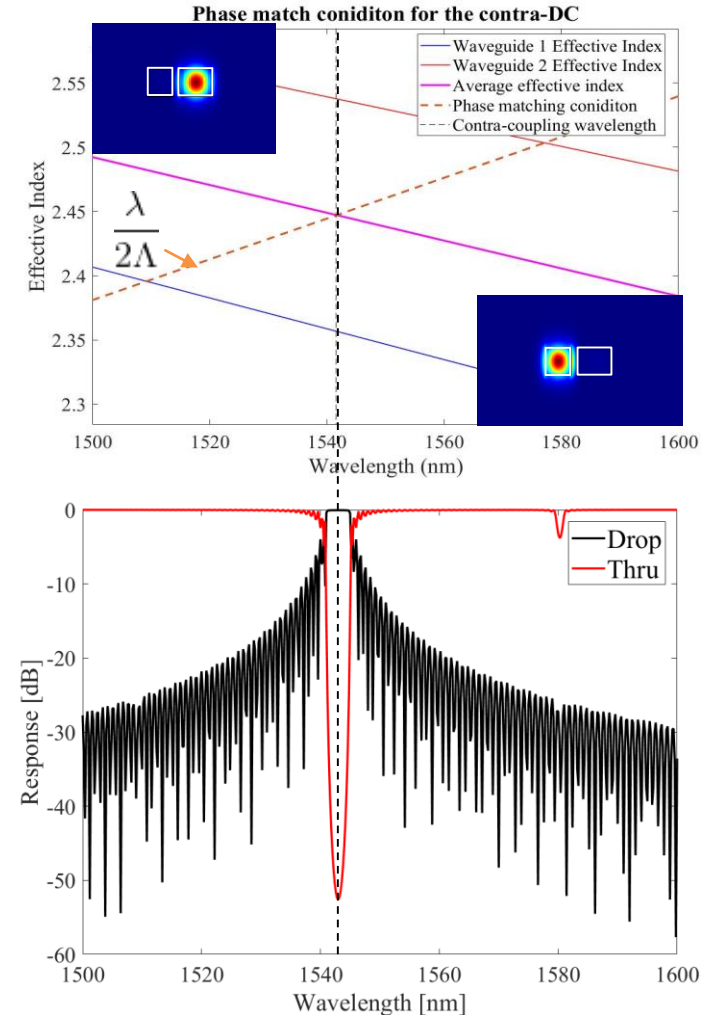
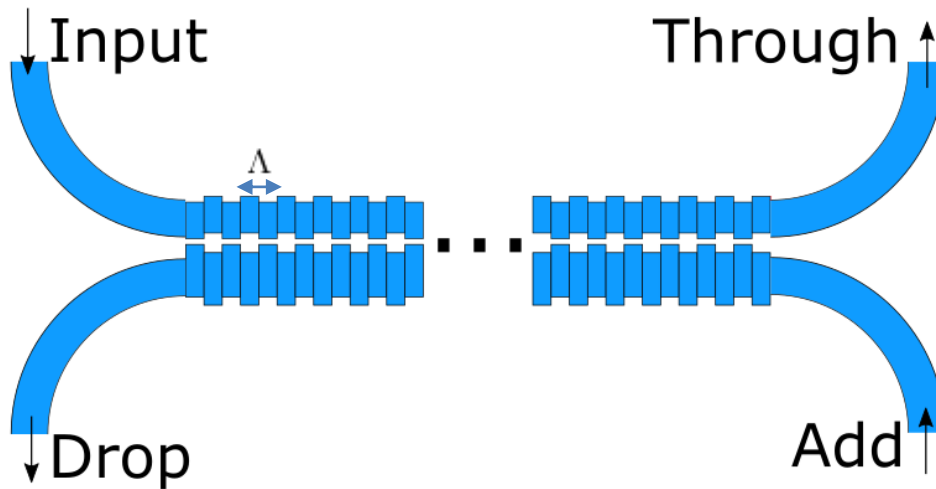


[1] S. Pathak, E. Lambert, P. Dumon, D. V. Thourhout, and W. Bogaerts, "Compact SOI-based AWG with flattened spectral response using a MMI," *8th IEEE International Conference on Group IV Photonics*, 2011.

[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

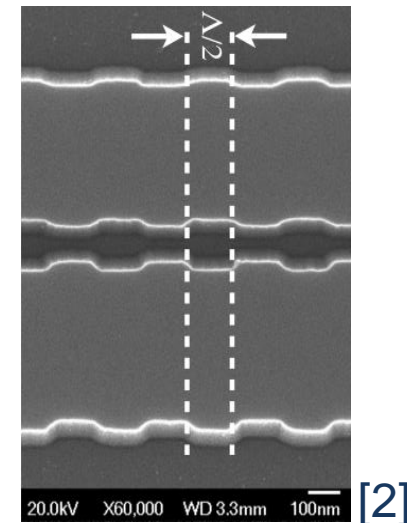
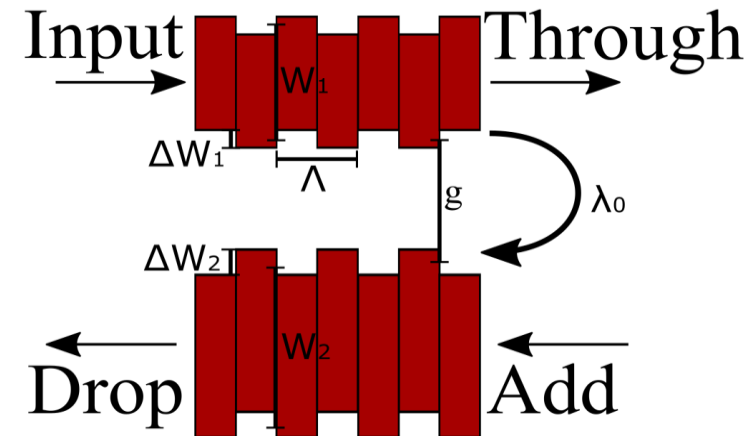
Contra-directional couplers overview

- **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]



[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]

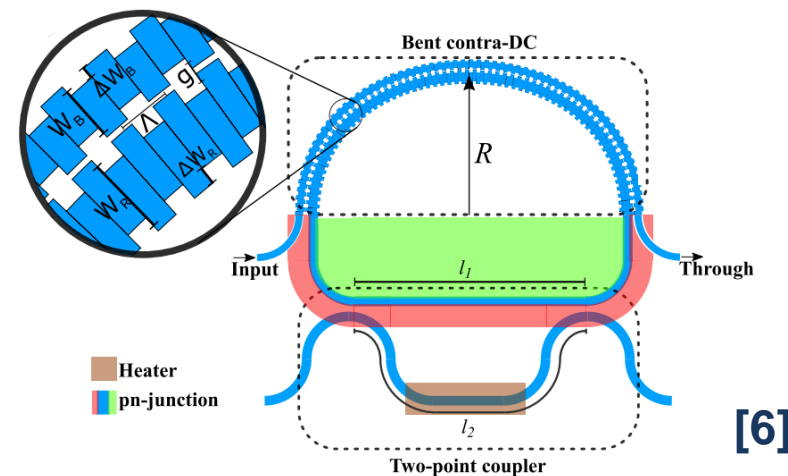
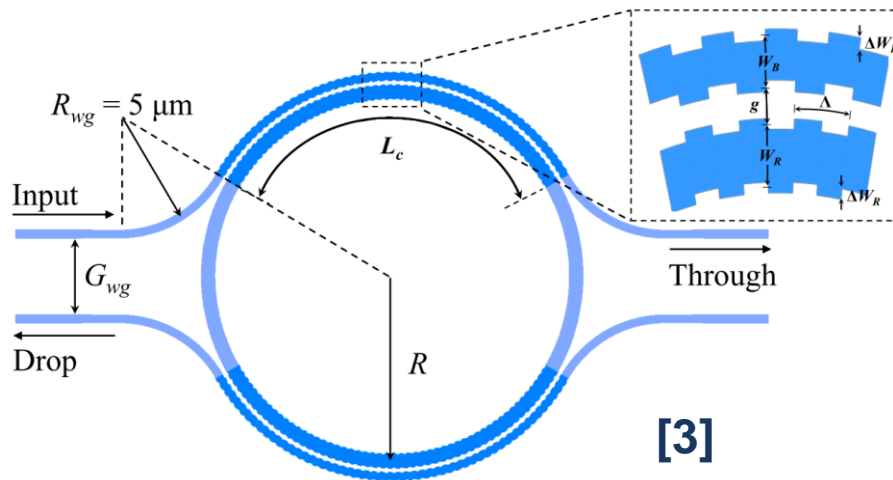
[3] W. Shi, X. Wang, W. Zhang, L. Chrostowski, and N. A. F. Jaeger, "Contra-directional couplers in silicon-on-insulator rib waveguides," *Optics Letters*, vol. 36, no. 20, p. 3999, May 2011.

[4] N. Eid, R. Boeck, H. Jayatilaka, 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. Jayatilaka, 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.

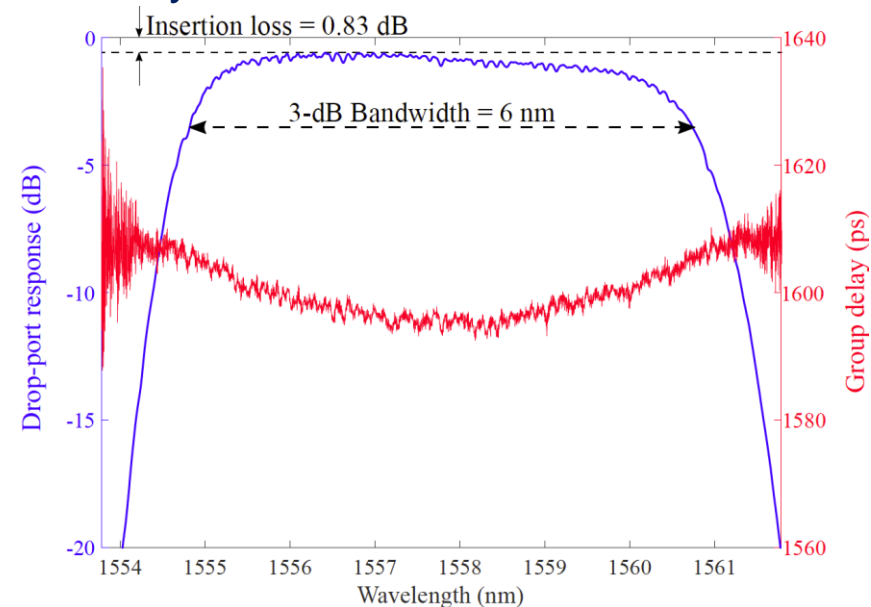
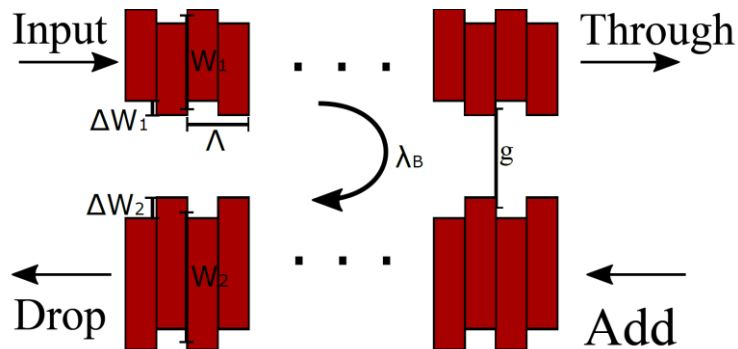


Modelling and Simulation Approaches

- **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
 - Coupling coefficients / κ

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

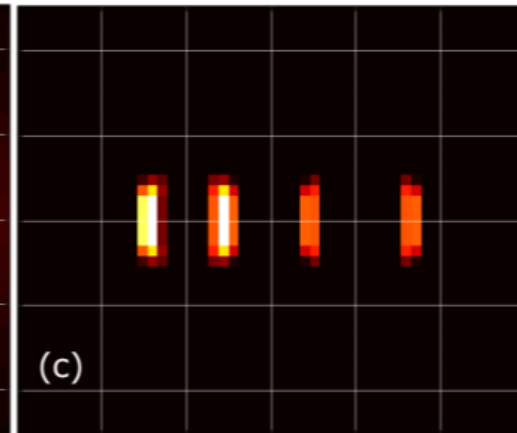
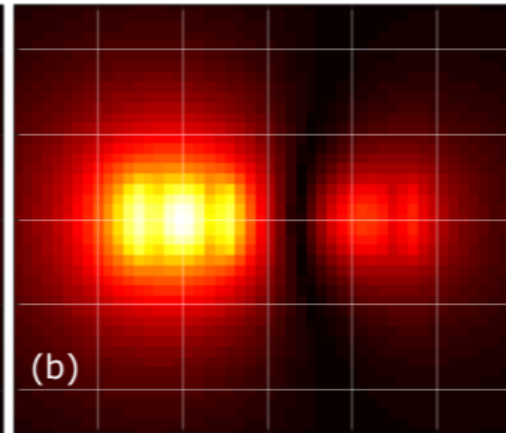
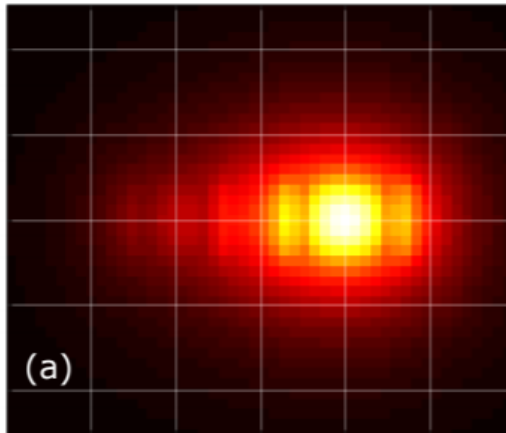
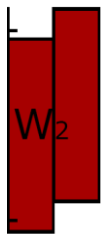
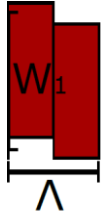
- Can be modelled analytically using:
 - Accurate for small perturbations
 - Easily implemented for simple perturbations
- Difficult to find the Fourier-expansion term ($\Delta\epsilon$) for unconventional perturbations shapes (ex: sinusoidal or litho. smoothed corrugations)

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

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

$$\kappa_{21} = \frac{\omega}{4} \iint \overset{(a)}{\mathbf{E}_2^*(x, y)} \cdot \overset{(c)}{\Delta\epsilon_1(x, y)} \overset{(b)}{\mathbf{E}_1(x, y)} dx dy$$

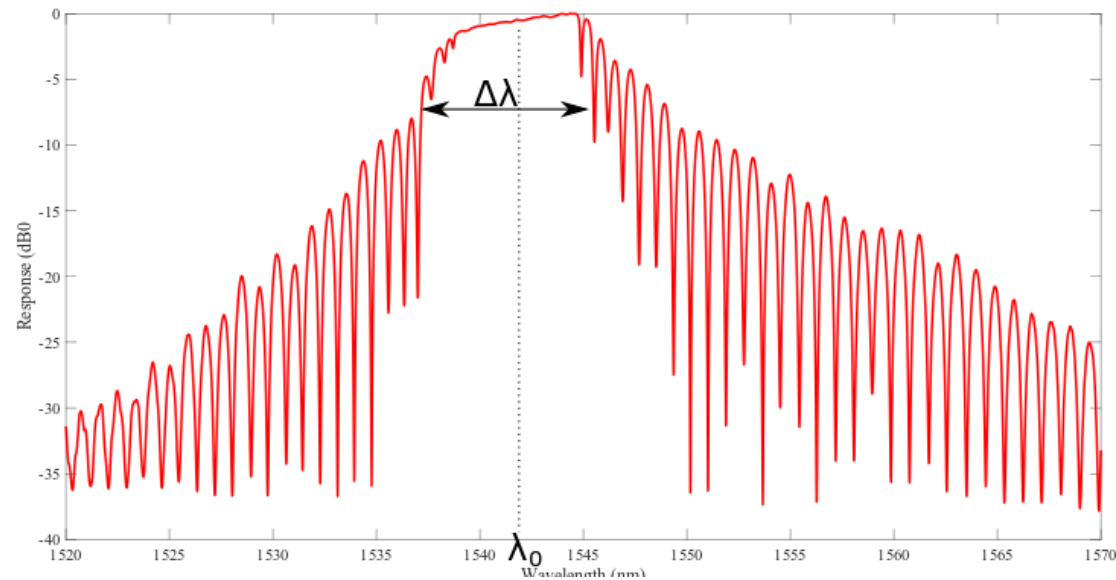
$$\kappa_{22} = \frac{\omega}{4} \iint \mathbf{E}_2^*(x, y) \cdot \Delta\epsilon_1(x, y) \mathbf{E}_2(x, y) dx dy$$



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

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

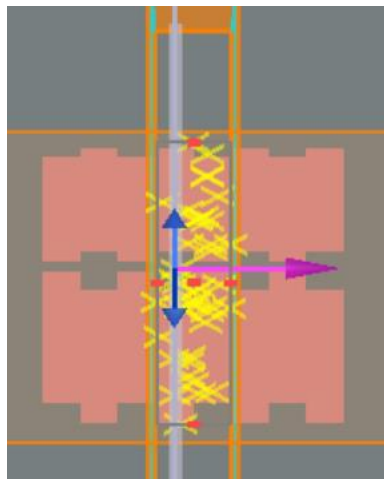


* Not always applicable

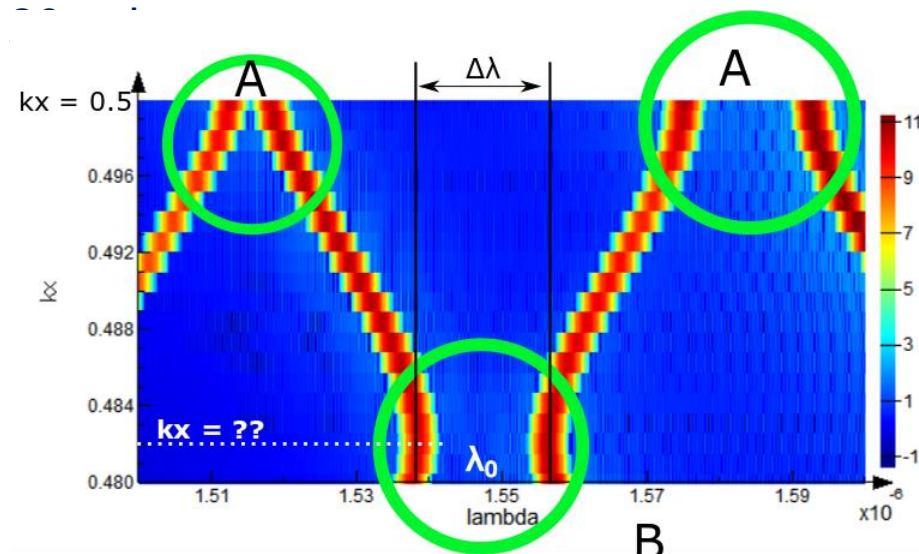
How to find Kappa? Simulation using Bloch boundary band-structure

- 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

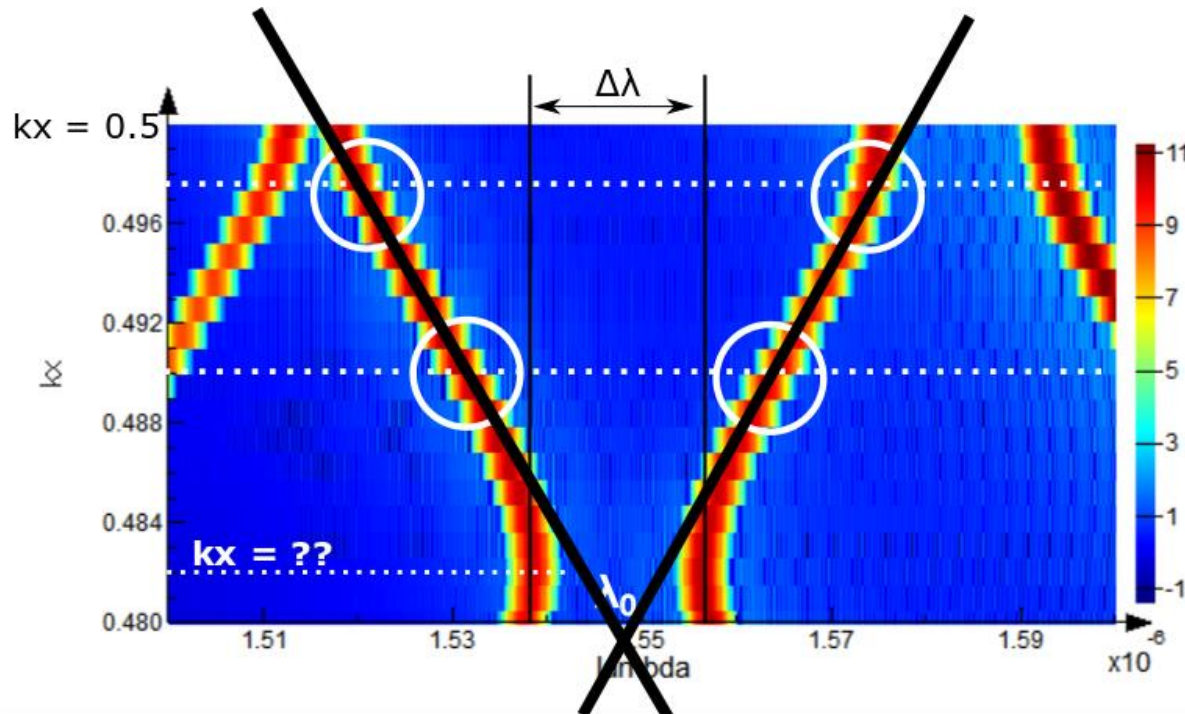


$$\kappa = \pi n_g \Delta\lambda / \lambda_0^2$$



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?



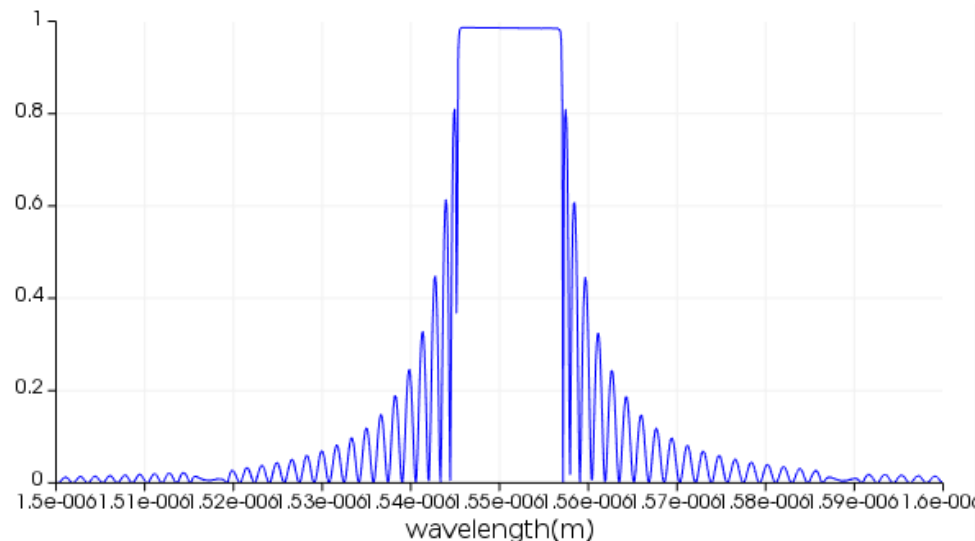
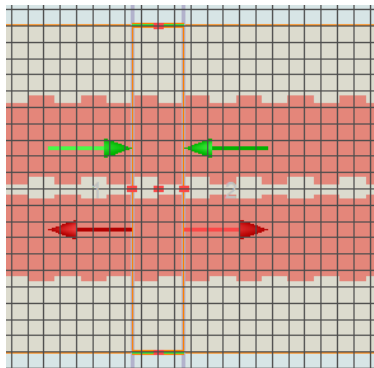
Test case:

	Kx	Bandwidth (nm)
Actual	0.4796	5.32
Predicted	0.4794	5.88

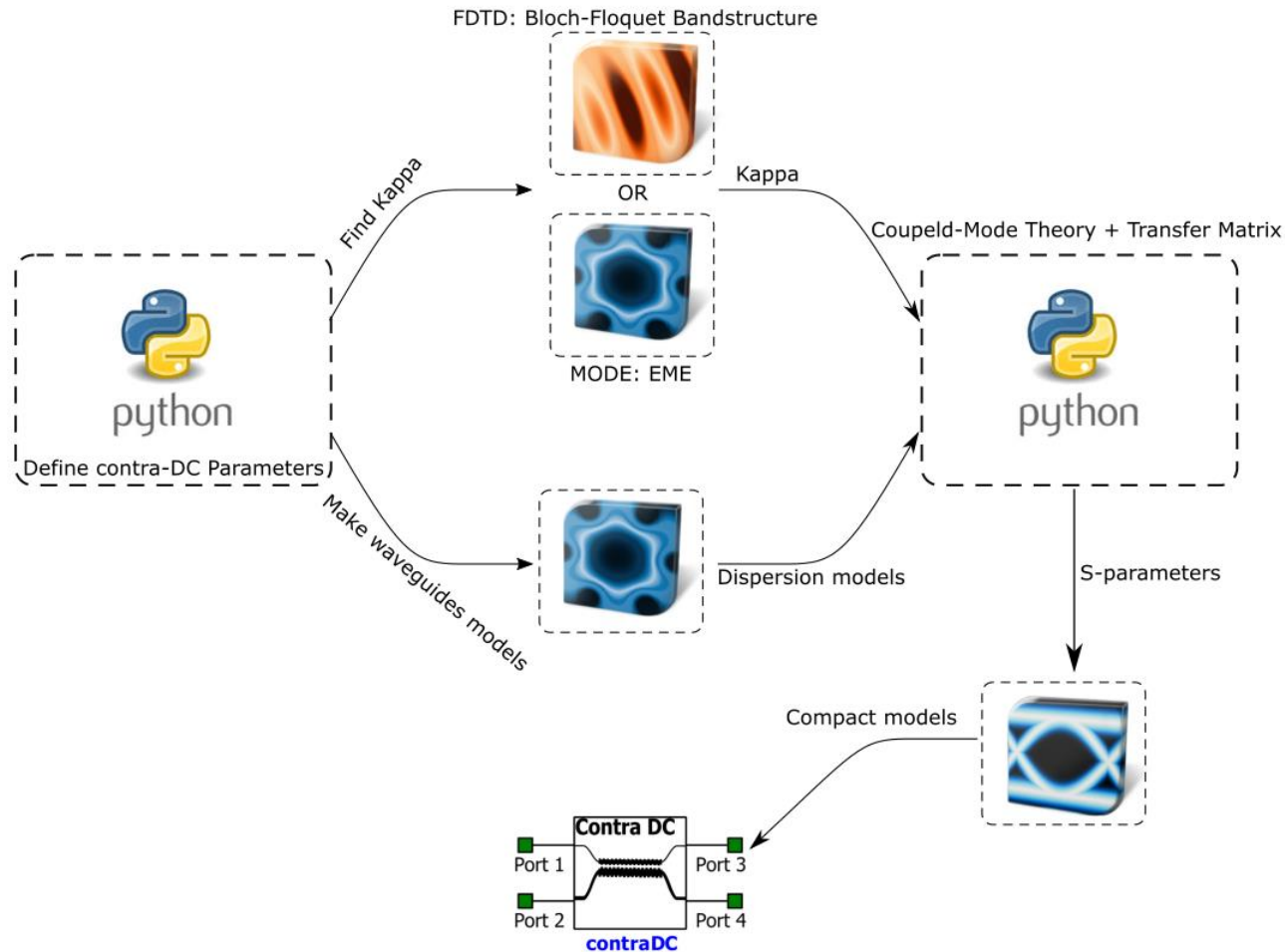
Error <10%

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

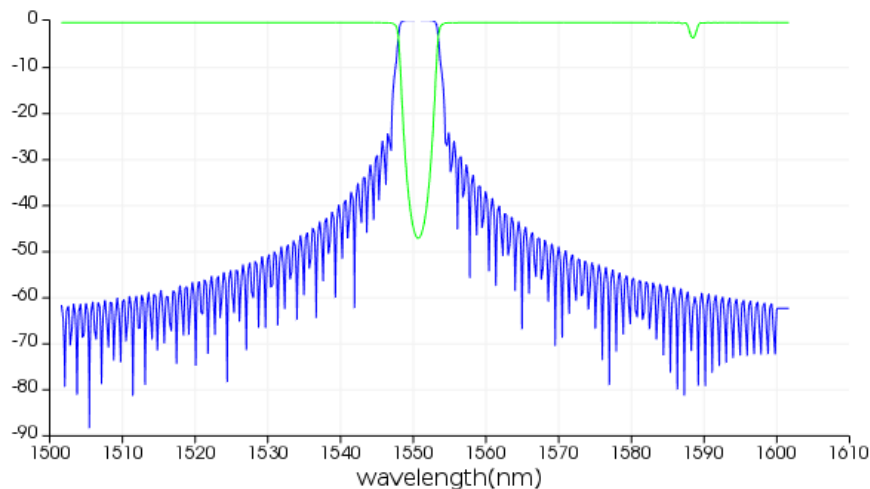
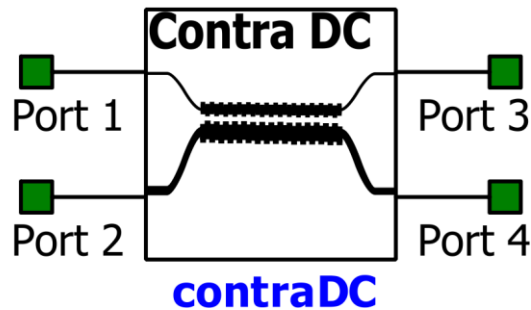


What's new in this approach?

- 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!



```

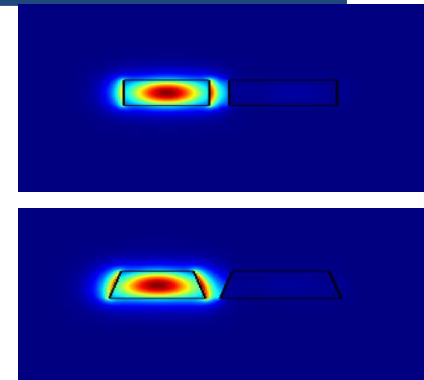
13 class contra_DC():
14     def __init__(self, *args):
15         # physical geometry parameters
16         self.w1 = 560e-9
17         self.w2 = 440e-9
18         self.dW1 = 24e-9
19         self.dW2 = 24e-9
20         self.gap = 100e-9
21         self.period = 318e-9
22         self.N = 1000
23
24         self.thick_si = 220e-9
25
26         self.slabs = False
27         self.thick_slabs = 90e-9
28
29         self.sinusoidal = False
30
31         self.apodization = 10
32
33         #behavioral parameters (leave as default)
34         self.pol = 'TE' # TE or TM
35         self.alpha = 3
36         self.kappa_contra = 30000
37         self.kappa_self1 = 300
38         self.kappa_self2 = 300
39
40     %% simulation parameters class constructor
41     class simulation():
42         def __init__(self, *args):
43             # make sure range is large enough to capture
44             self.lambda_start = 1480e-9
45             self.lambda_end = 1600e-9
46             self.resolution = 501
47
48             self.deviceTemp = 300
49             self.chipTemp = 300

```

Optional

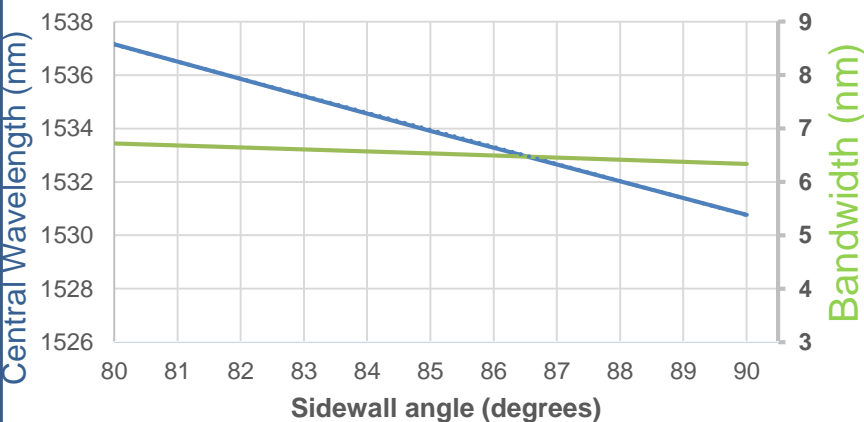
Further improvements can be done on...

- 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



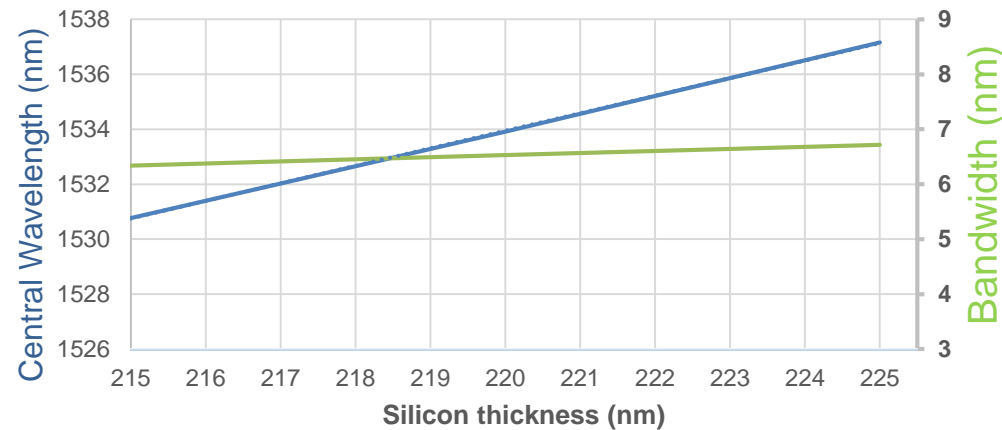
$$\delta(\lambda_0)/\delta(\theta) = 0.63 \text{ nm/degree}$$

Sensitivity to sidewall angle variations (θ)



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

Sensitivity to height variations (H)



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Contributors

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