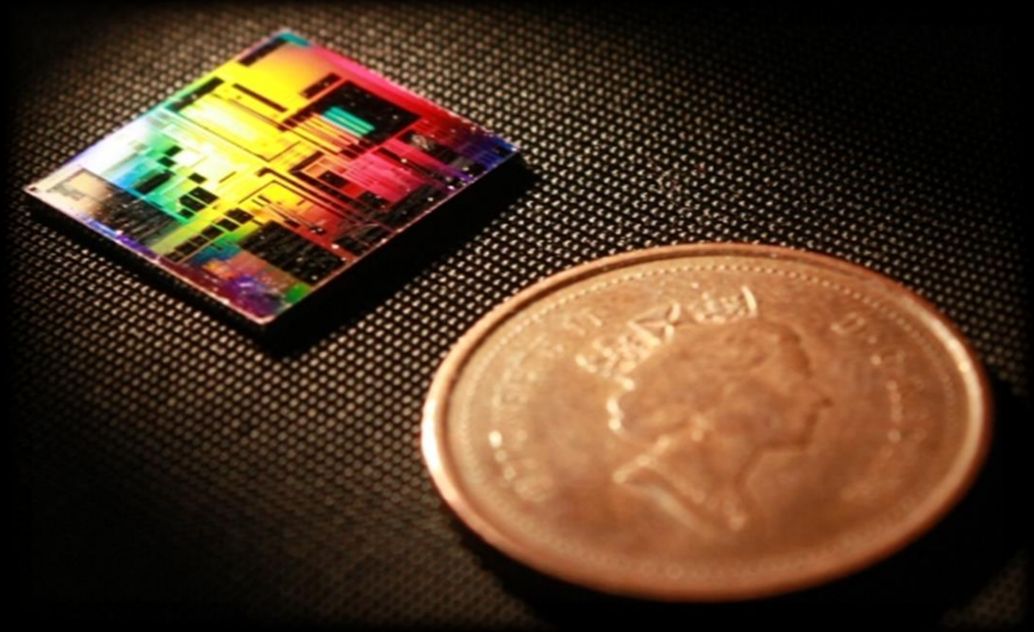
CONTRA-DIRECTIONAL COUPLERS

Mustafa Hammood

2020-11-26



SiEPIC FAB

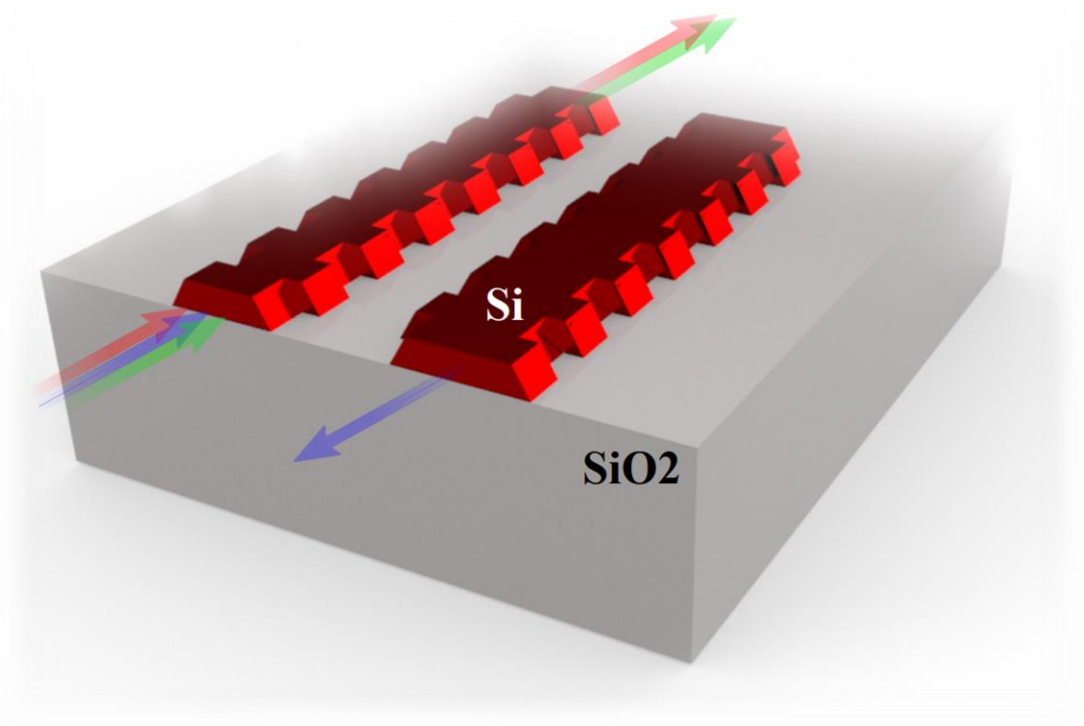
OUTLINE [1.5 HOURS]

- **Introduction** **[20 mins]**
  - WDM Filters on Integrated Photonics
  - Theory and photonic band diagrams

- **Practical Design Challenges**
  - Lithography Modelling
  - Fabrication imperfections and variations

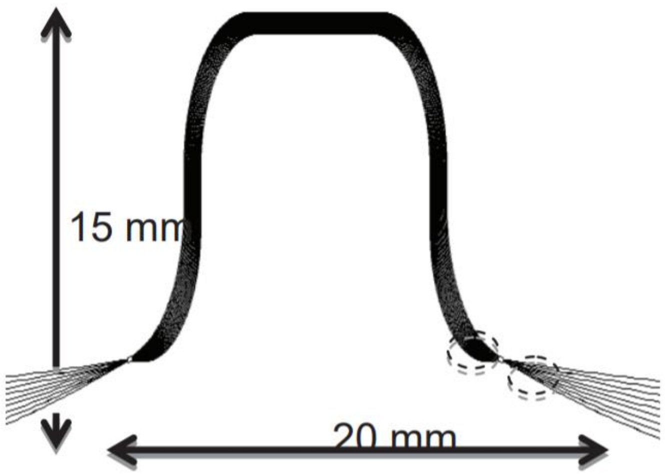
- **Designs and applications** **[20 mins]**
  - Cascaded filters
  - Multi-mode gratings
  - FSR-free rings and modulators
  - Sub-wavelength grating

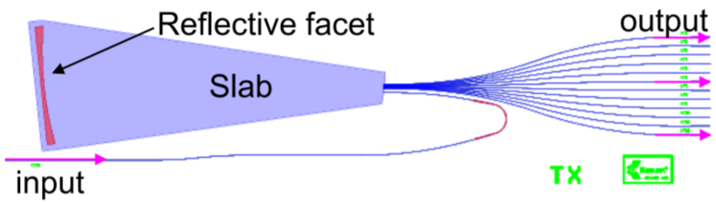
- **Modeling and design activity** **[25 mins]**
  - Coupled-mode theory + Transfer Matrix method
  - Design your own WDM system

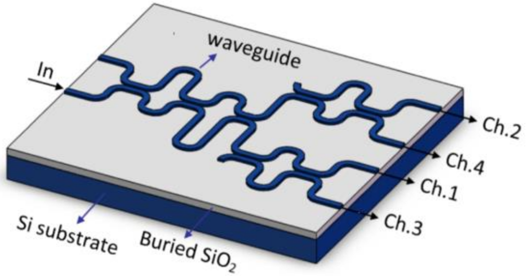


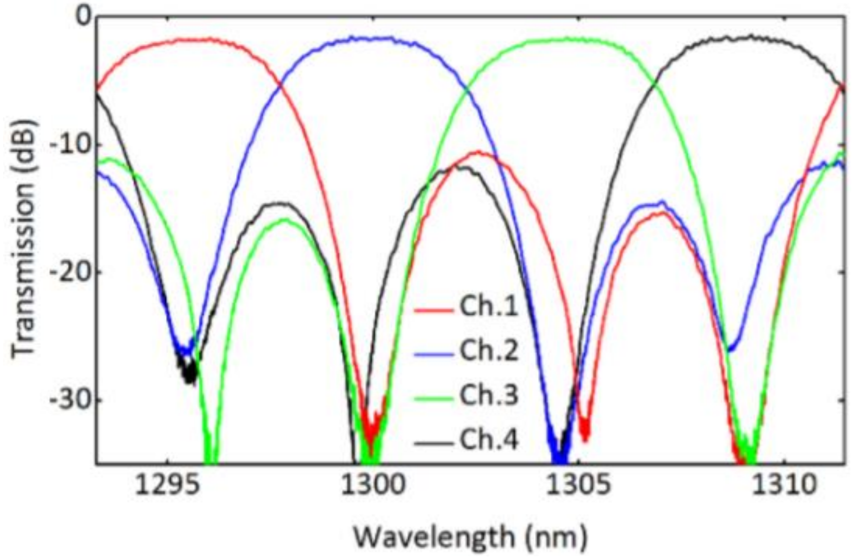
WDM ON SILICON

- For Coarse Wavelength Division Multiplexing (CWDM): We need 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), Echelle gratings, Mach-Zehnder lattice filters, and contra-directional couplers (contra-DCs).



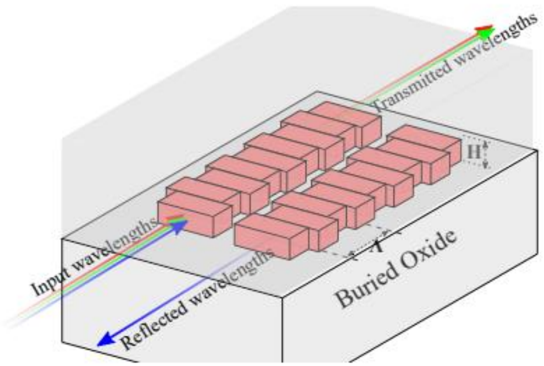


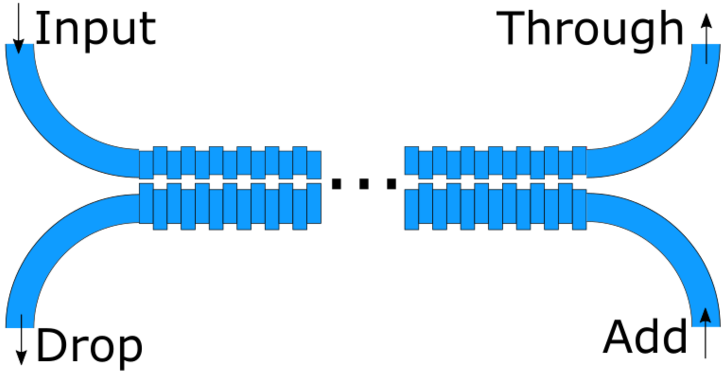


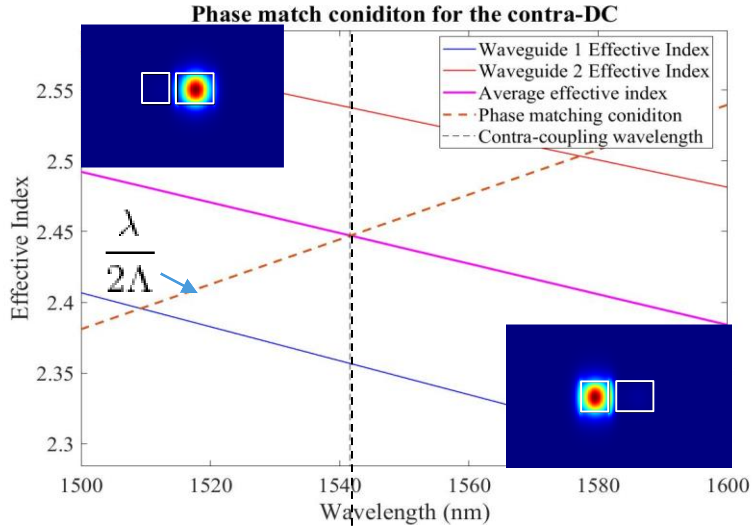


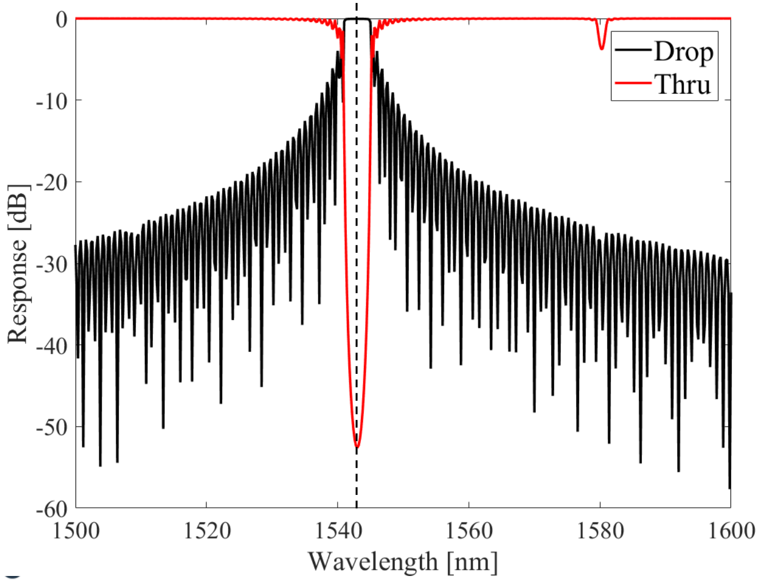
CONTRA-DIRECTIONAL COUPLERS

- **2-waveguides system, 4-port Device:**
  - Input, Through, Add, Drop
- Asymmetric waveguides to reduce forward coupling
- Light at the phase-matched wavelengths couples backwards into the second waveguide (contra)



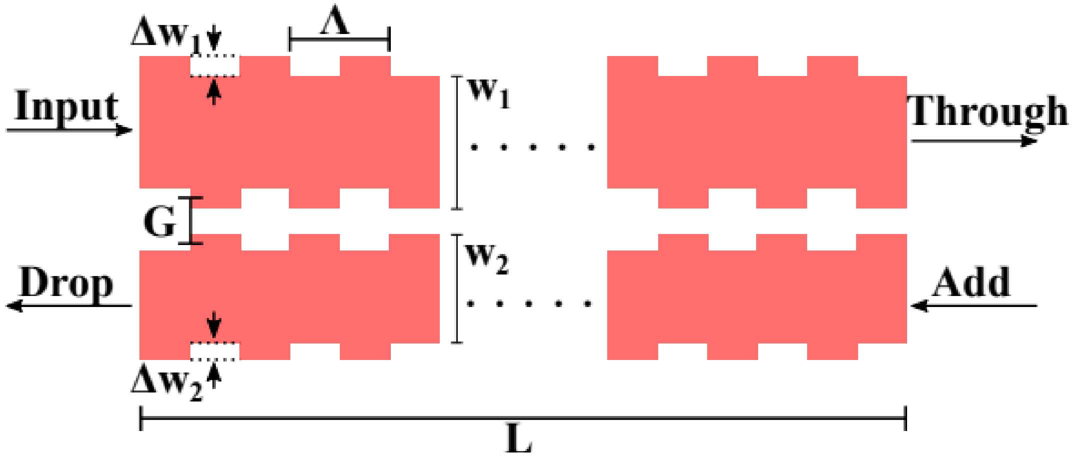


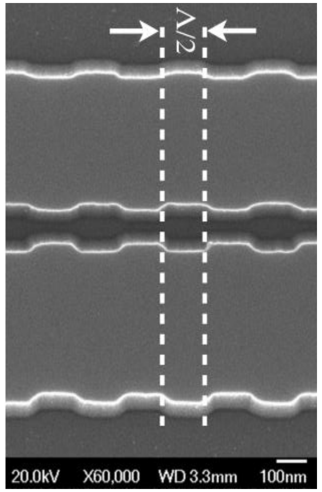




CONTRA-DIRECTIONAL COUPLERS

- **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.

THEORY & PHOTONIC BAND DIAGRAMS

CONTRA-DIRECTIONAL COUPLERS

- Coupled-mode theory, Transfer-Matrix method

$$\boldsymbol{E}(x,y,z) = \left[A^+(z)e^{-j\widehat{\beta}_1 z} + A^-(z)e^{j\widehat{\beta}_1 z}\right]\boldsymbol{E_1}(x,y) + \left[B^+(z)e^{-j\widehat{\beta}_2 z} + B^-(z)e^{j\widehat{\beta}_2 z}\right]\boldsymbol{E_2}(x,y)$$

$$\frac{dA^+}{dz} = -j\kappa_{11}A^- e^{j2\Delta\widehat{\beta}_1 z} - j\kappa_{12}B^- e^{j(\Delta\widehat{\beta}_1+\Delta\widehat{\beta}_2)z}$$

$$\frac{dB^+}{dz} = -j\kappa_{12}A^- e^{j(\Delta\widehat{\beta}_1+\Delta\widehat{\beta}_2)z} - j\kappa_{22}B^- e^{j2\Delta\widehat{\beta}_2 z}$$

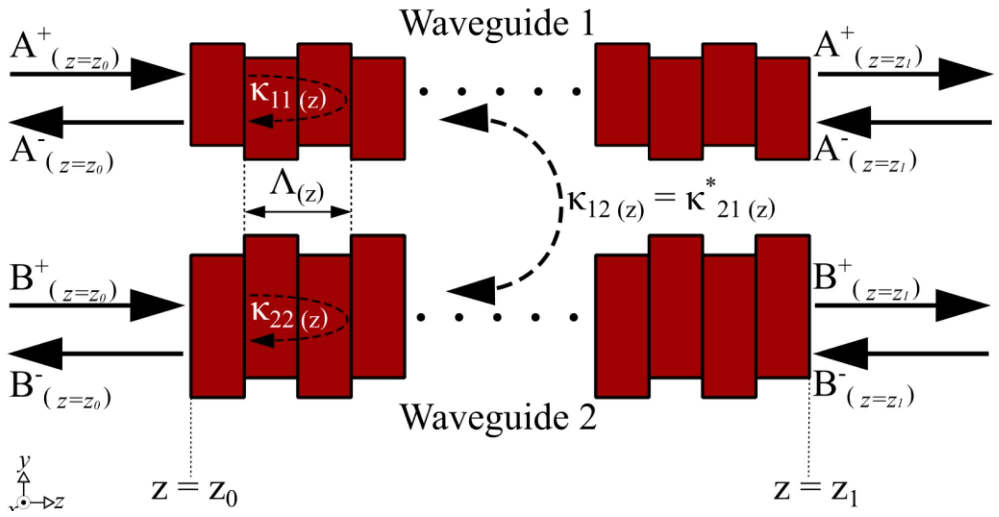
$$\frac{dA^-}{dz} = j\kappa_{11}^* A^+ e^{-j2\Delta\widehat{\beta}_1 z} + j\kappa_{12}^* B^+ e^{-j(\Delta\widehat{\beta}_1+\Delta\widehat{\beta}_2)z}$$

$$\frac{dB^-}{dz} = j\kappa_{12}^* A^+ e^{-j(\Delta\widehat{\beta}_1+\Delta\widehat{\beta}_2)z} + j\kappa_{22}^* B^+ e^{-j2\Delta\widehat{\beta}_2 z}$$

$$\kappa_{11} = \frac{\omega}{4}\iint \boldsymbol{E_1^*}(x,y)\,\Delta\varepsilon_1(x,y)\boldsymbol{E_1}(x,y)\,dx\,dy$$

$$\kappa_{12} = \kappa_{21}^* = \frac{\omega}{4}\iint \boldsymbol{E_1^*}(x,y)\,\Delta\varepsilon_1(x,y)\boldsymbol{E_2}(x,y)\,dx\,dy$$

$$\kappa_{22} = \frac{\omega}{4}\iint \boldsymbol{E_2^*}(x,y)\,\Delta\varepsilon_1(x,y)\boldsymbol{E_2}(x,y)\,dx\,dy$$



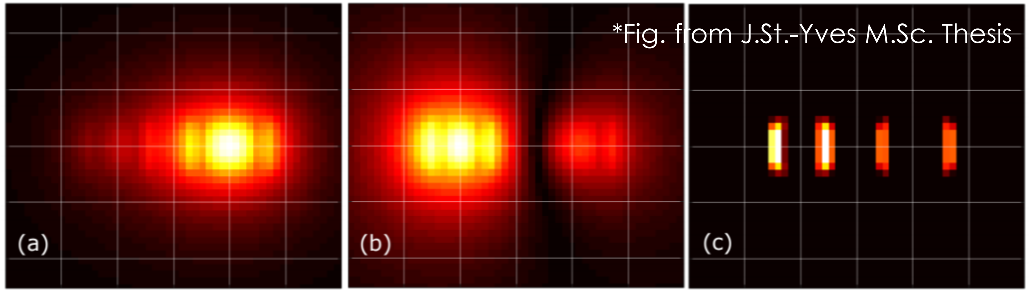
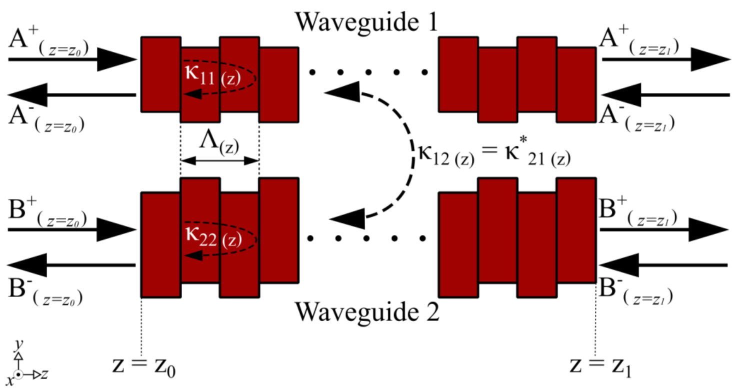


*Fig. from J.St.-Yves M.Sc. Thesis

M. Hammood

CONTRA-DIRECTIONAL COUPLERS

- Coupled-mode theory, Transfer-Matrix method



$$S_1 = \begin{bmatrix} j\widehat{\Delta\beta_1} & 0 & 0 & 0 \\ 0 & j\widehat{\Delta\beta_2} & 0 & 0 \\ 0 & 0 & -j\widehat{\Delta\beta_1} & 0 \\ 0 & 0 & 0 & -j\widehat{\Delta\beta_2} \end{bmatrix}$$

$$S_2 = \begin{bmatrix} -j\widehat{\Delta\beta_1} & 0 & -j\kappa_{11}e^{j2\widehat{\Delta\beta_1}z_1} & -j\kappa_{12}e^{j(\widehat{\Delta\beta_1}+\widehat{\Delta\beta_2})z_1} \\ 0 & -j\widehat{\Delta\beta_2} & -j\kappa_{12}e^{j(\widehat{\Delta\beta_1}+\widehat{\Delta\beta_2})z_1} & -j\kappa_{22}e^{j2\widehat{\Delta\beta_2}z_1} \\ j\kappa_{11}^{*}e^{-j2\widehat{\Delta\beta_1}z_1} & j\kappa_{21}e^{-j(\widehat{\Delta\beta_1}+\widehat{\Delta\beta_2})z_1} & j\widehat{\Delta\beta_1} & 0 \\ j\kappa_{21}^{*}e^{-j(\widehat{\Delta\beta_1}+\widehat{\Delta\beta_2})z_1} & j\kappa_{22}^{*}e^{-j2\widehat{\Delta\beta_2}z_1} & 0 & j\widehat{\Delta\beta_2} \end{bmatrix}$$

$$E(z) = \begin{bmatrix} A^{+}(z) \\ B^{+}(z) \\ A^{-}(z) \\ B^{-}(z) \end{bmatrix}$$

$$E(z_0) = C(z_0, z_1)E(z_1)$$

$$C(z_0, z_1) = e^{S_1(z_1 - z_0)}e^{S_2(z_1 - z_0)}$$

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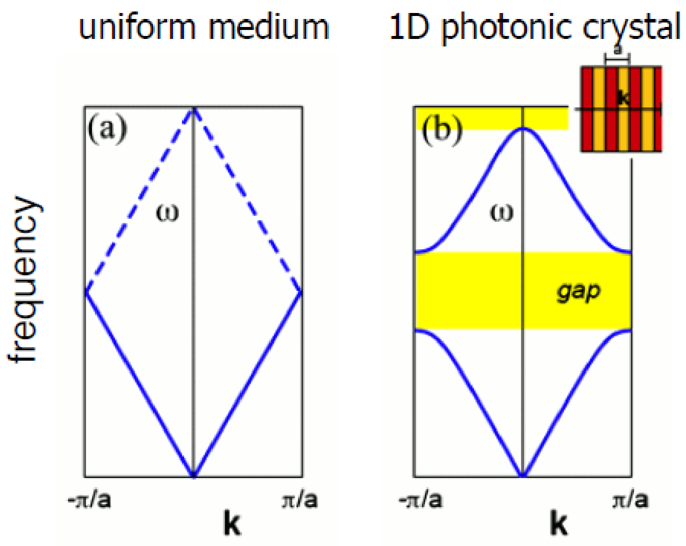
Electrical and Computer Engineering

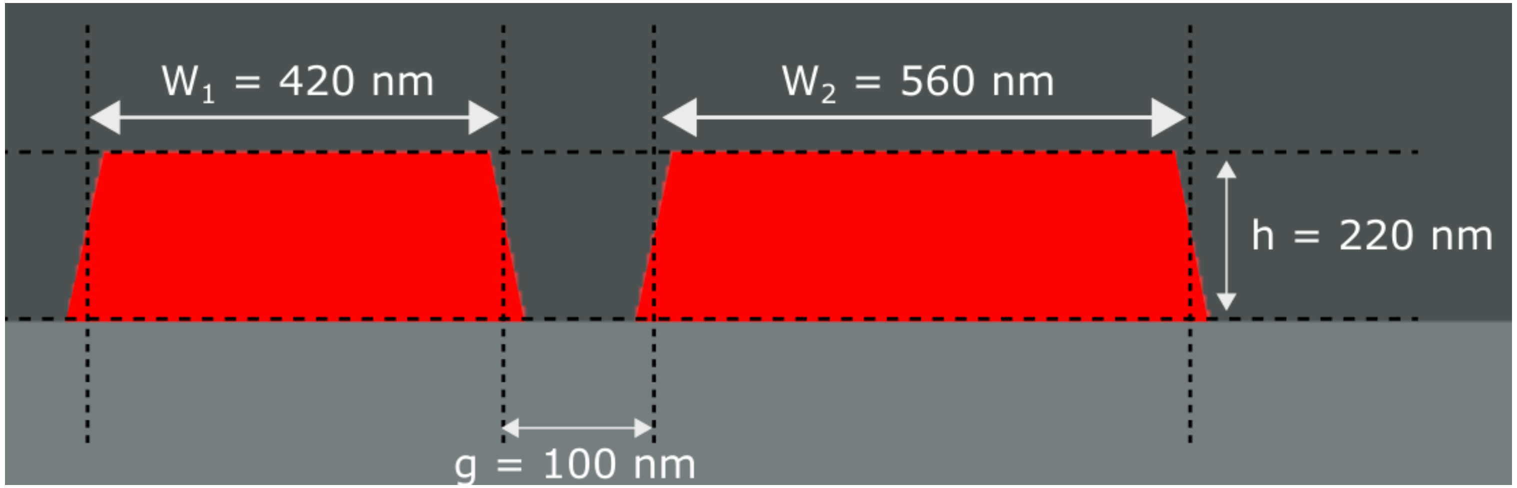
SiEPIC FAB

PHOTONIC BAND DIAGRAMS

- For a single 1-D periodic structure, the degenerate $k = \pi/\Lambda$ plane waves of a uniform medium are split into standing waves by a dielectric periodicity, forming the lower and upper edges of the band gap.

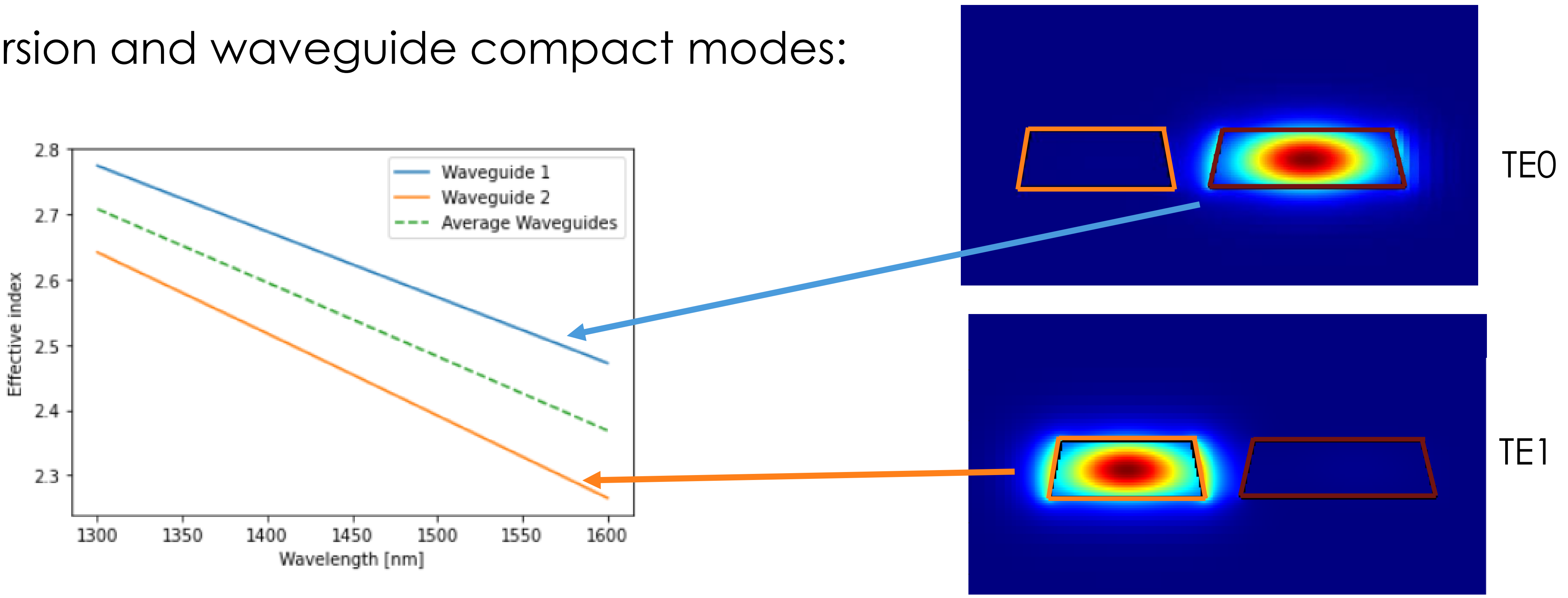


- Cross section of a two-waveguide system:

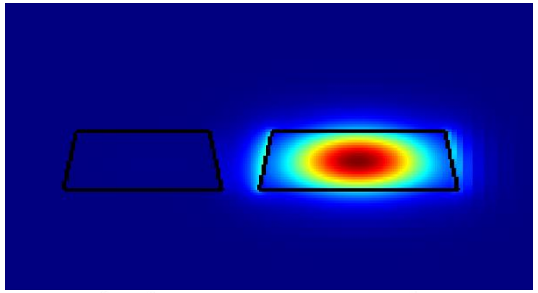


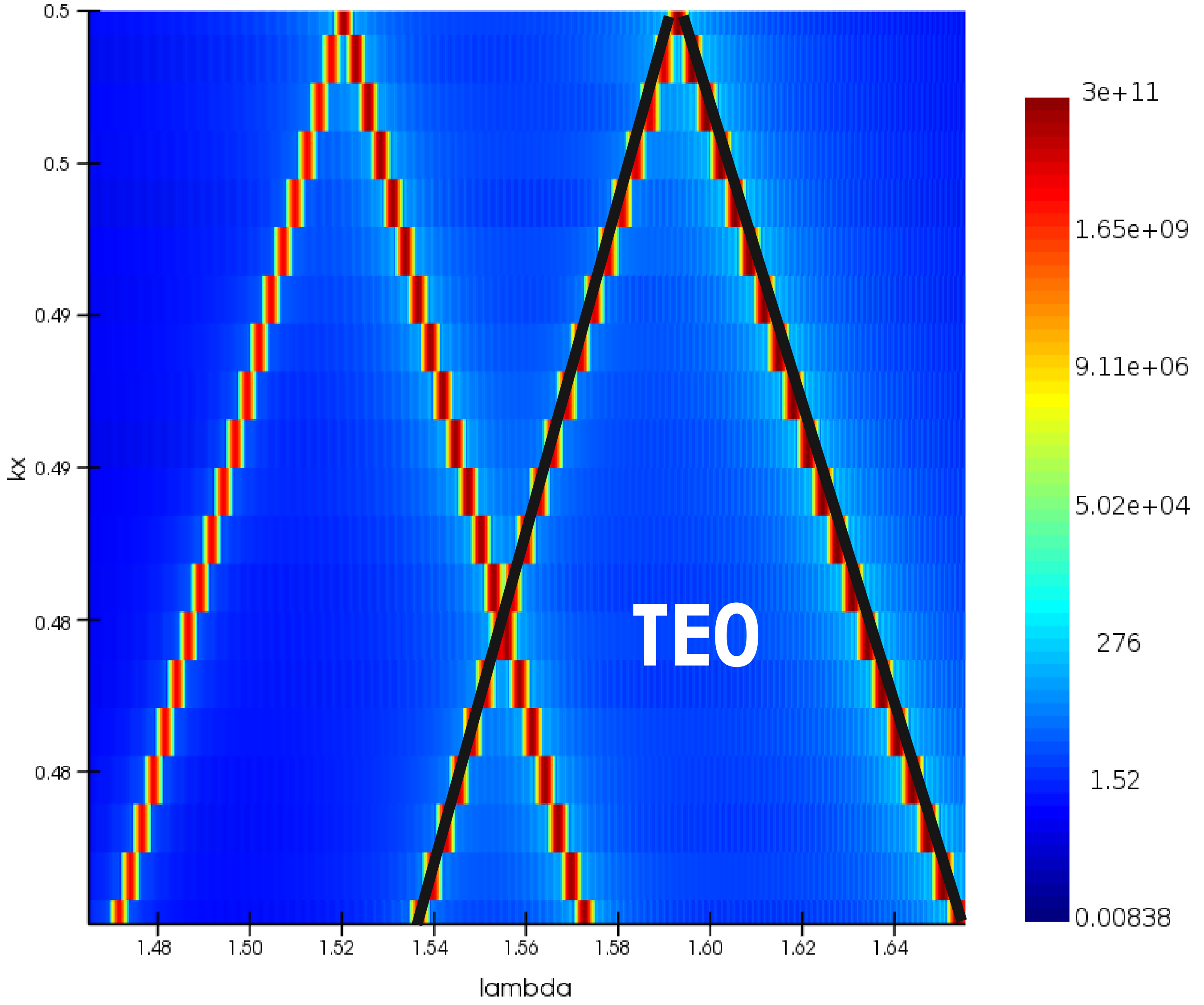
PHOTONIC BAND DIAGRAMS

- Dispersion and waveguide compact modes:



PHOTONIC BAND DIAGRAMS





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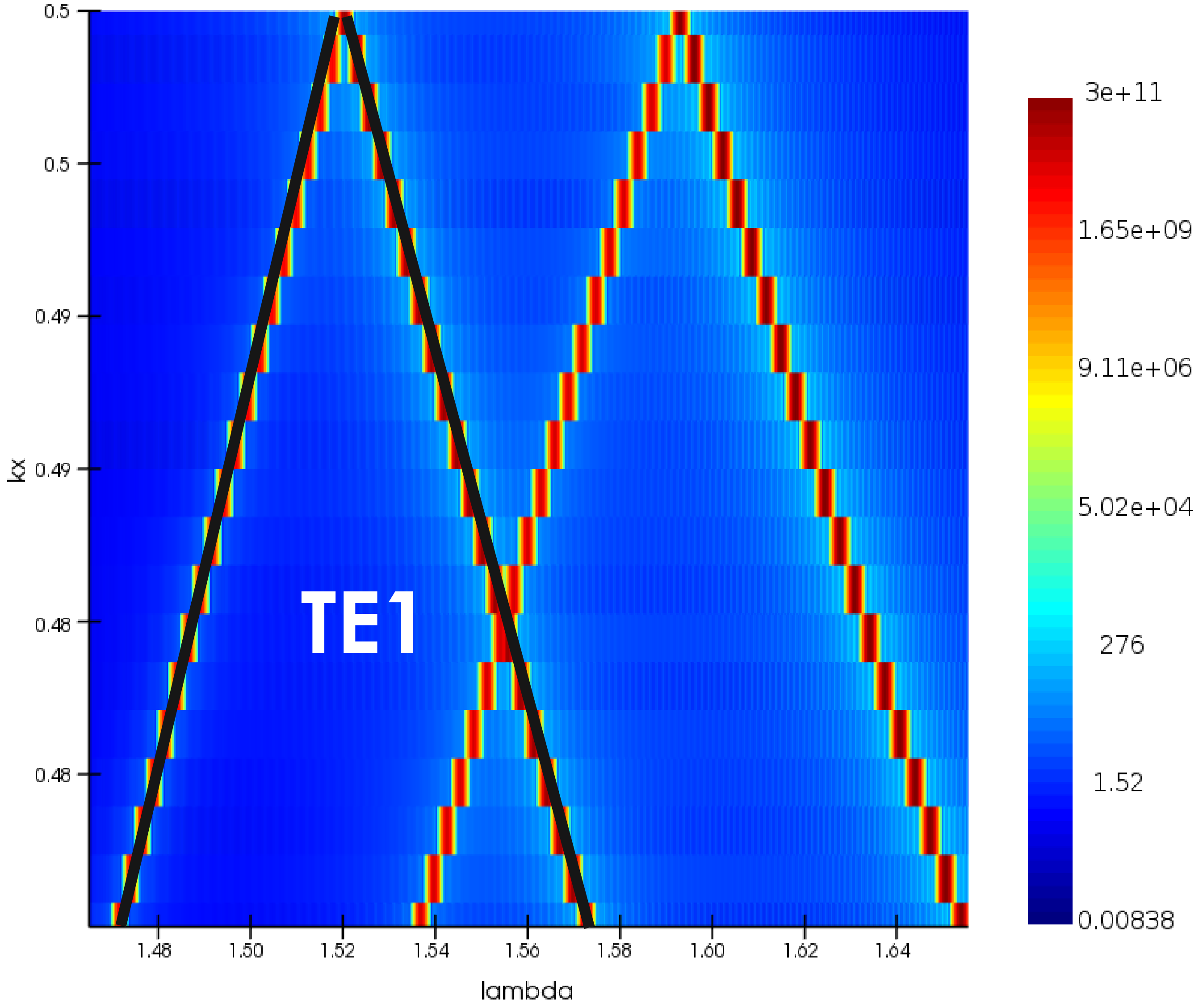
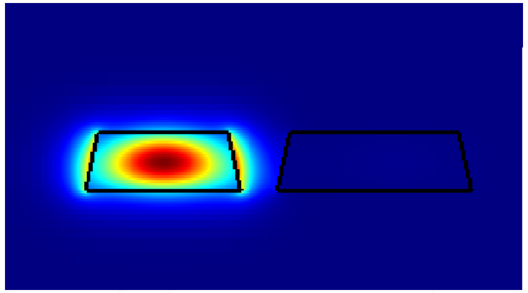




PHOTONIC BAND DIAGRAMS

PERTURBING THE SYSTEM

What happens when the waveguides are corrugated periodically?

PHOTONIC BAND DIAGRAMS

Unperturbed Waveguides

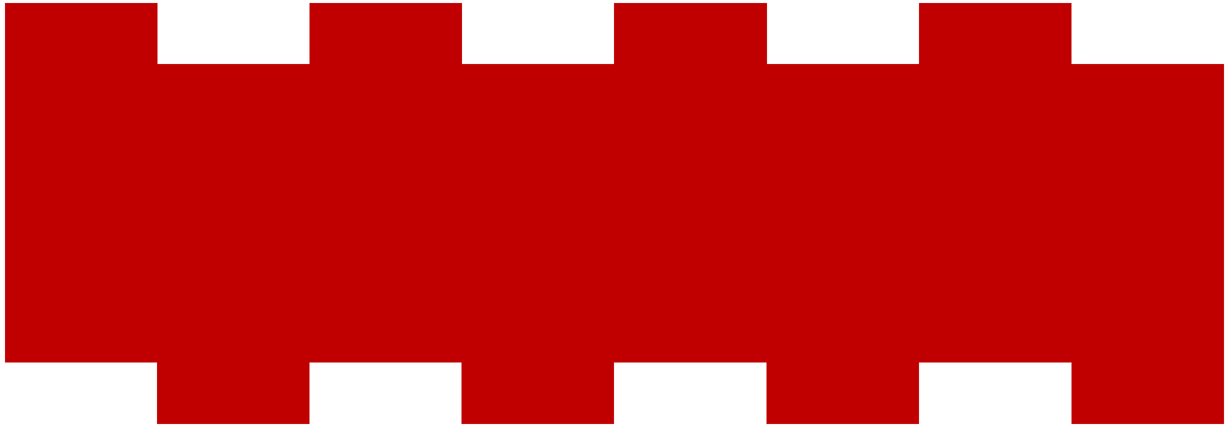
Waveguide 1

Waveguide 2

PHOTONIC BAND DIAGRAMS

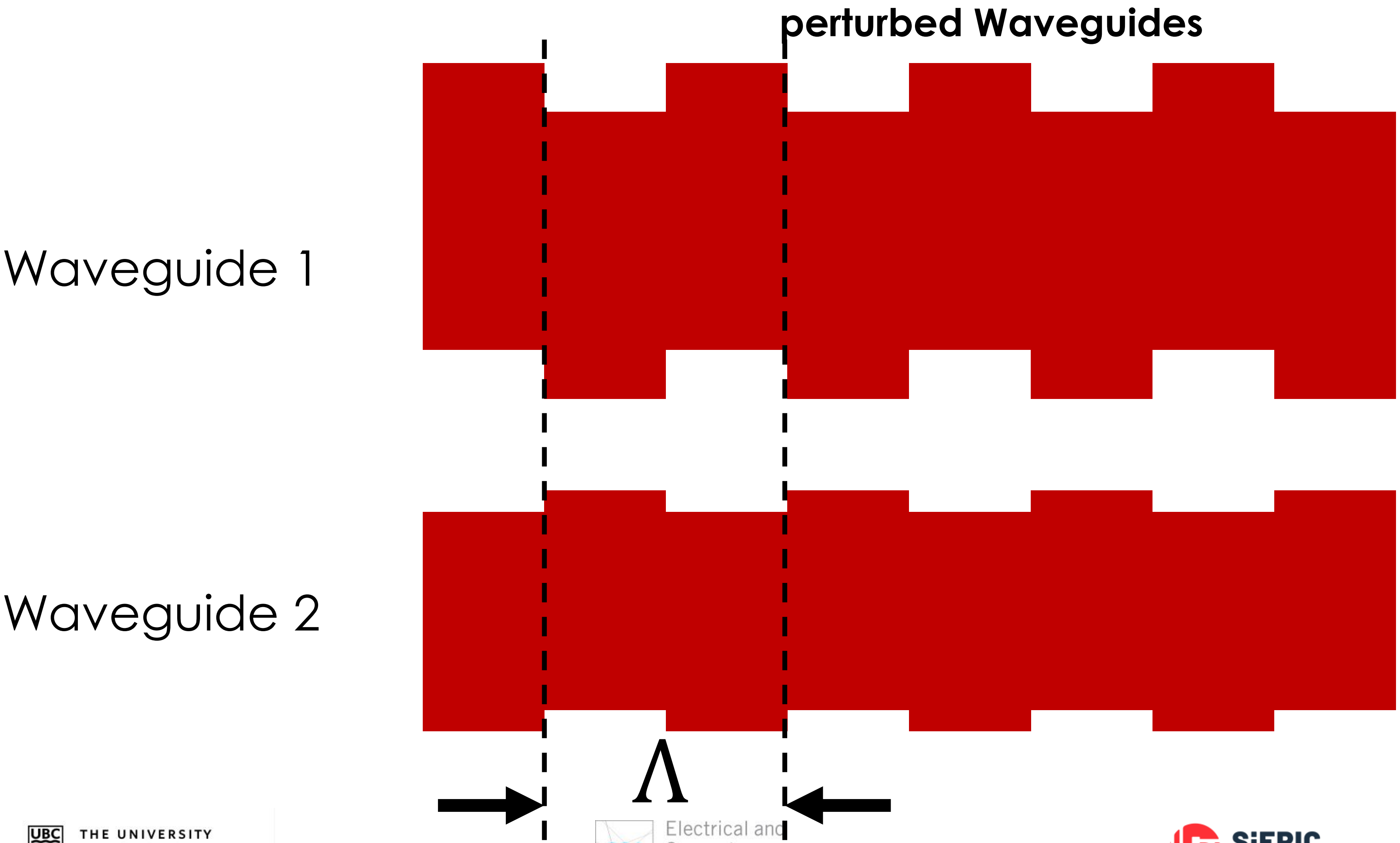
perturbed Waveguides

Waveguide 1



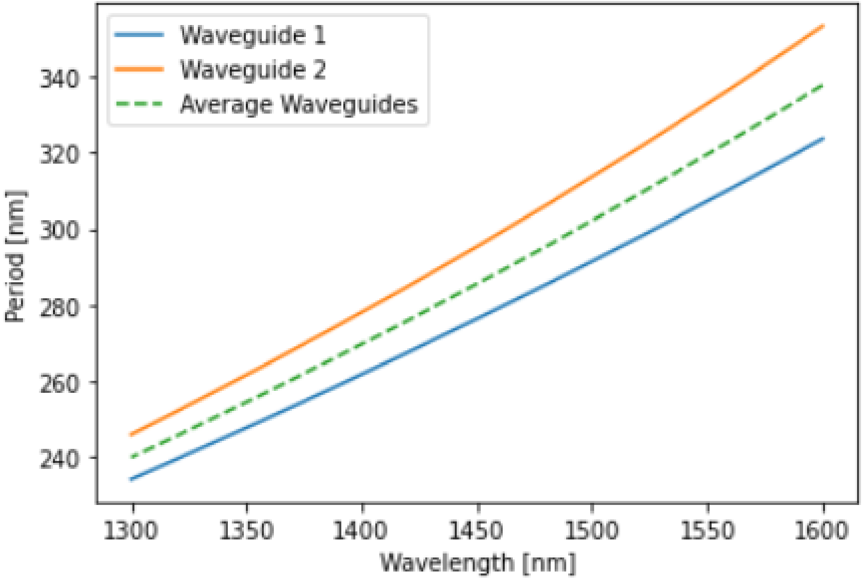
Waveguide 2

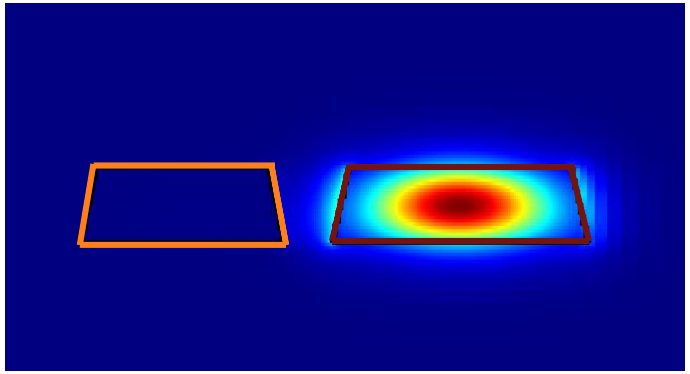
PHOTONIC BAND DIAGRAMS



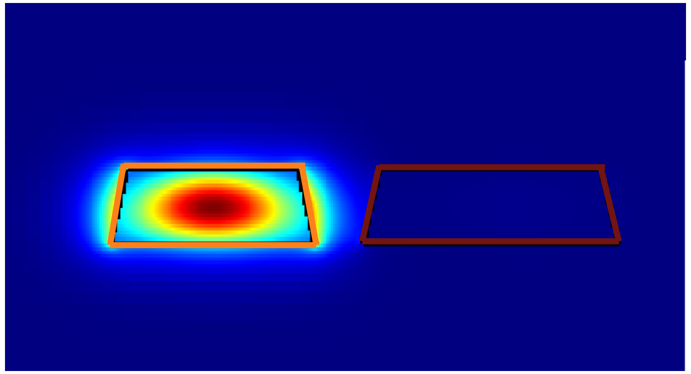
PHOTONIC BAND DIAGRAMS

$$\Lambda = \frac{\lambda}{2\, n(\lambda)}$$





TE0

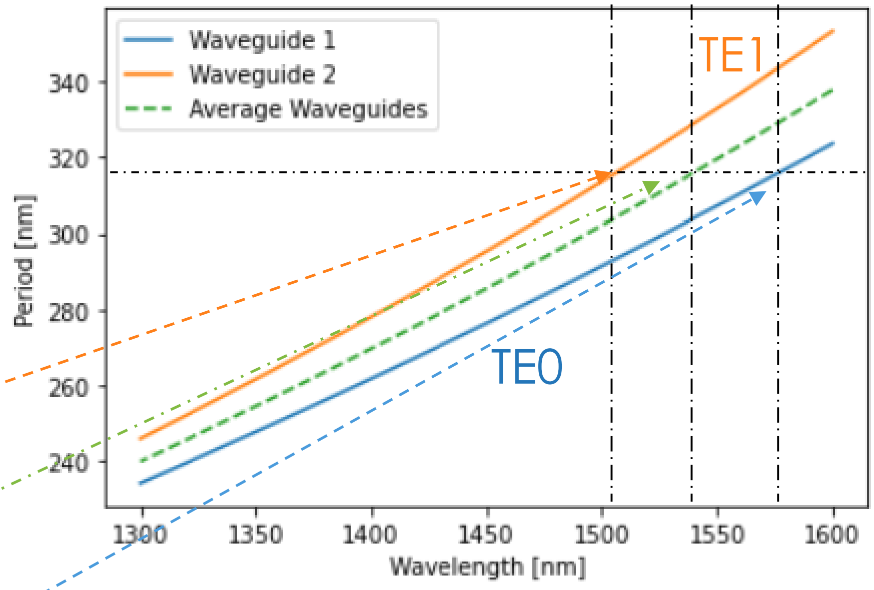


TE1

PHOTONIC BAND DIAGRAMS

- Designer choice: Pick a perturbation period of $\Lambda = 318\, nm$

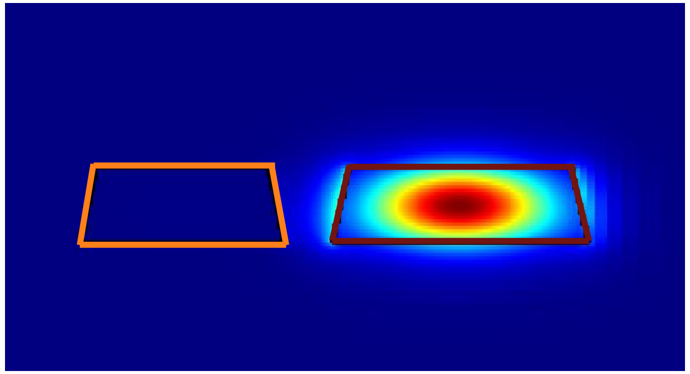
$$\Lambda = \frac{\lambda}{2\, n(\lambda)}$$



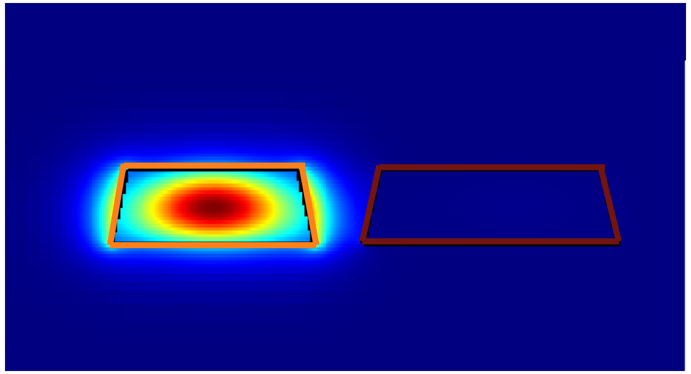
λ_{wg2} = 1511.4 nm

λ_{CDC} = 1545.6 nm

λ_{wg1} = 1582.9 nm



TE0

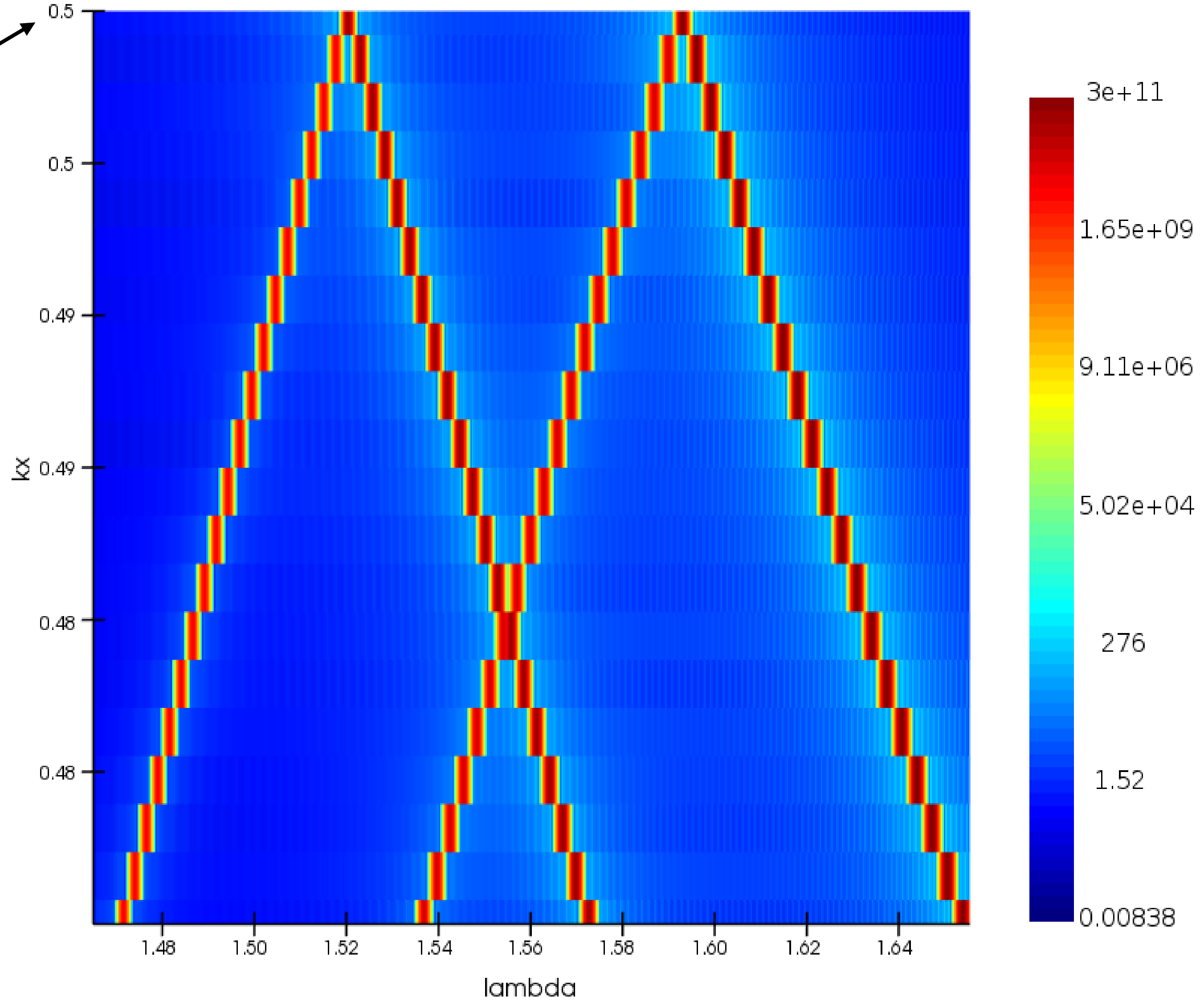


TE1

PHOTONIC BAND DIAGRAMS

$$k_{x0} = \frac{\pi}{\Lambda} = 0.5$$

$$k_x = \frac{2\,\pi\, n_{(y)}}{\lambda}$$

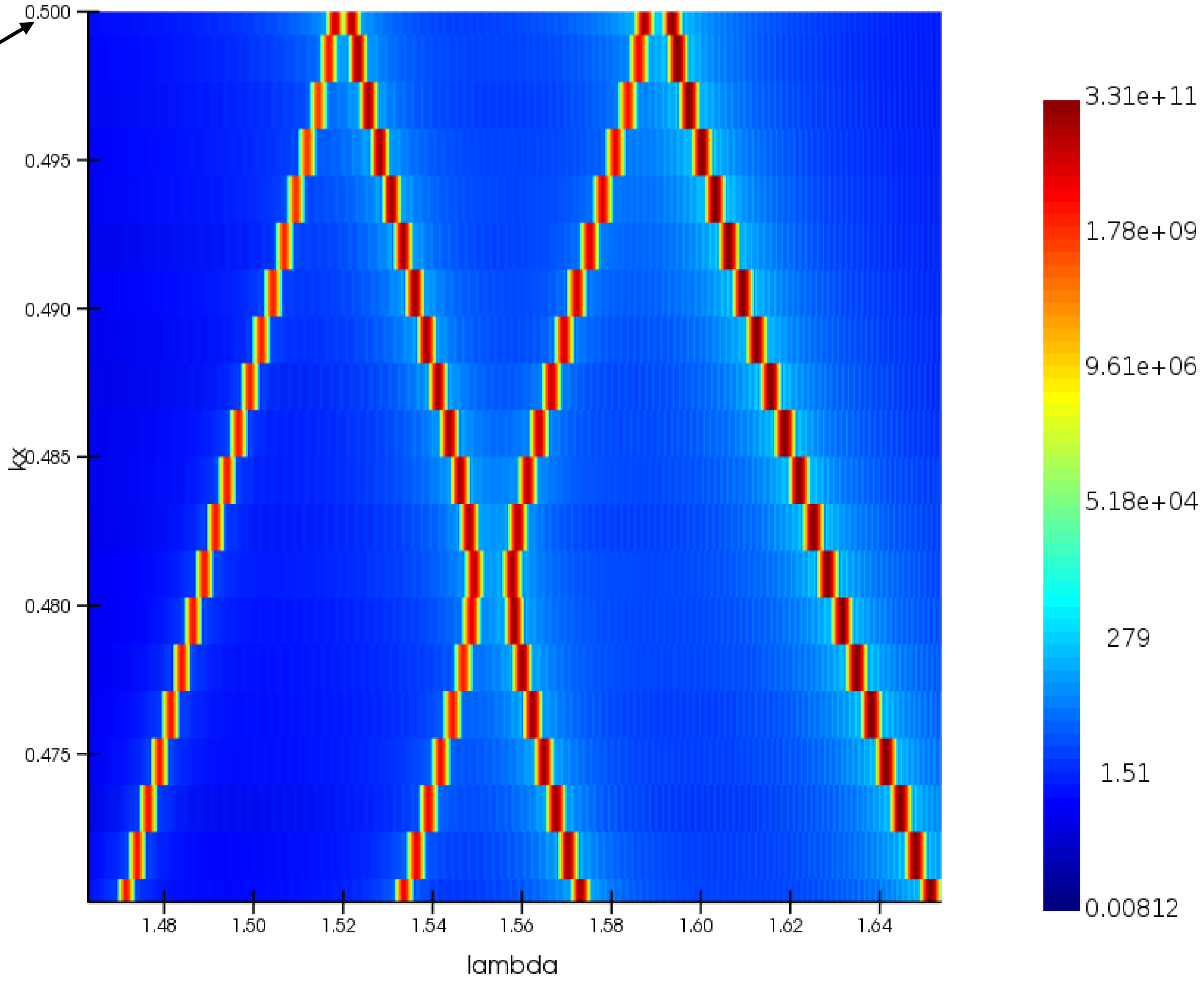


perturbed Waveguides

PHOTONIC BAND DIAGRAMS

$$k_{x0} = \frac{\pi}{\Lambda} = 0.5$$

$$k_x = \frac{2\,\pi\, n_{(y)}}{\lambda}$$



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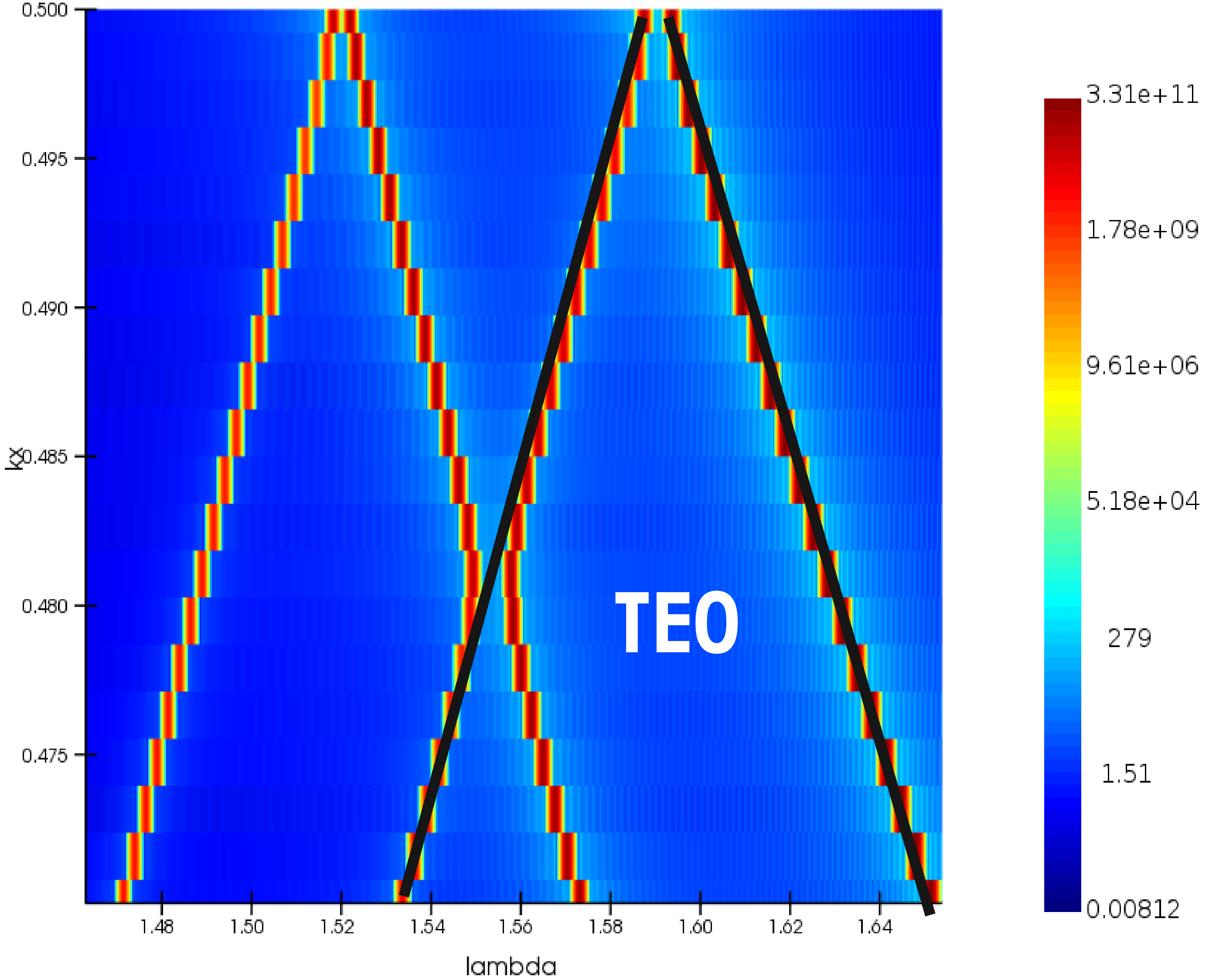

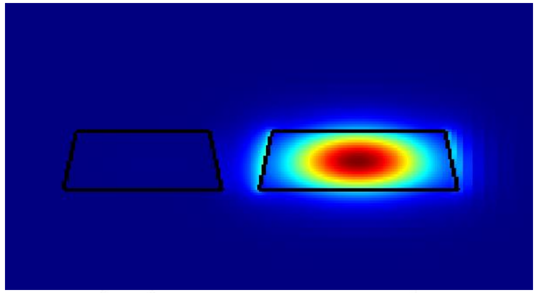

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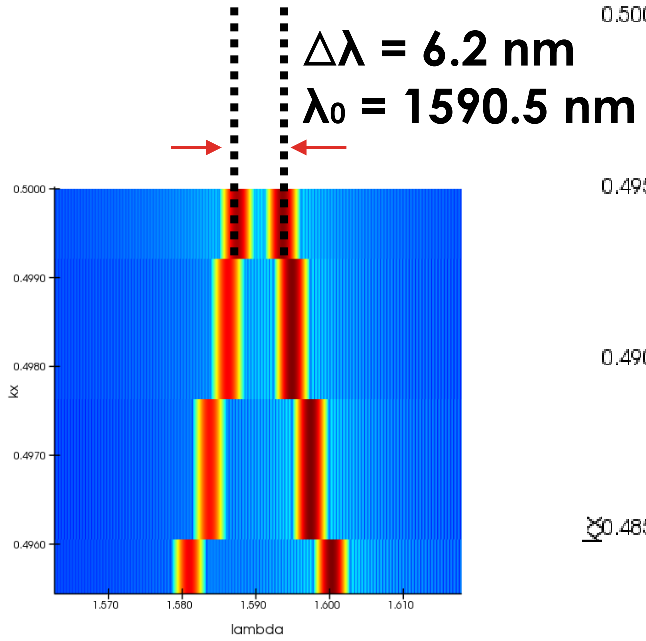
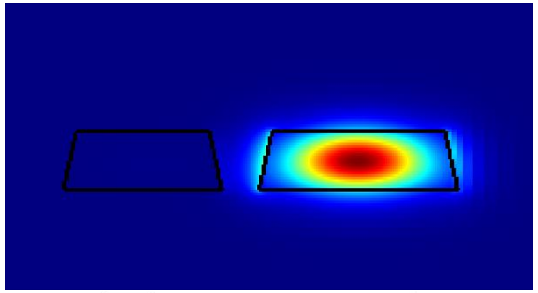
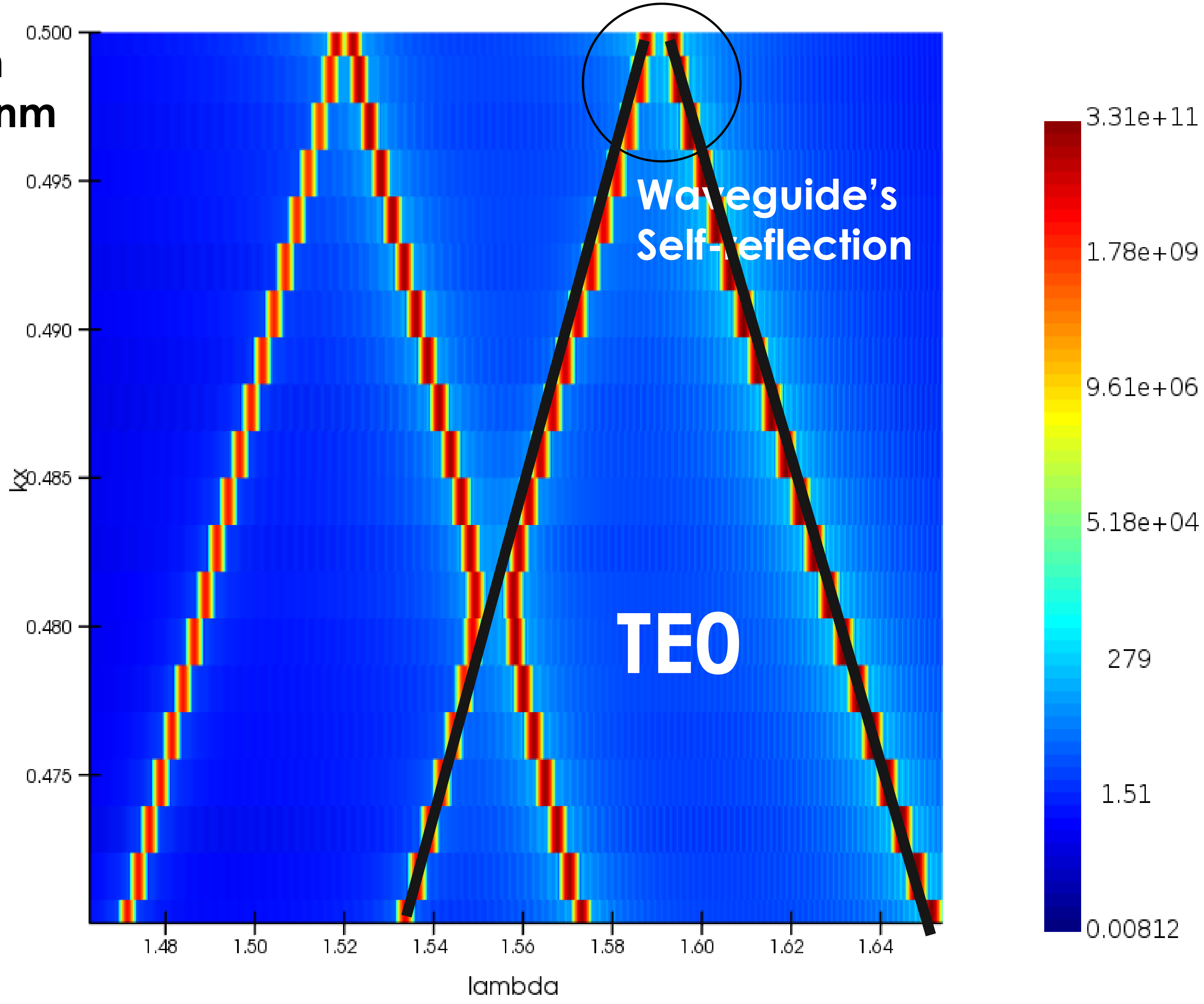
PHOTONIC BAND DIAGRAMS







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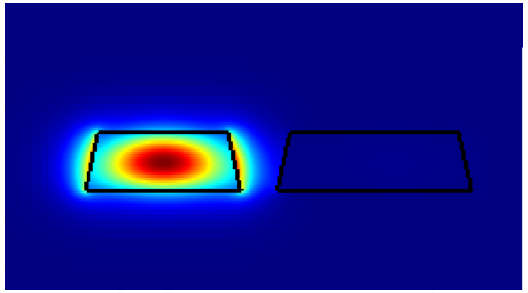
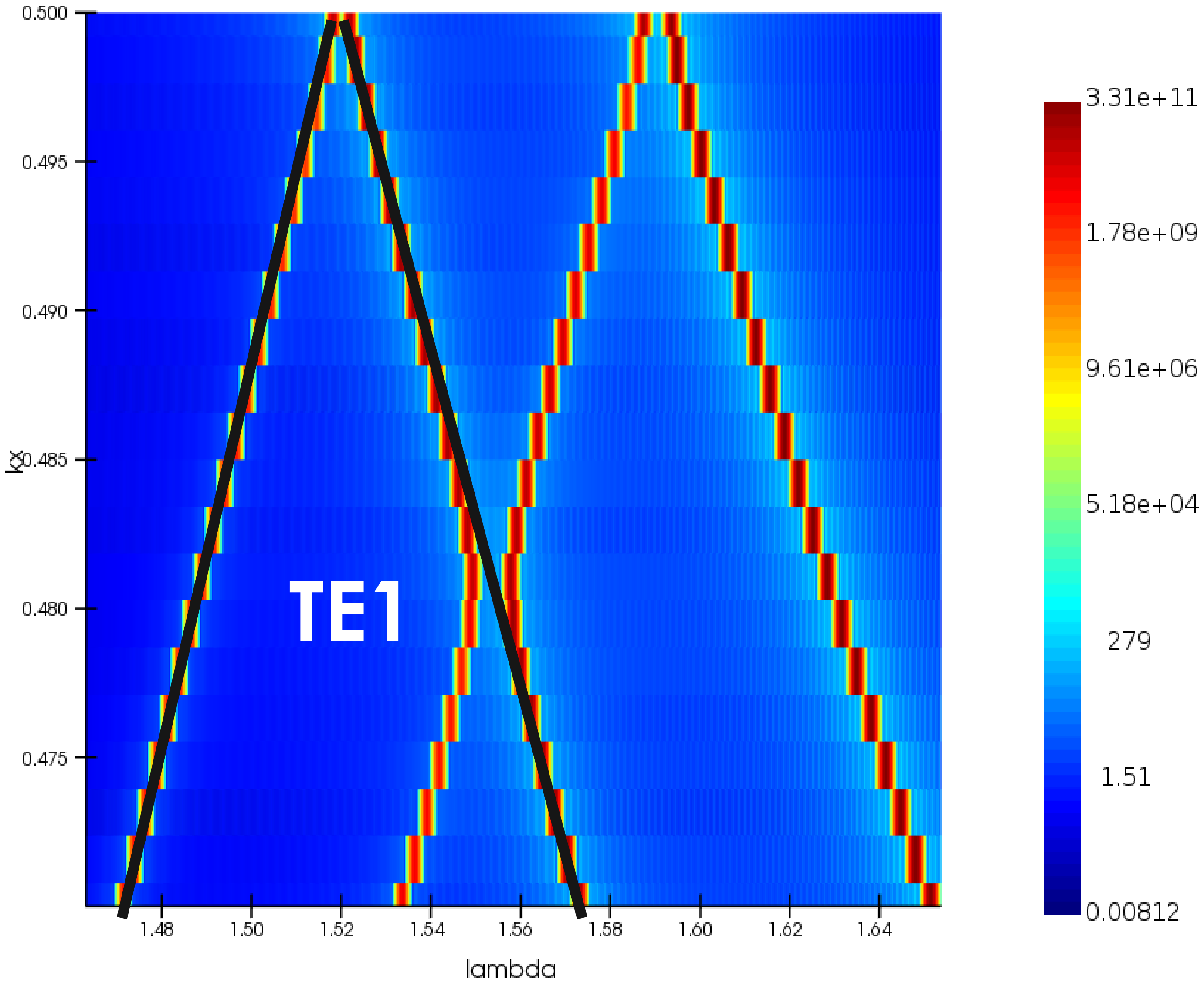
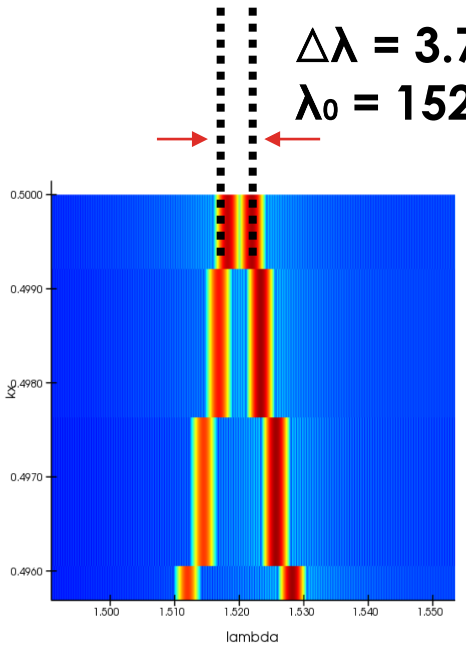
PHOTONIC BAND DIAGRAMS

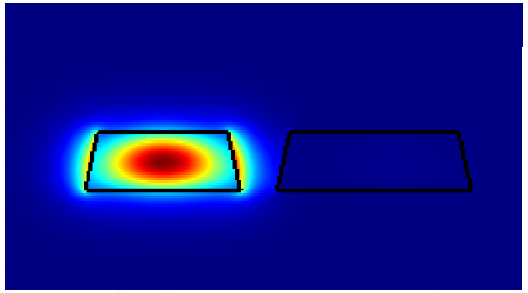


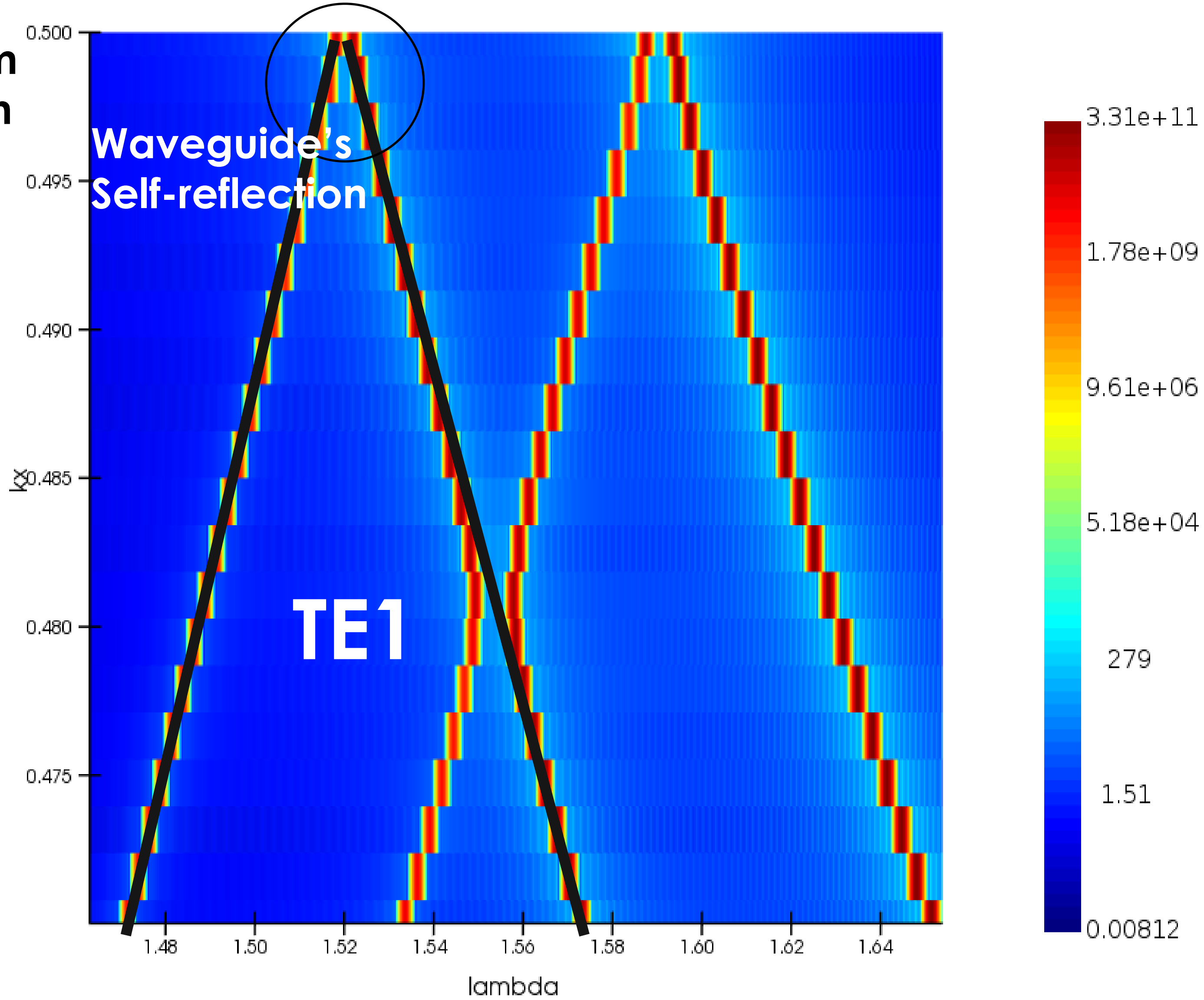


PHOTONIC BAND DIAGRAMS

$\Delta\lambda$ = 3.75 nm
λ_0 = 1520 nm







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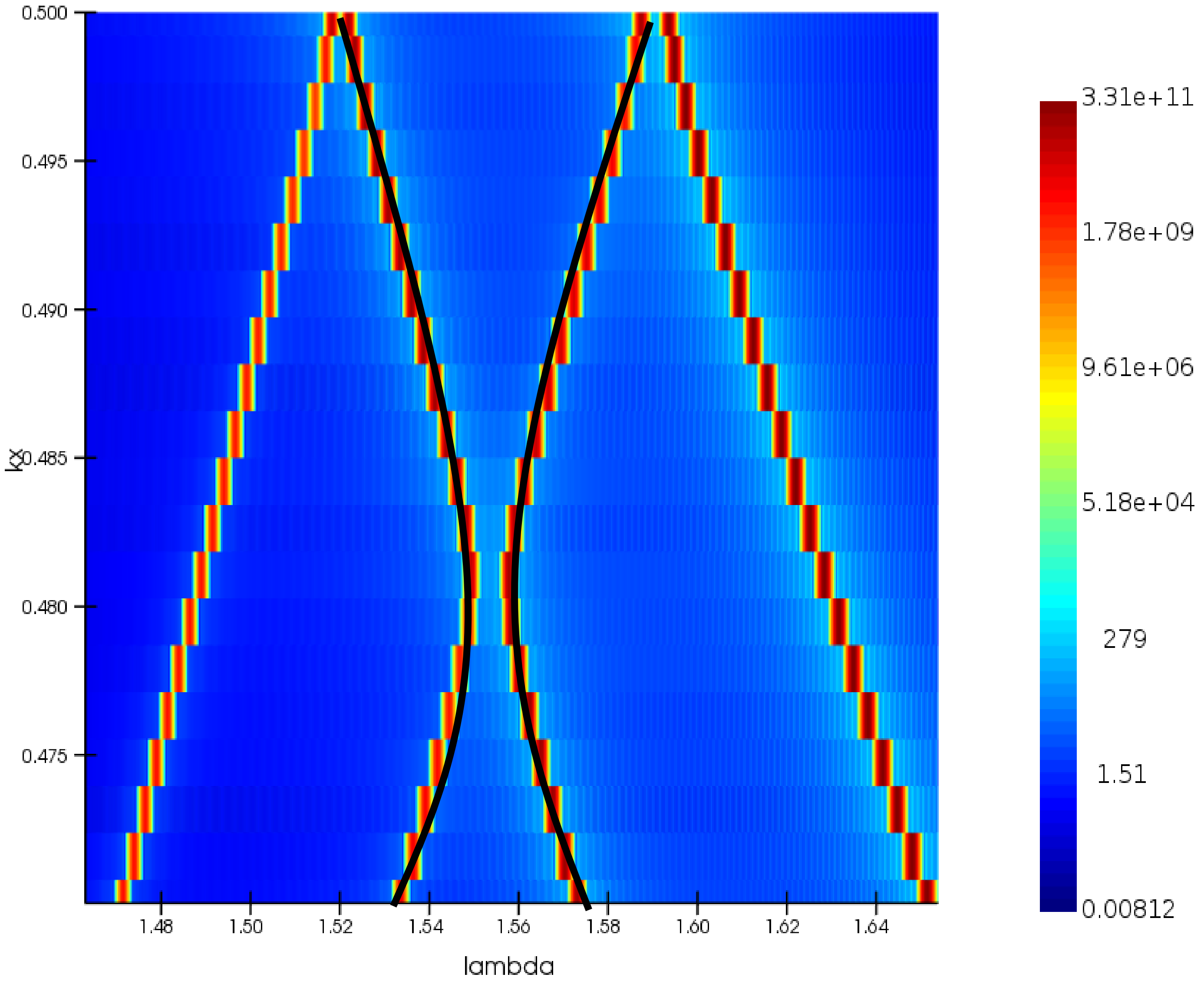
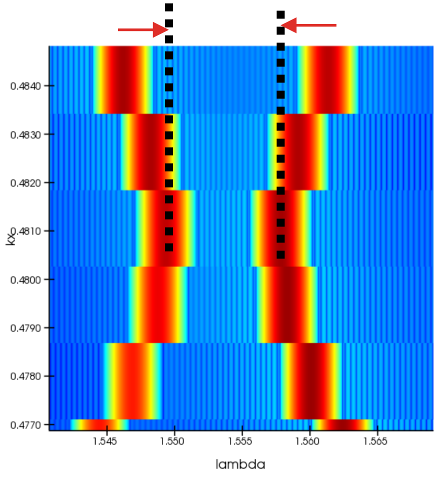
PHOTONIC BAND DIAGRAMS

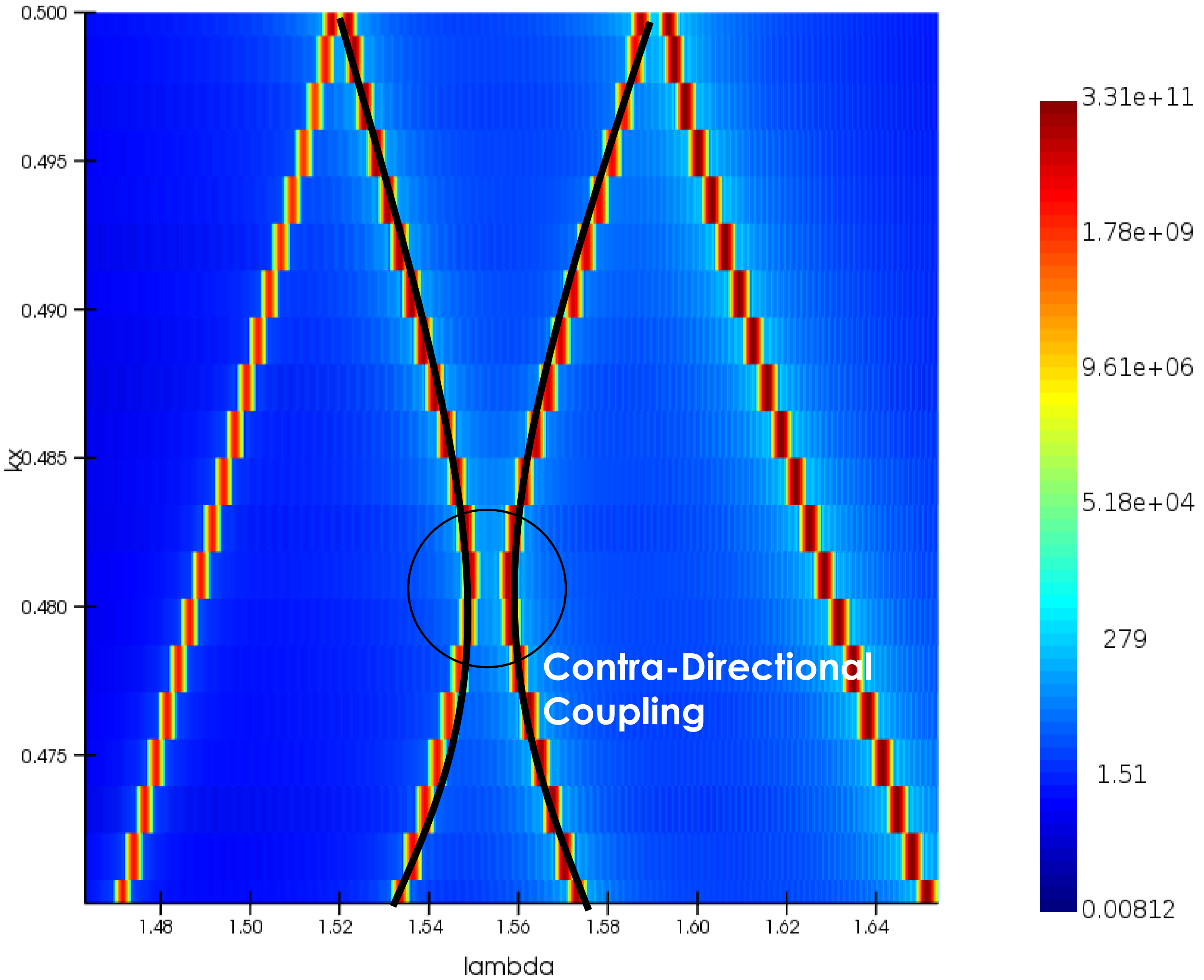


PHOTONIC BAND DIAGRAMS

Δλ = 8.4 nm
λ_0 = 1553.5 nm

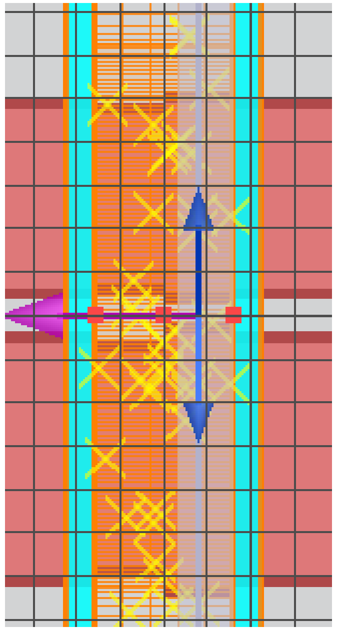


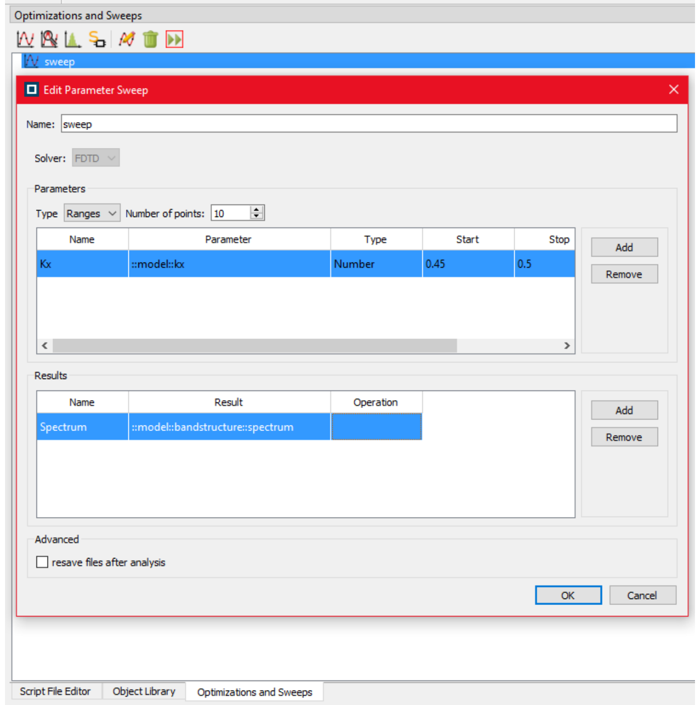
$$\kappa = \pi n_g \Delta\lambda / \lambda_0^{\,2}$$



PHOTONIC BAND DIAGRAMS IN FDTD

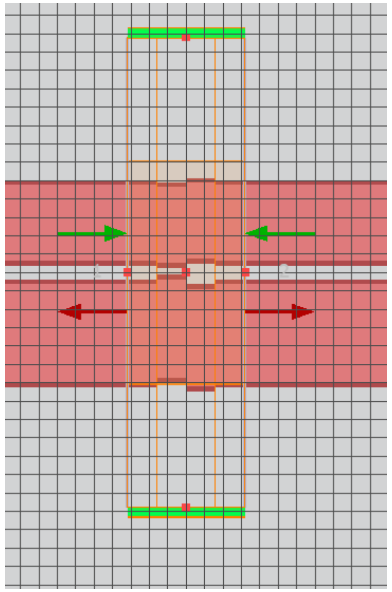
- Tutorial available through FDTD -> Bandstructure -> MAIN_Bandstructure.lsf
- Create a sweep to generate the band diagram after running the script:

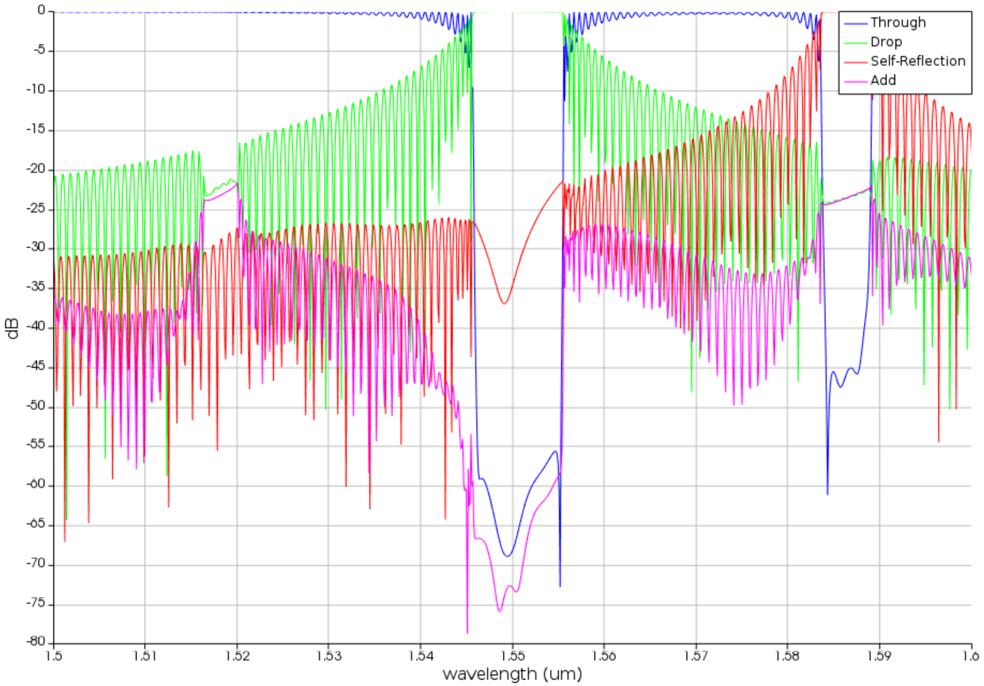




SIMULATE CONTRA-DC IN EME

- Similar to the previously discussed Bragg gratings EME simulations…
- Run EME -> MAIN_EME.lsf in Lumerical MODE





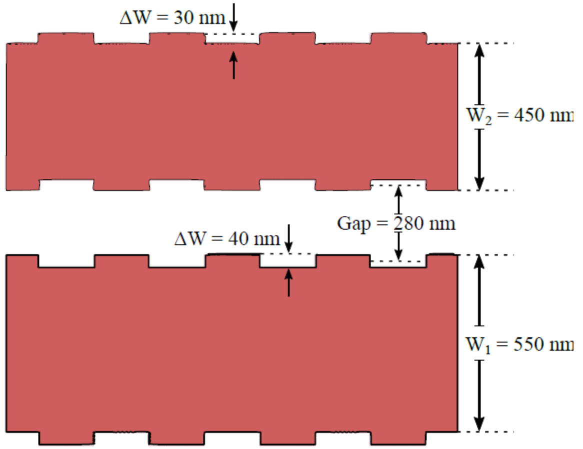
PRACTICAL DESIGN

Somethings to consider before fabrication…

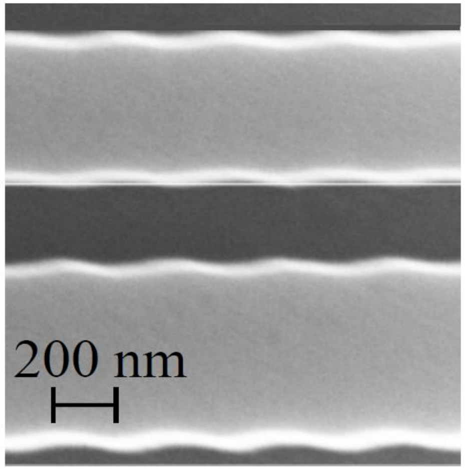
LITHOGRAPHY EFFECTS

- Low throughput of the electron-beam process makes it unsuitable for large-scale production of photonic devices.
- CMOS-compatible processes, such as deep-ultraviolet (DUV) lithography, have been proven suitable.
- Performance of devices are affected by lithography effects such as smoothing and proximity effects.
- Such effects change the response of a contra-DC significantly, and therefore, must be accounted for prior to fabrication.

Mask

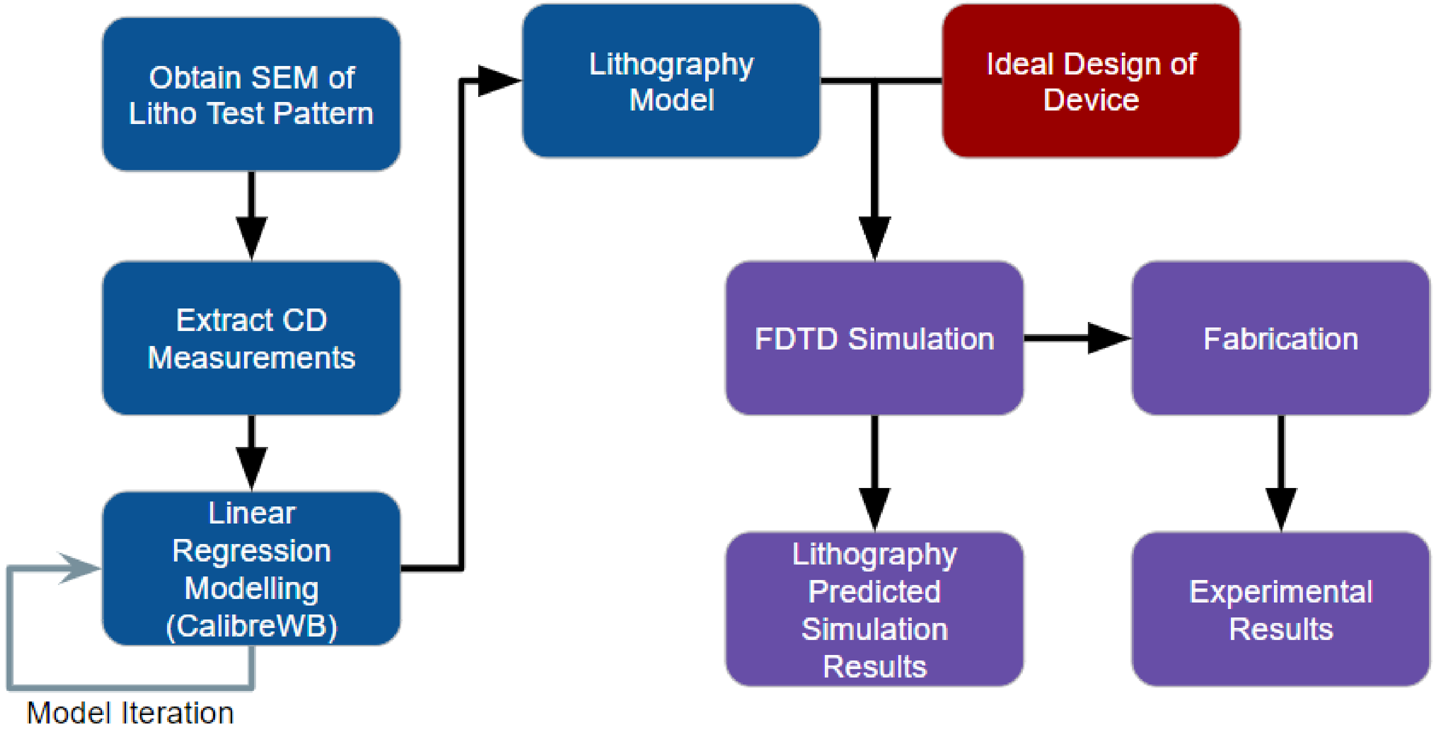


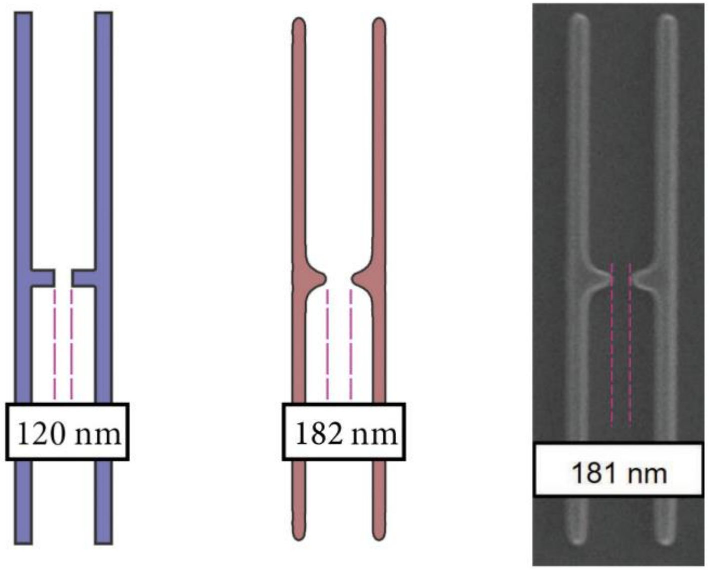
SEM



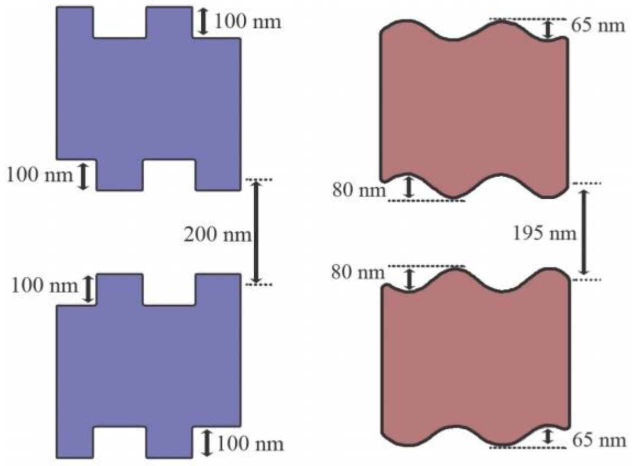
LITHOGRAPHY EFFECTS

- Lithography effects can be modelled using computational lithography predictive models.





(a) Test Pattern (b) Simulation (c) Fabricated

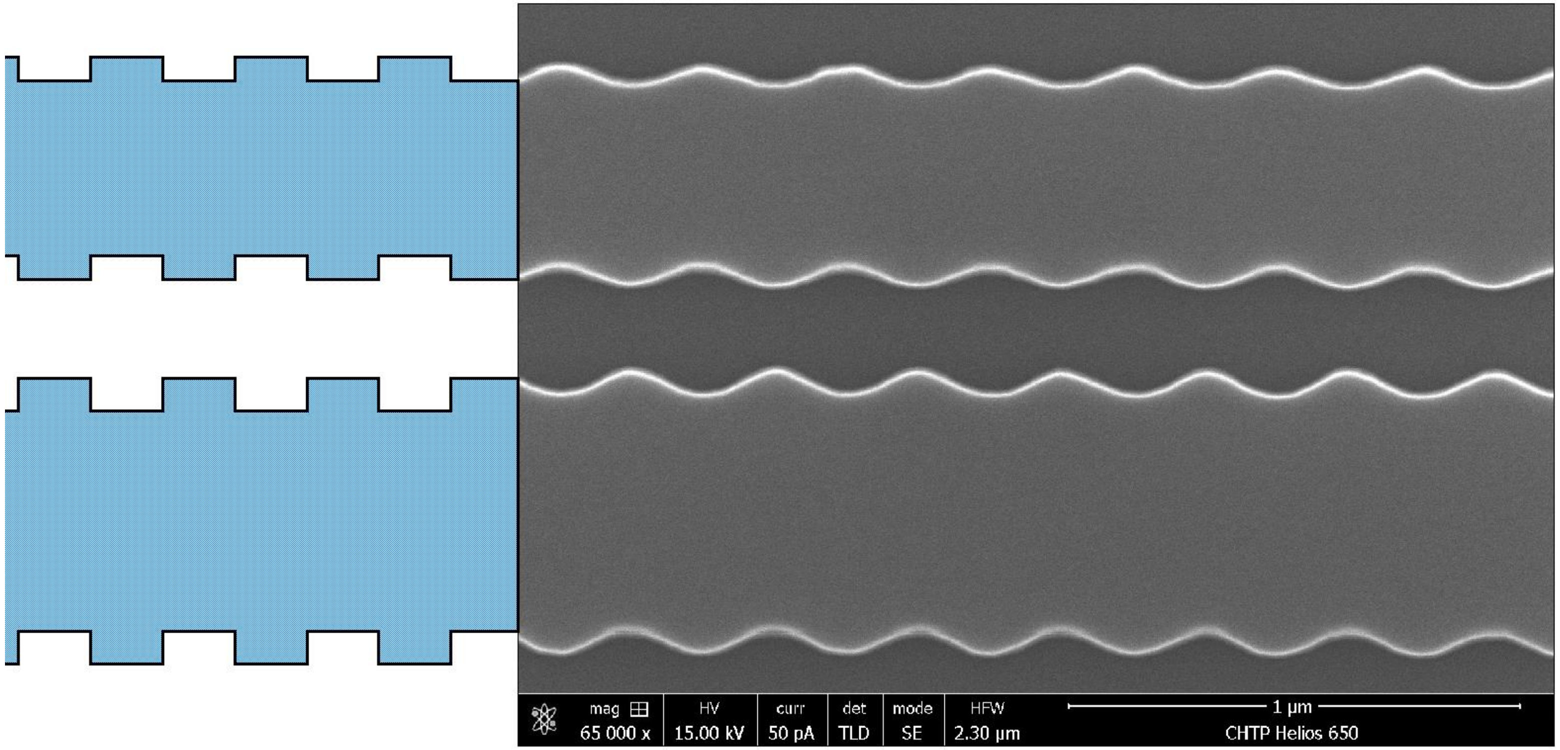


(a) Ideal Mask (b) Post-Lithography

S. Lin et al, JSTQE 2020
10.1109/JSTQE.2019.2958931

LITHOGRAPHY EFFECTS

- Lithography effects can be modelled using computational lithography predictive models.



LITHOGRAPHY EFFECTS

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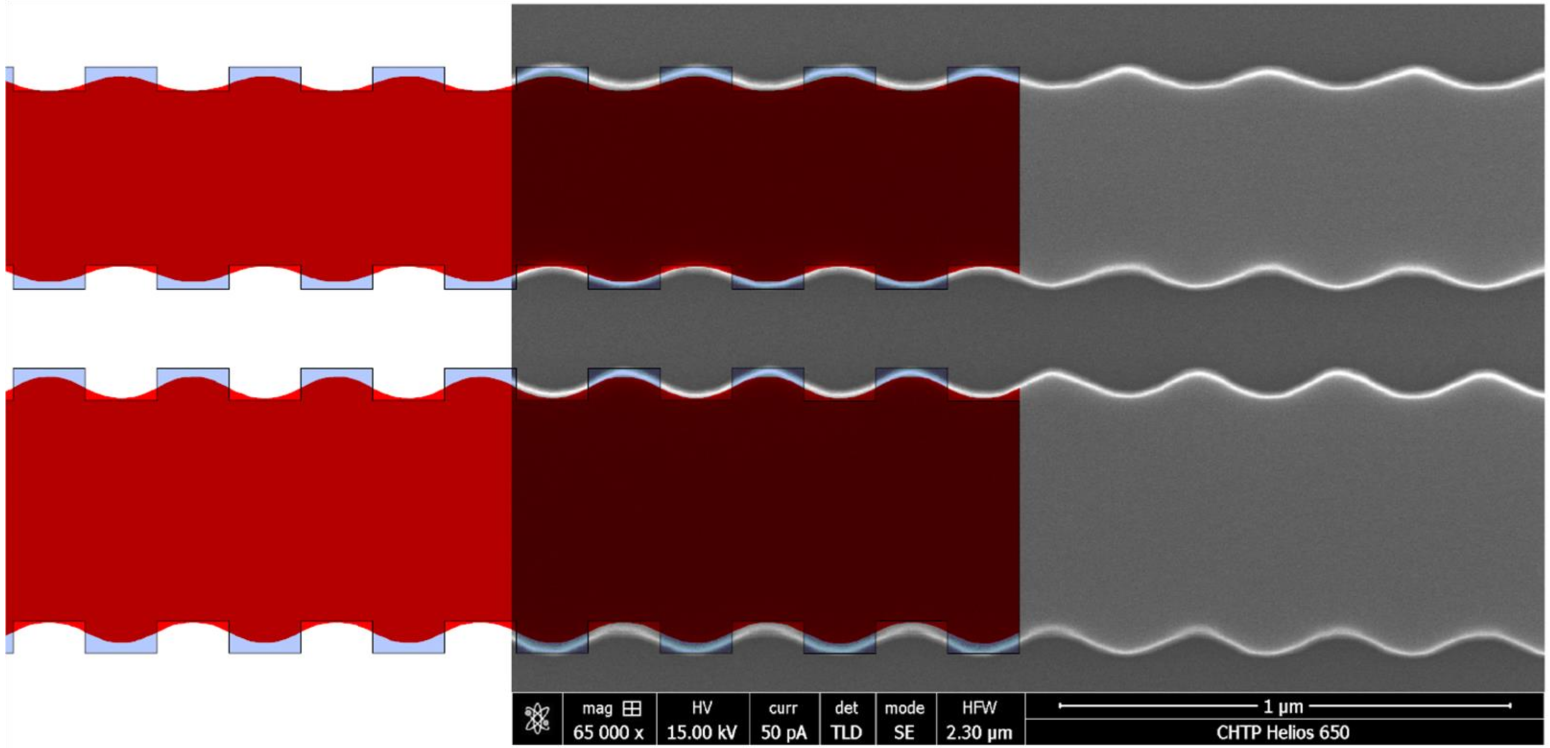
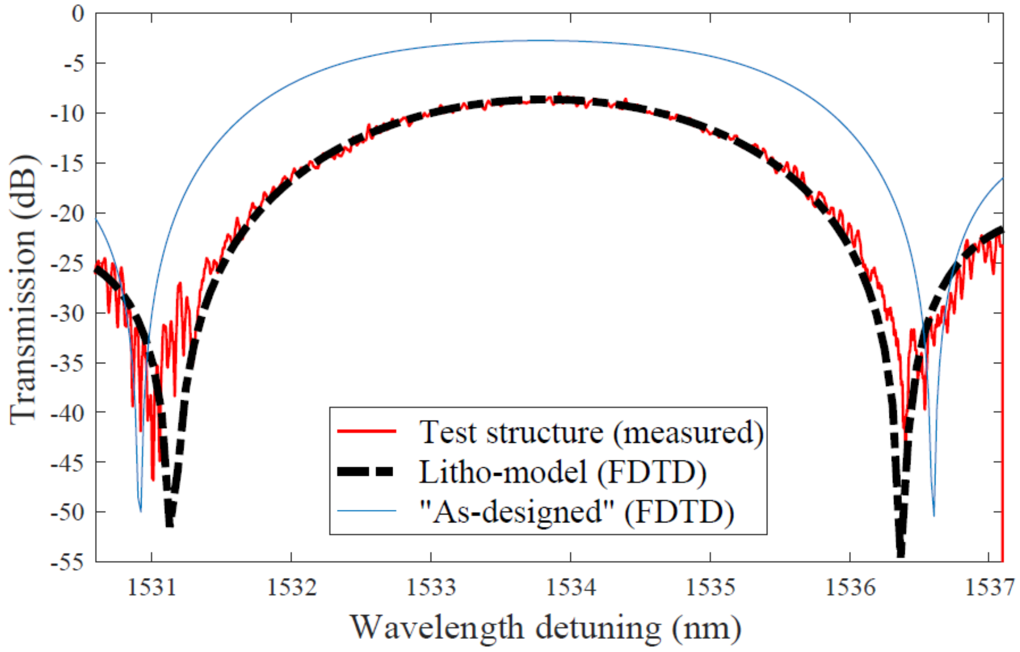
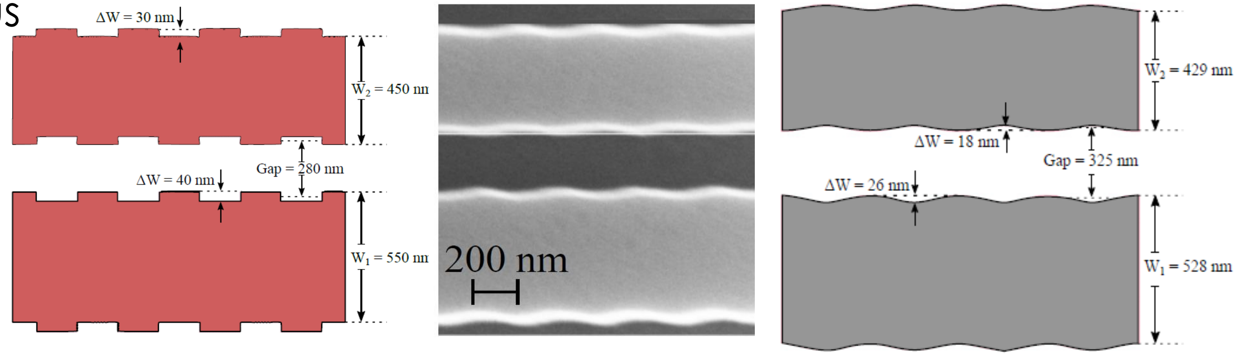


LITHOGRAPHY EFFECTS

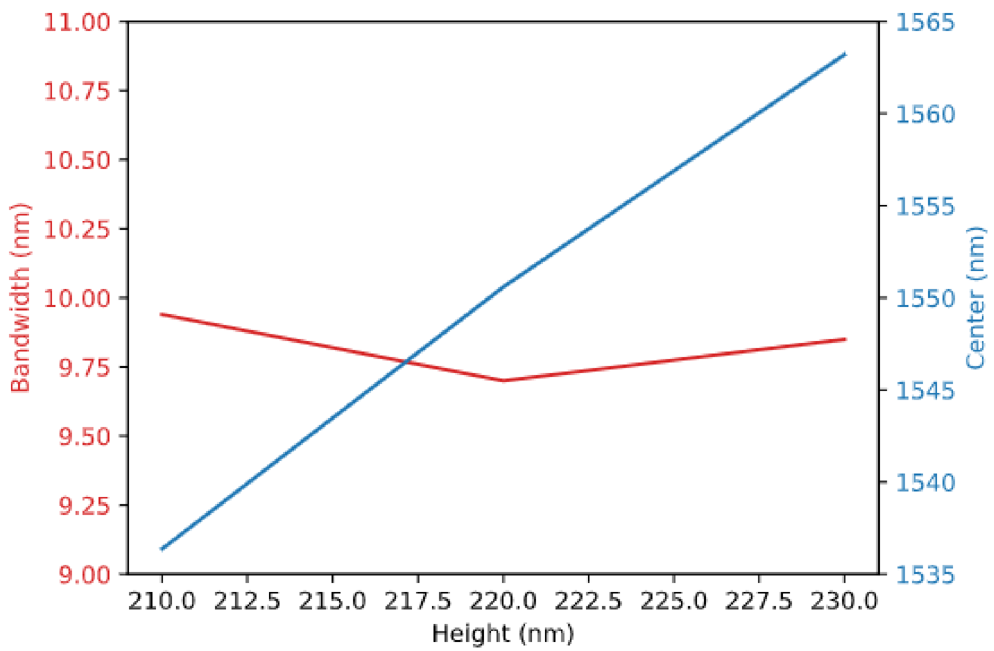
- A reference contra-DC device is designed:
  - Device (ideal) is simulated
  - Device is measured
  - Computational lithography models are applied to predict the fabricated geometry
  - Device (predicted) is simulated
- Knowing predicted device performance allows us to preemptively correct for lithography effects.

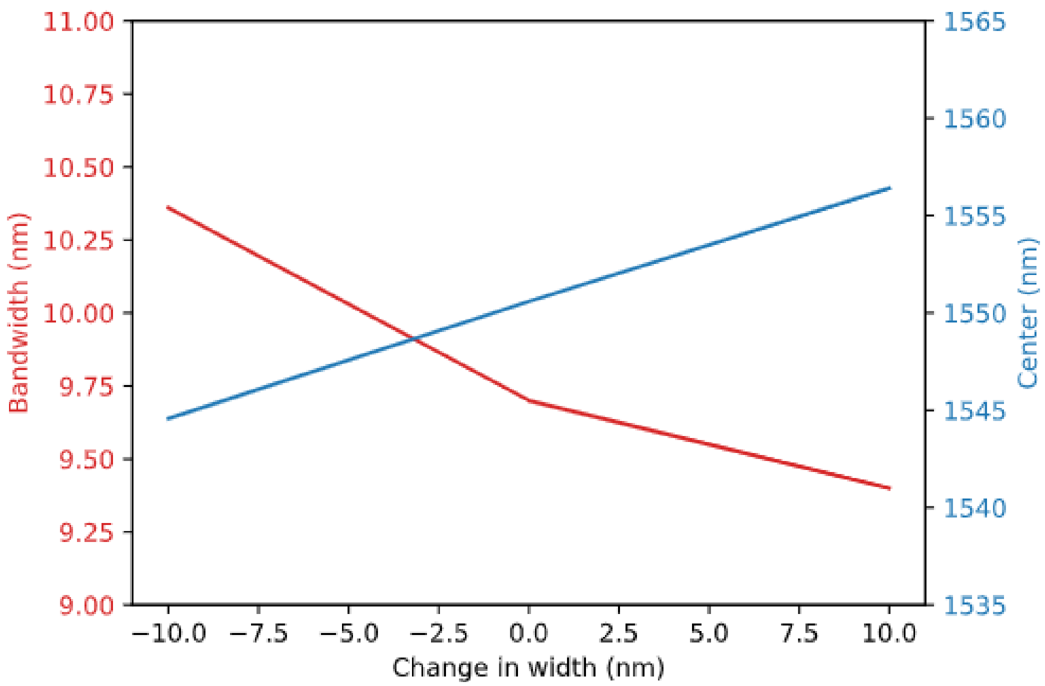




EFFECTS OF FABRICATION VARIATION

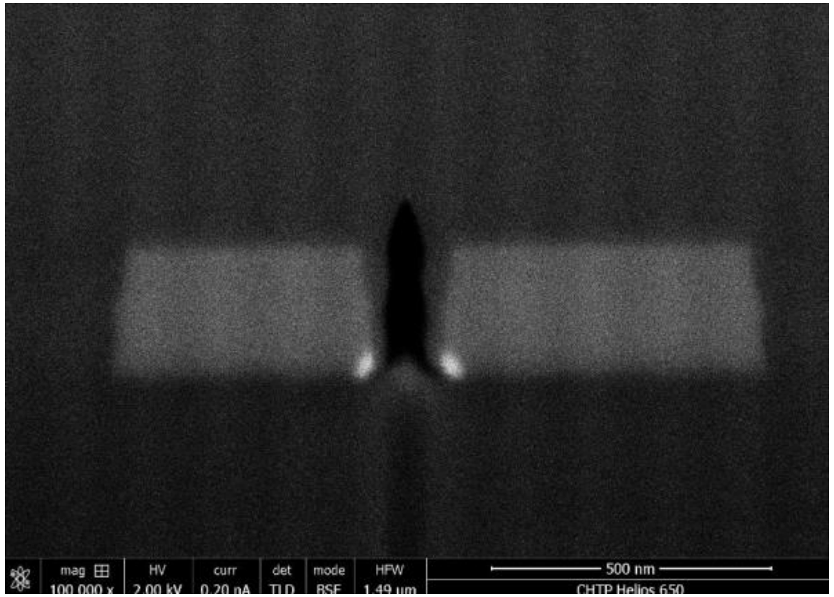
- Changes in device height and width affect the central wavelength and bandwidth
  - How to minimize these affects? How to account for them?

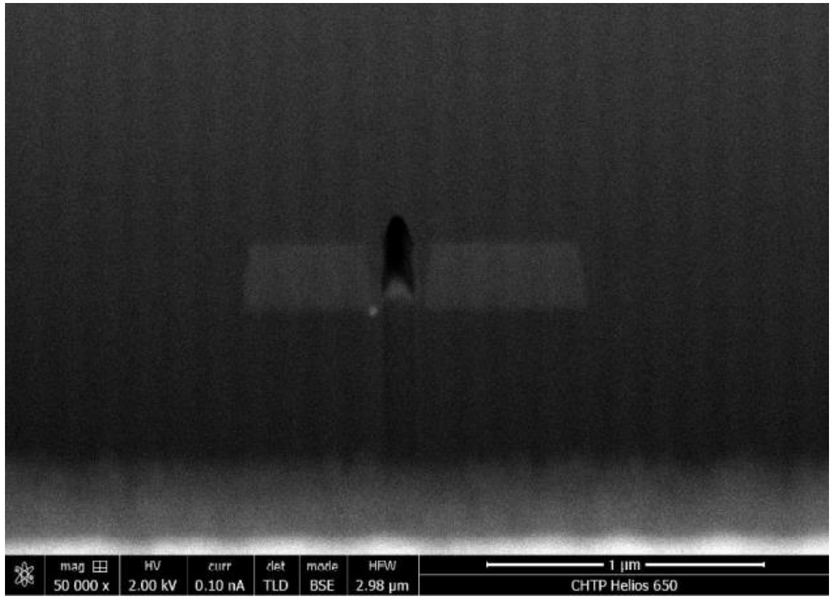




OTHER EFFECTS TO CONSIDER

- Oxide voids due to non-uniform oxide deposition
  - How to minimize it? Model it?





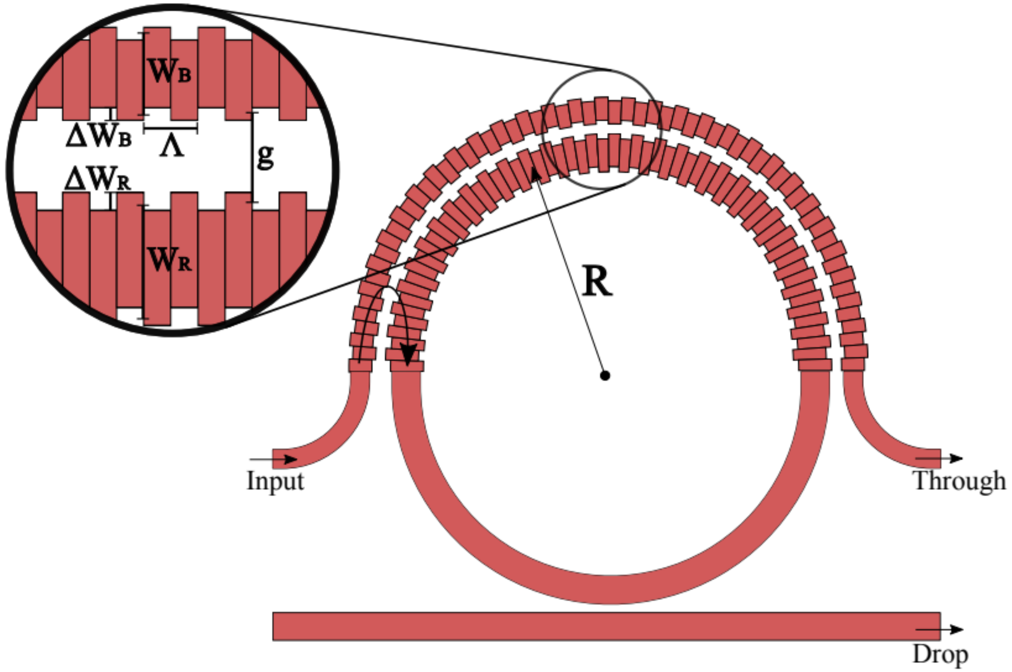
DESIGNS AND APPLICATIONS

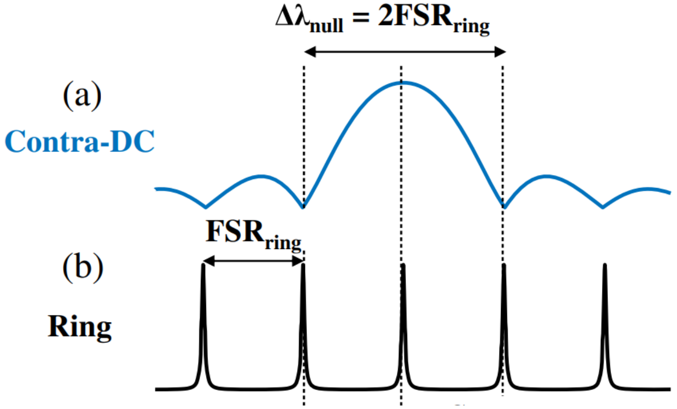
To inspire your next work!

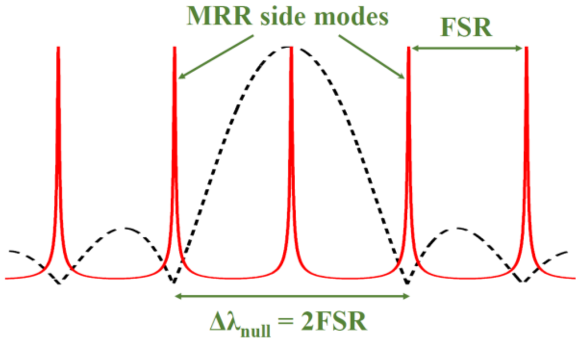
A. Mistry et al, OL 2018
10.1364/OL.43.006041

FSR-FREE RINGS

- Contra-DCs can be integrated into the coupling regions of micro-ring resonators to suppress all the resonances, except those at the Bragg wavelength.







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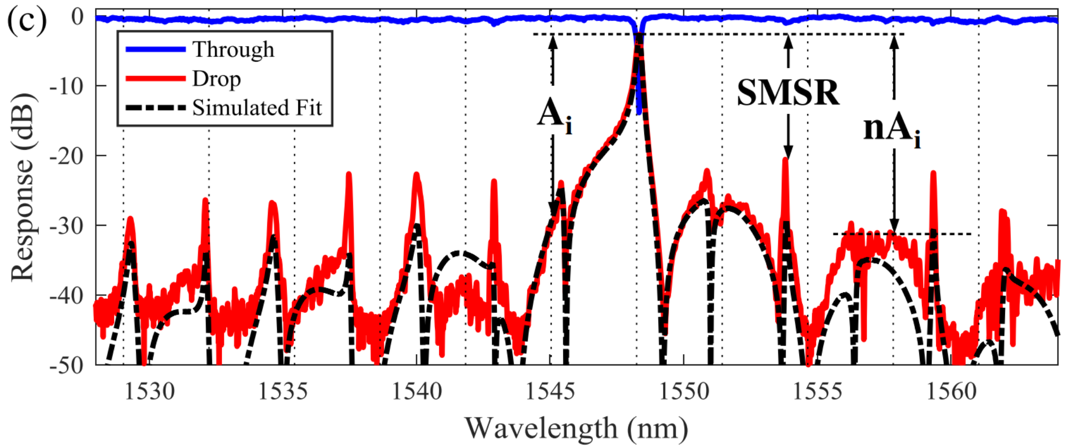
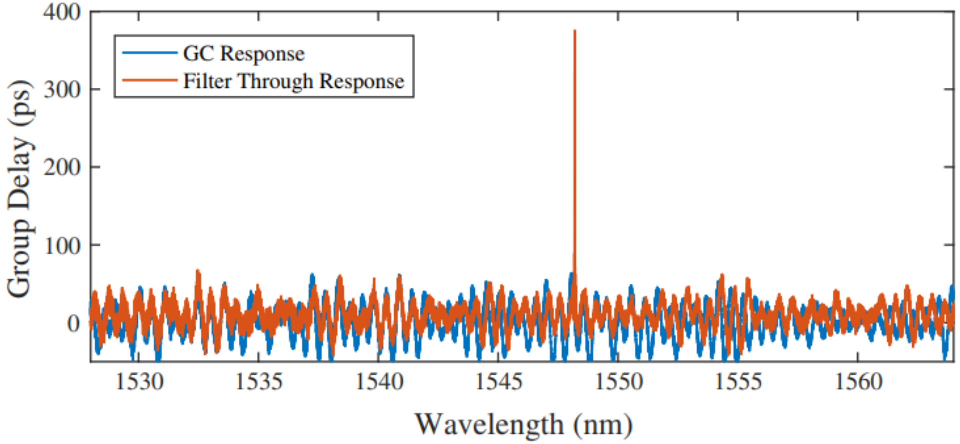
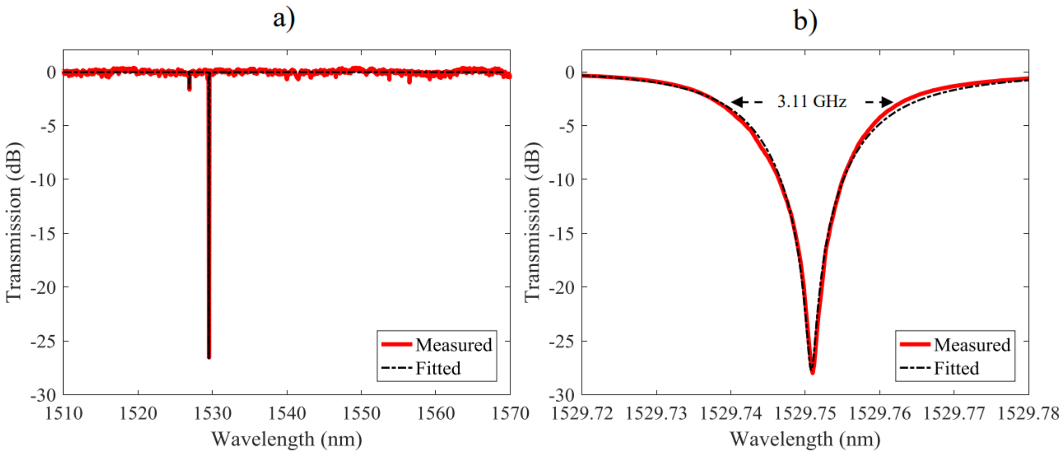


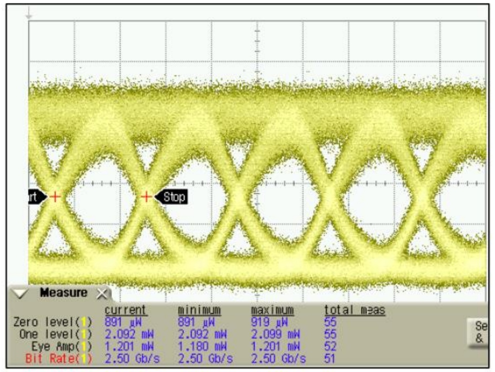


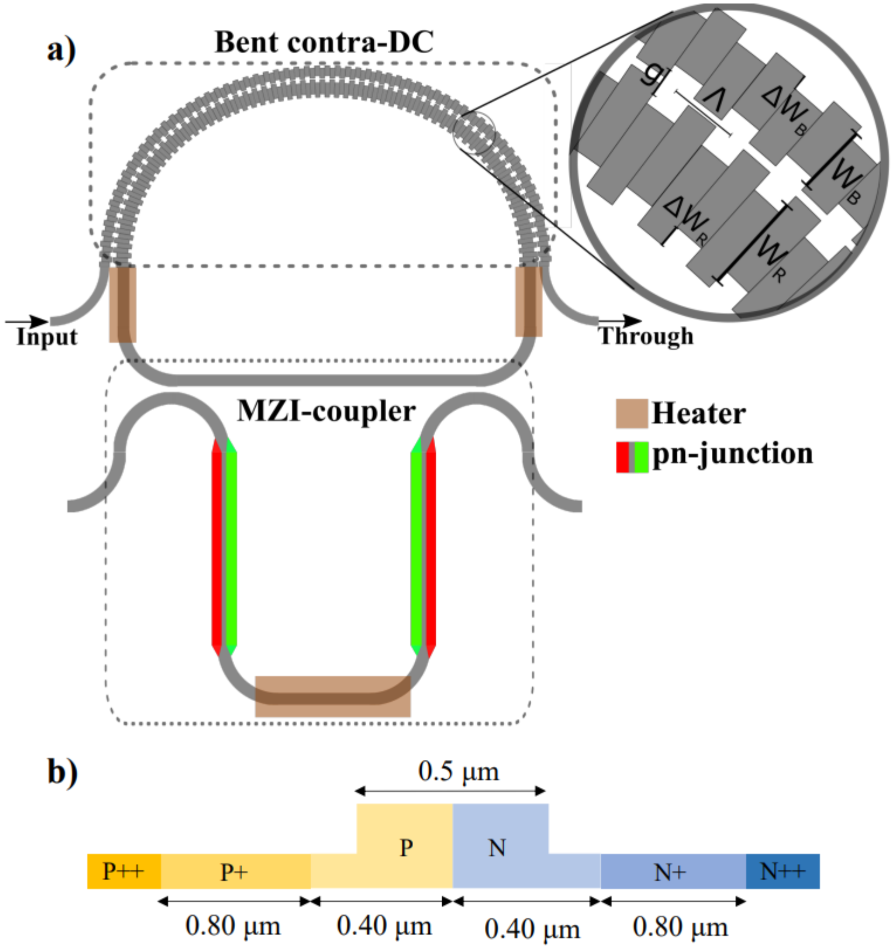
A. Mistry et al, PW 2020
10.1117/12.2545947

FSR-FREE RINGS

- Can be turned into an FSR-free ring modulator!

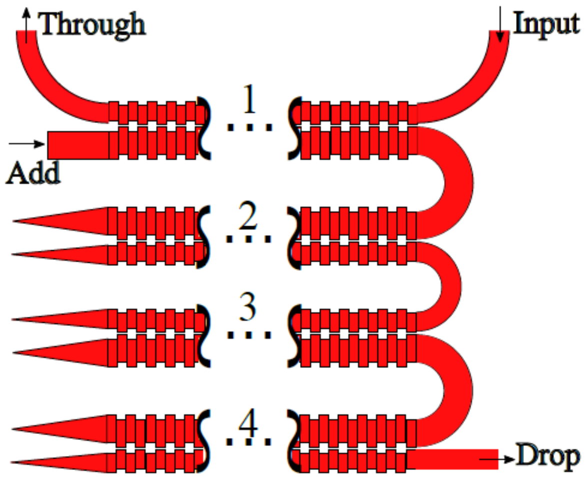


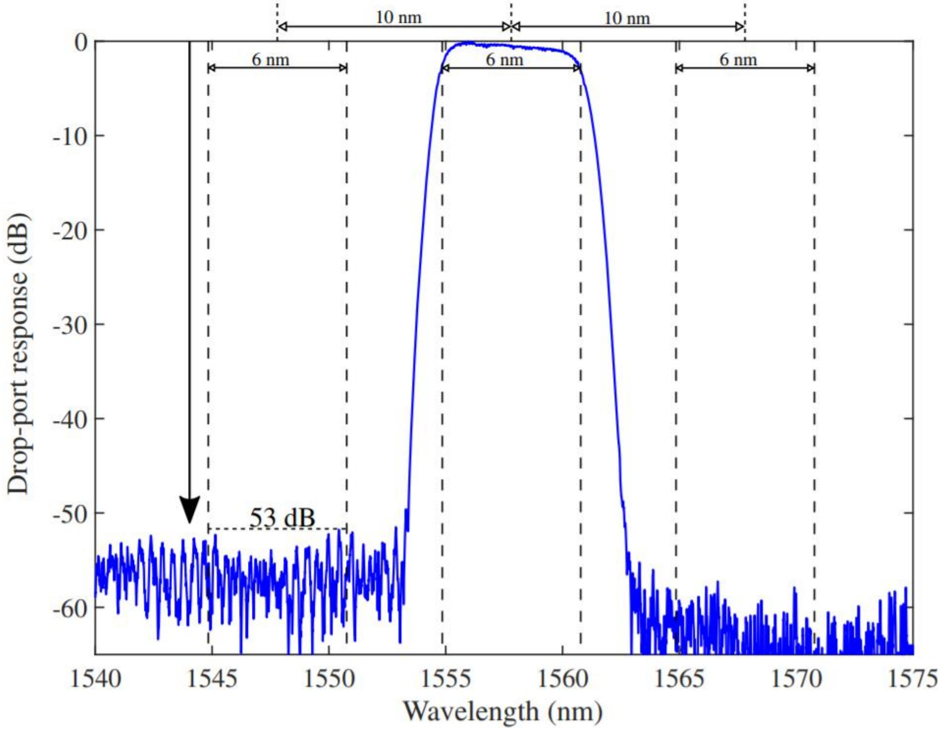


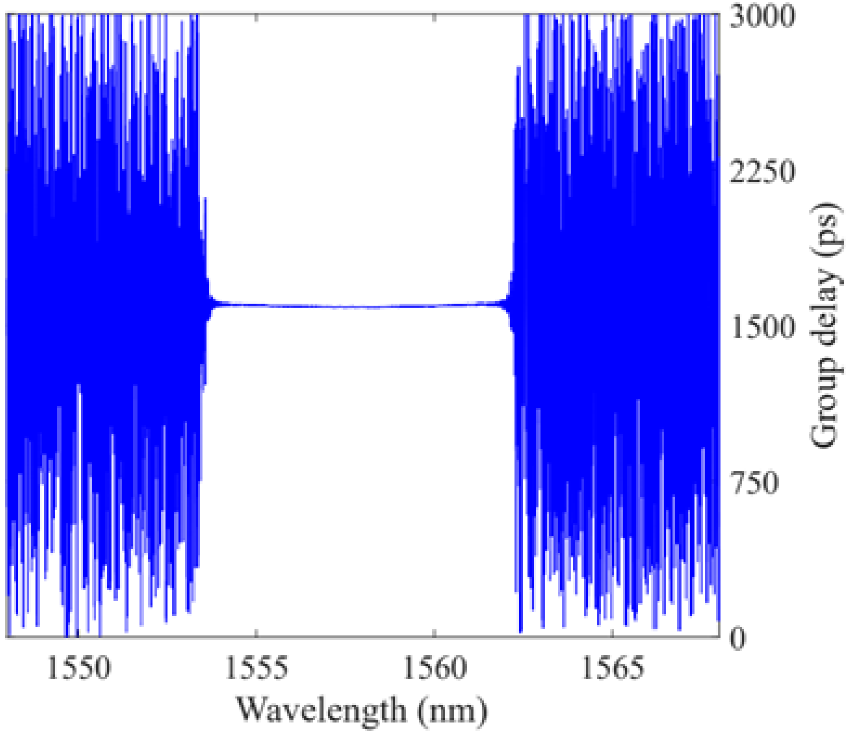


CASCADED CONTRA-DCS

- Cascading the drop ports of contra-DCs allows designers to suppress the side-lobes while maintaining low insertion losses due to high reflectivity.



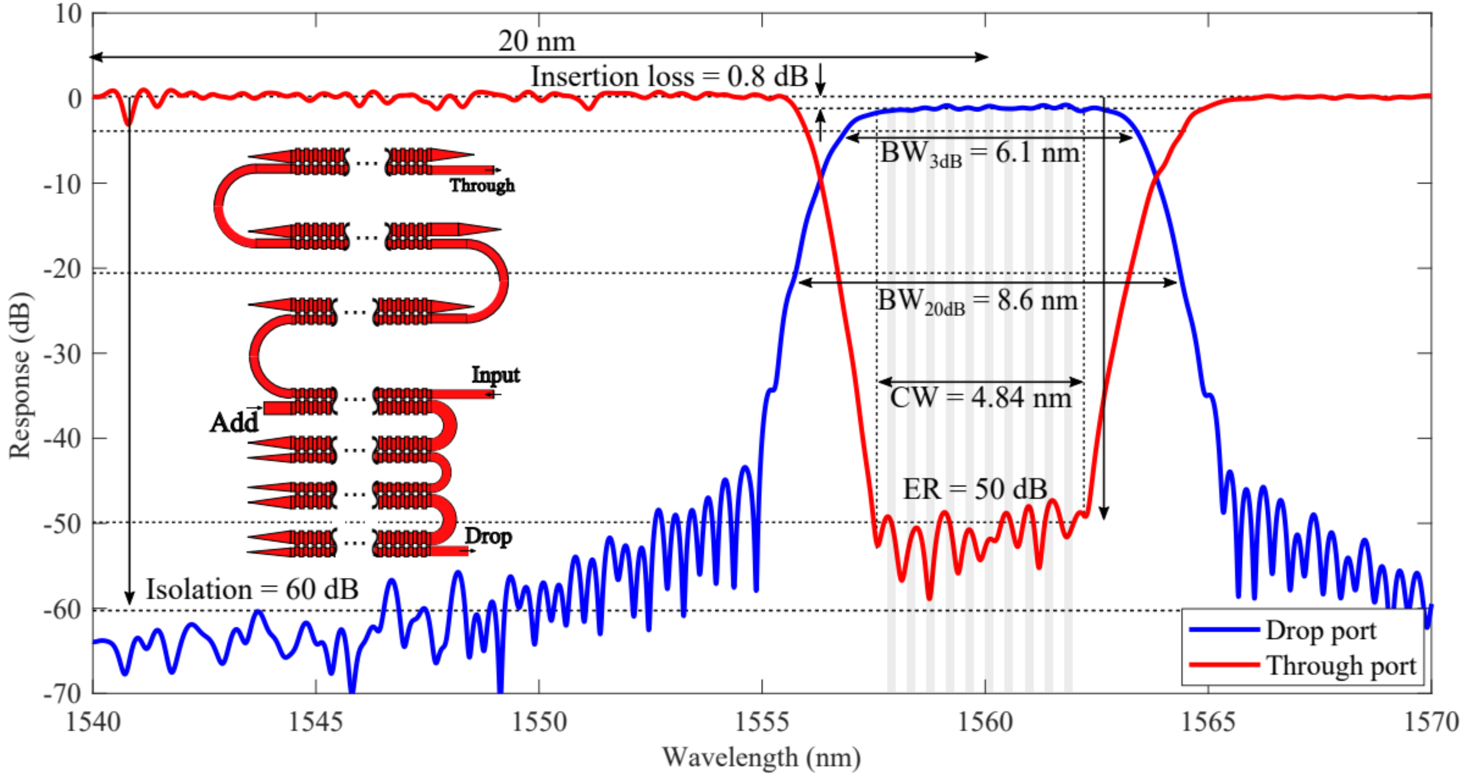




M. Hammood et al, PN 2019
10.1109/PN.2019.8936494

CASCADED CONTRA-DCS

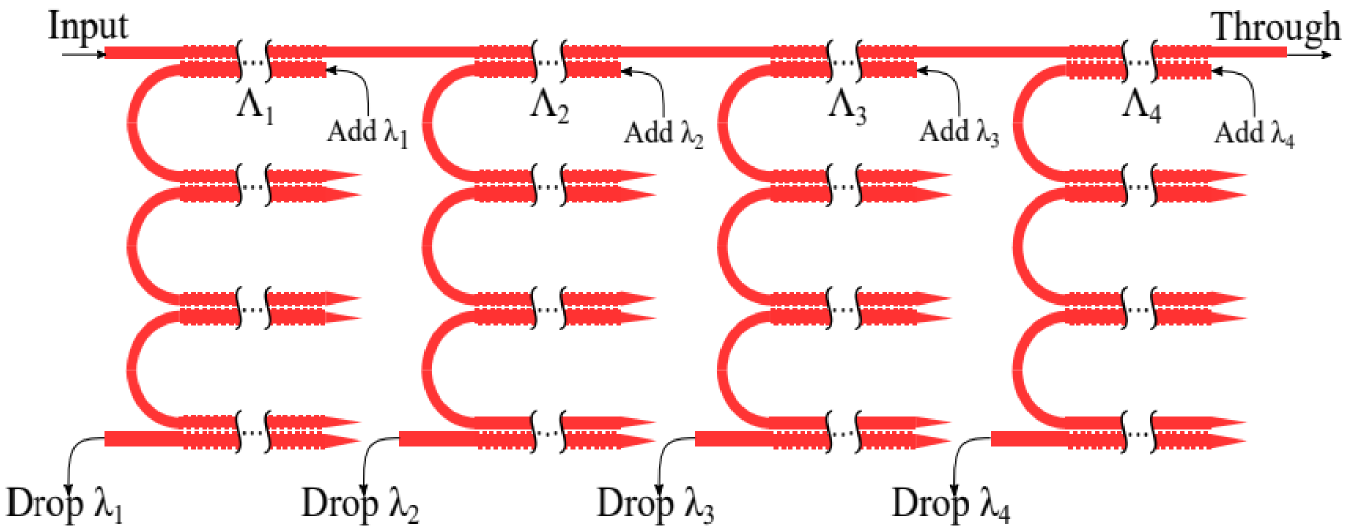
- Similarly, we can apply the same concept to the **Through-port** and achieve ultra-high extinction ratio filters

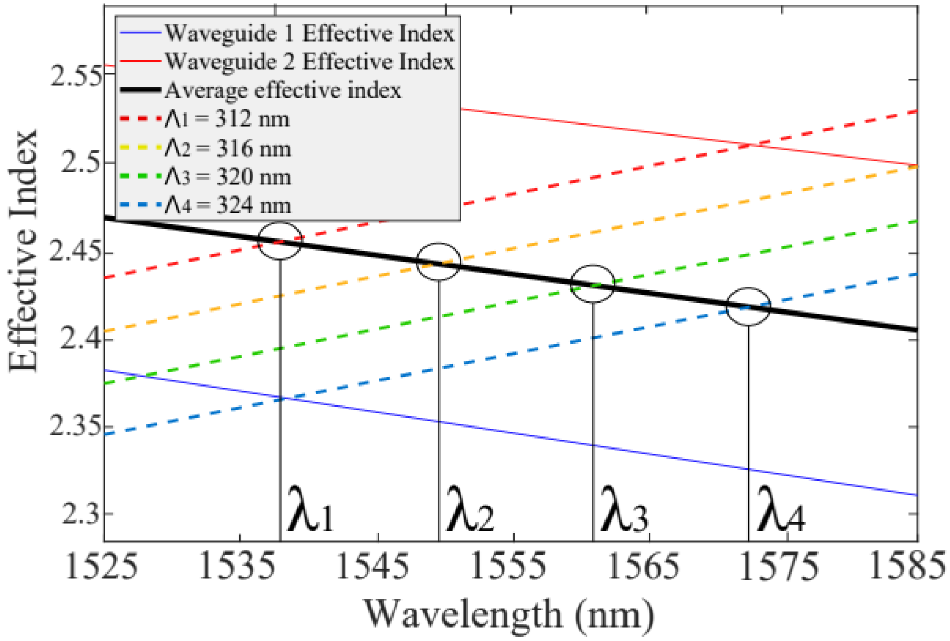


M. Hammood et al, OFC 2020
https://ieeexplore.ieee.org/document/9083168

CASCADED CONTRA-DCS

- Create functional C-WDM filters on silicon with record breaking figures-of-merit!





THE UNIVERSITY OF BRITISH COLUMBIA

Electrical and Computer Engineering

SiEPIC FAB

M. Hammood et al, OFC 2020
https://ieeexplore.ieee.org/document/9083168

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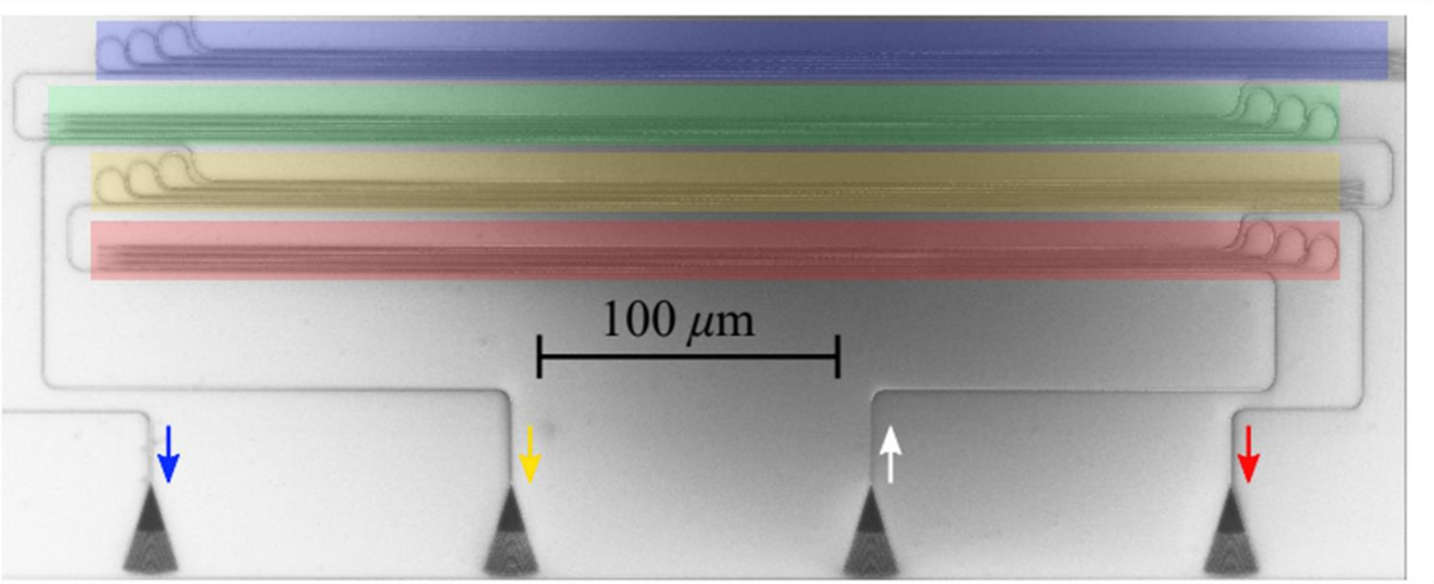
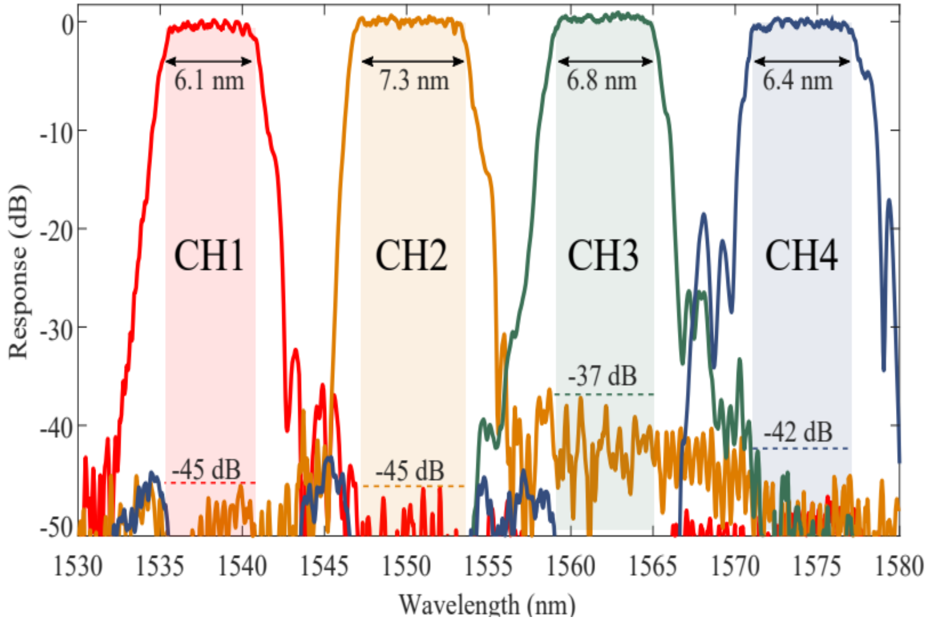




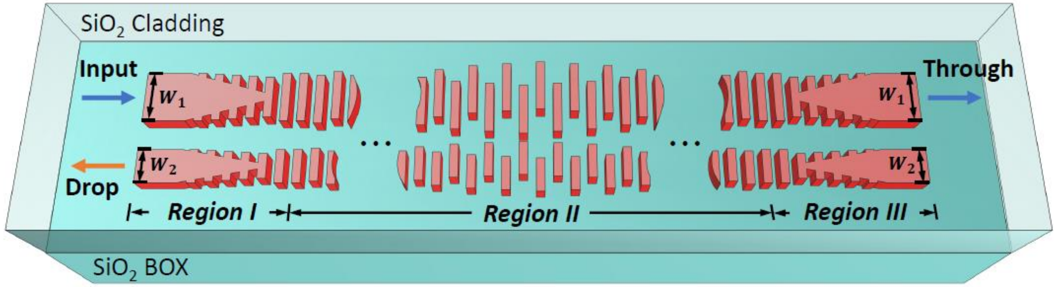
Han Yun et al, OL 2020
10.1364/OL.44.004929

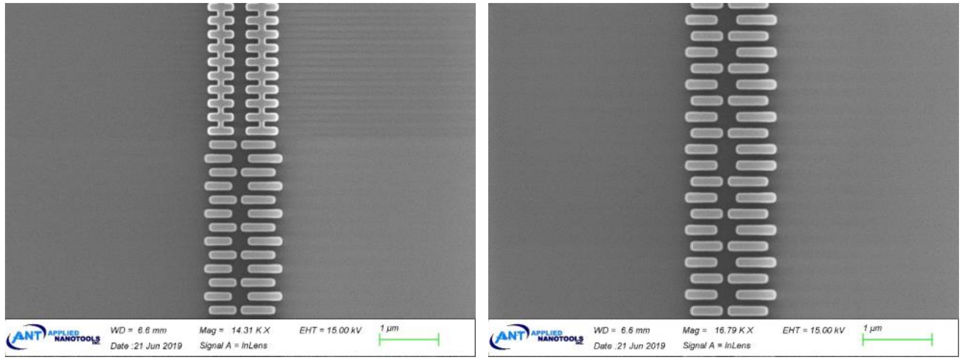
SUB-WAVELENGTH CONTRA-DCS

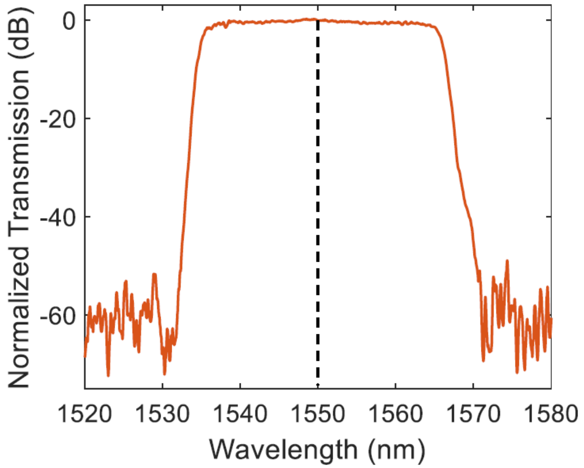
- Use sub-wavelength waveguides in a contra-DC configuration

- Low mode-confinement significantly increases the coupling coefficient
  - Significantly shorter devices
  - Wider bandwidths

- **Insertion loss:** <0.85 dB
- **Bandwidth:** up-to 33 nm
- **Isolation:** >55 dB (stacked – 3 stage)



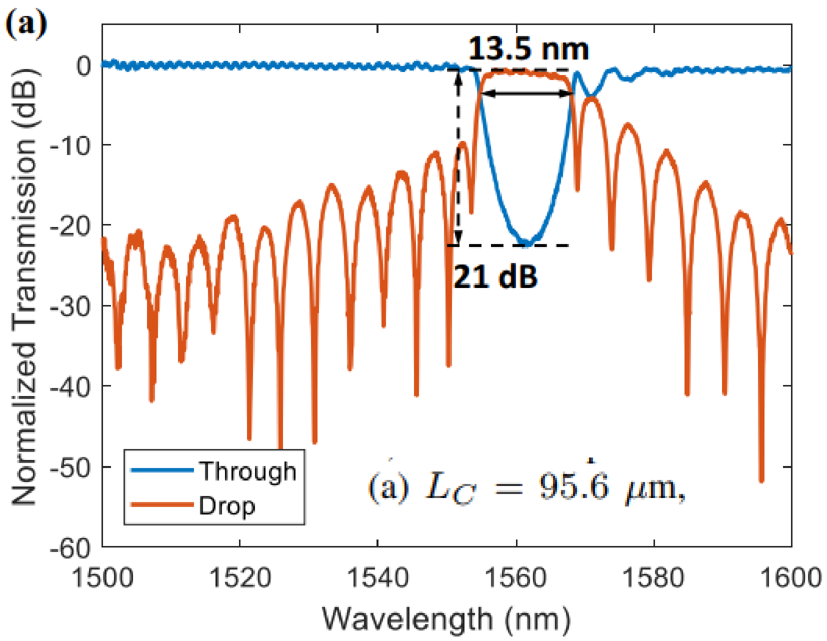


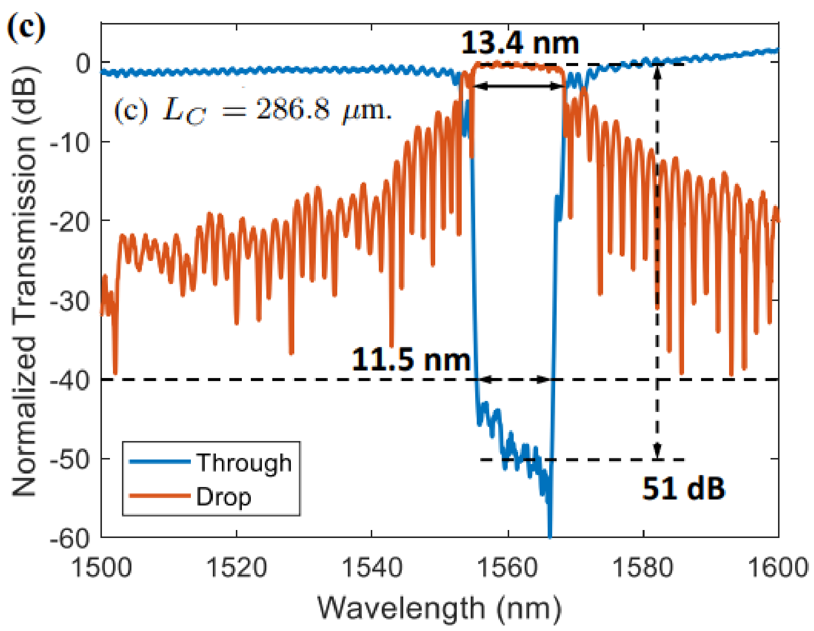


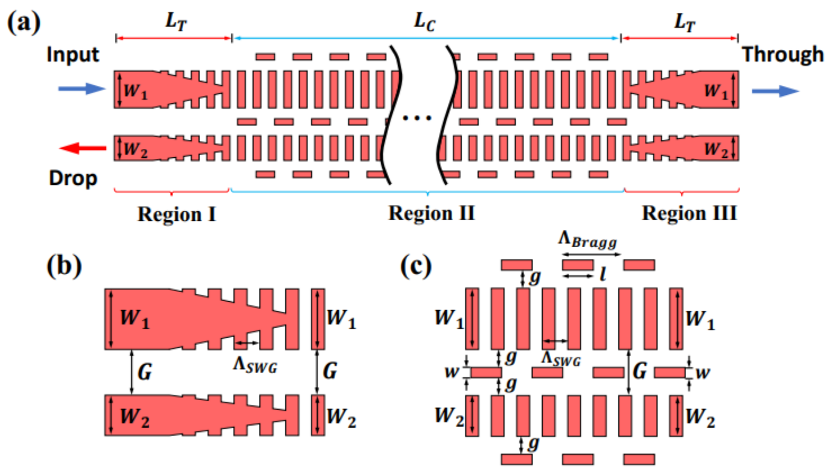
Han Yun et al, IEMCON 2020
10.1109/IEMCON.2019.8936256

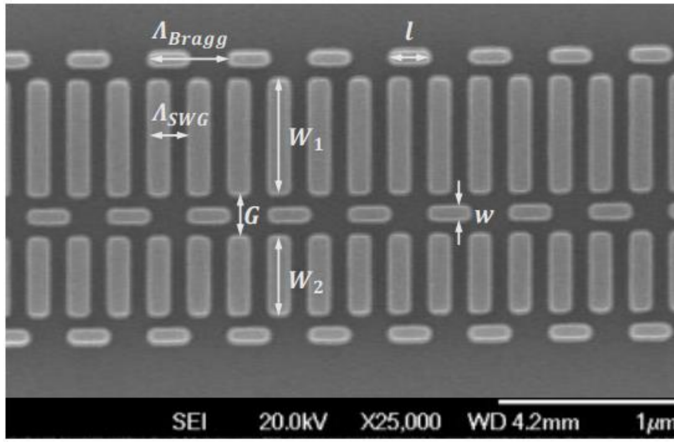
SUB-WAVELENGTH CONTRA-DCS

- Using unperturbed sub-wavelength waveguides
- Using cladding modulations:
    - Allows more flexibility to control the coupling strength



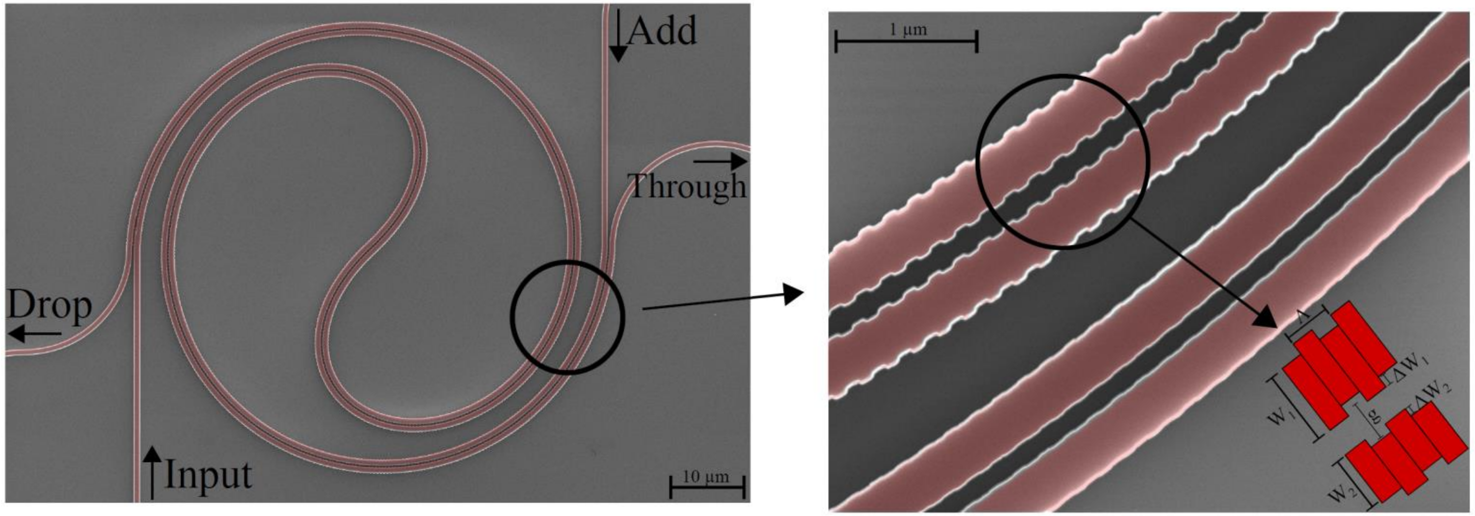






SPIRAL CONTRA-DCS

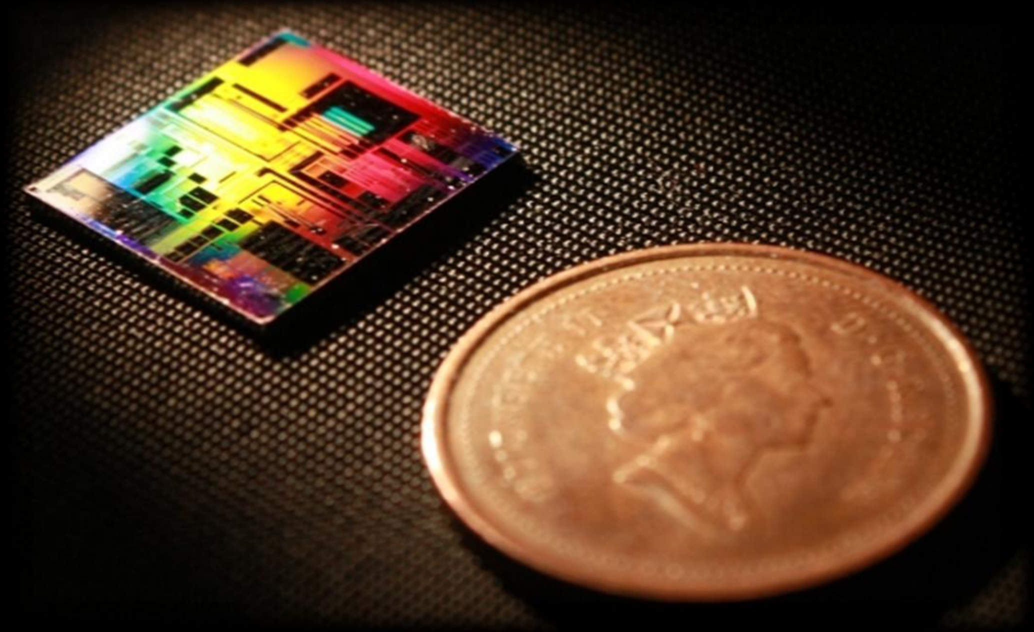
- With more complex perturbation profiles (apodization, chirped, etc.) , greater number of periods is needed.
- High index contract of silicon vs glass allows us to bend light tightly. We can use Spirals to optimize the
- Consideration the effective index vs bend radius!
- ~2000 Perturbation periods compacted in an area of 45 x 45 μm^2:



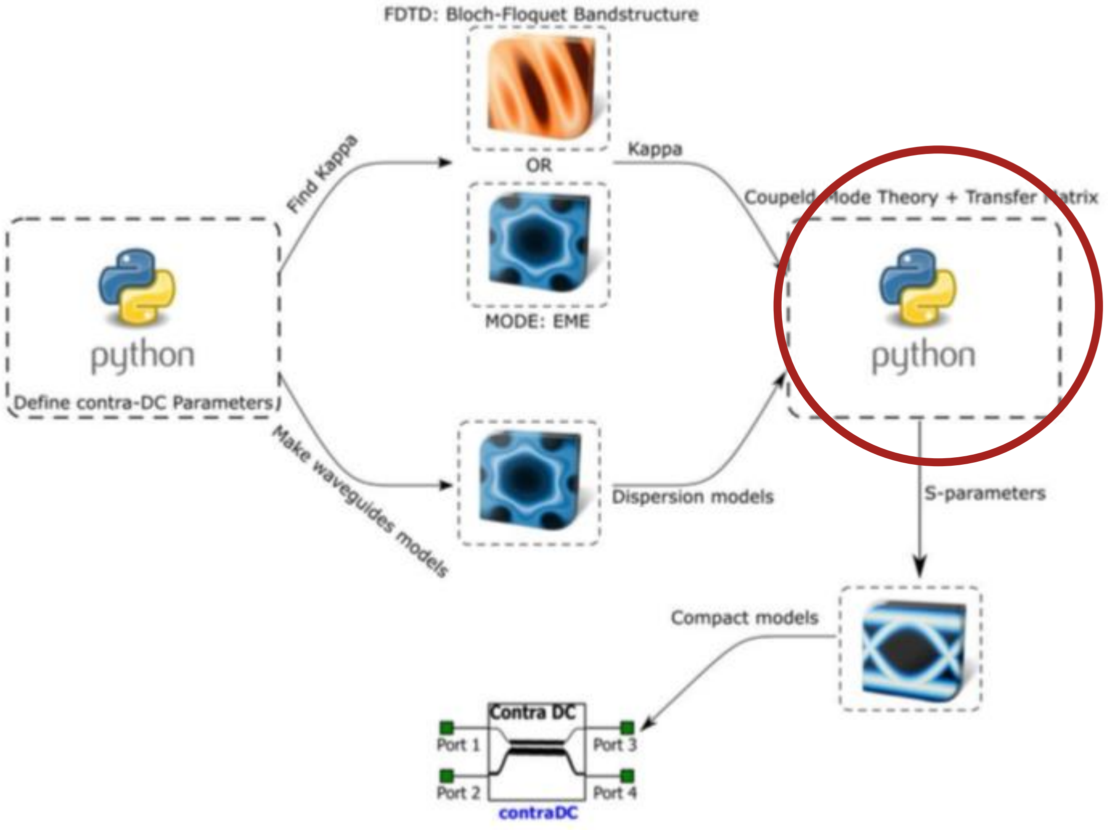
CONTRA-DIRECTIONAL COUPLERS: **SIMULATION**

Jonathan Cauchon

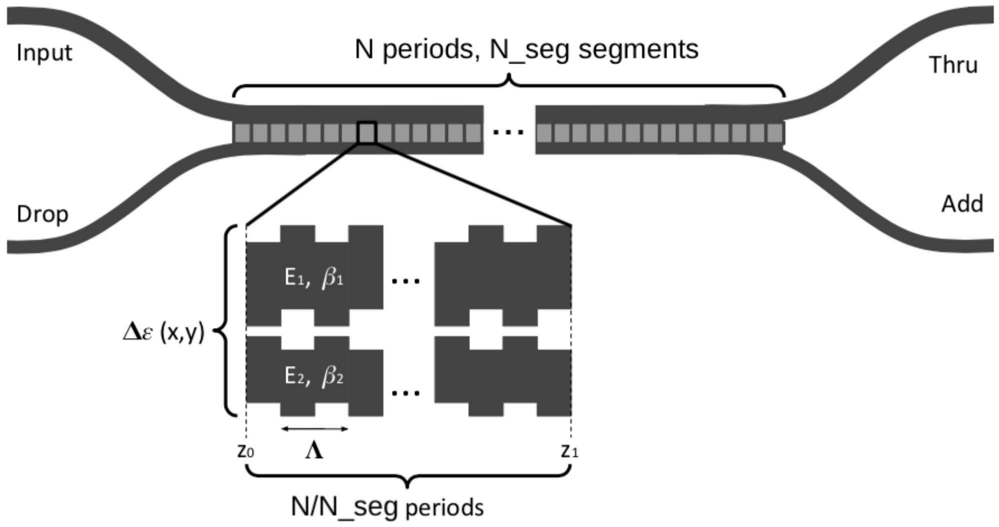
2020-11-26



TRANSFER-MATRIX MODEL IMPLEMENTATION



- TMM model implemented in Python
- Full parametrization
- Many pre-set configurations to get started quickly
- Main concept: sub-divide a contra-DC into uniform grating segments:



TO GET STARTED

- Start designing contra-DCs in 5 minutes
- Requirements: Python 3.6+
- Can be run in a Python IDE, Python-building text editor, or Jupyter notebook

```
git clone https://github.com/JonathanCauchon/Contra-DC
```

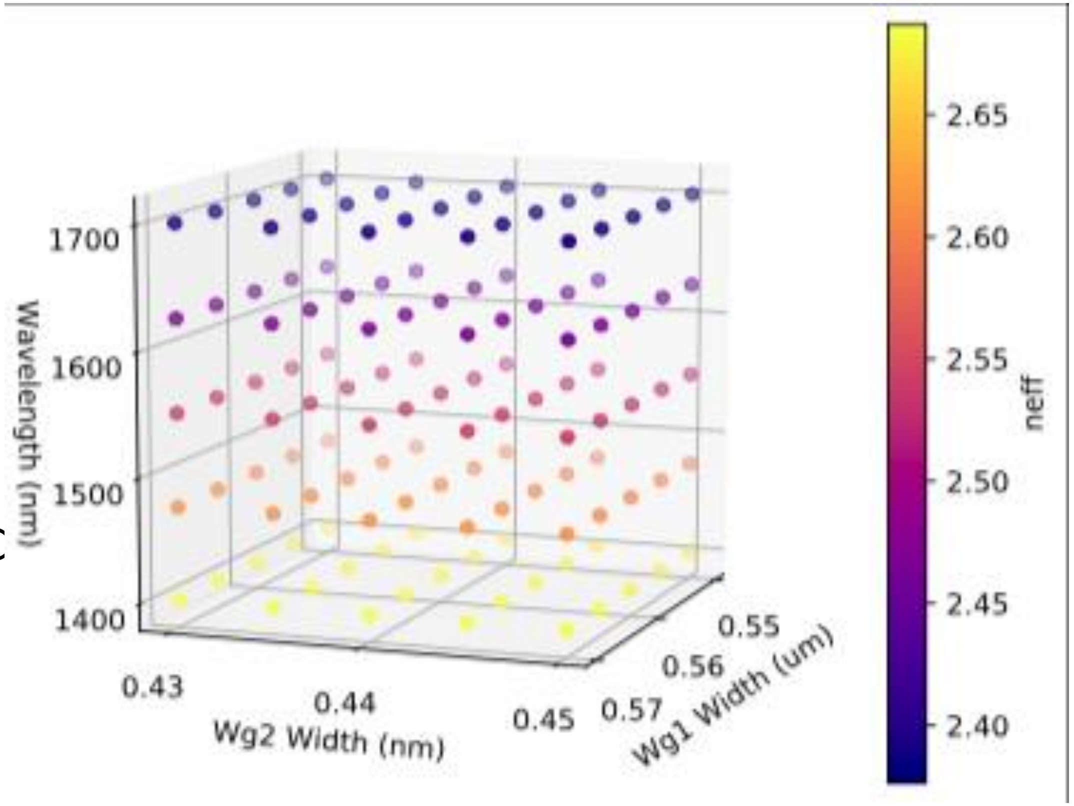
- Read the documentation to learn about the member functions and parameters in depth:

https://jonathancauchon.github.io/Contra-DC/

WHAT'S IN THE BOX

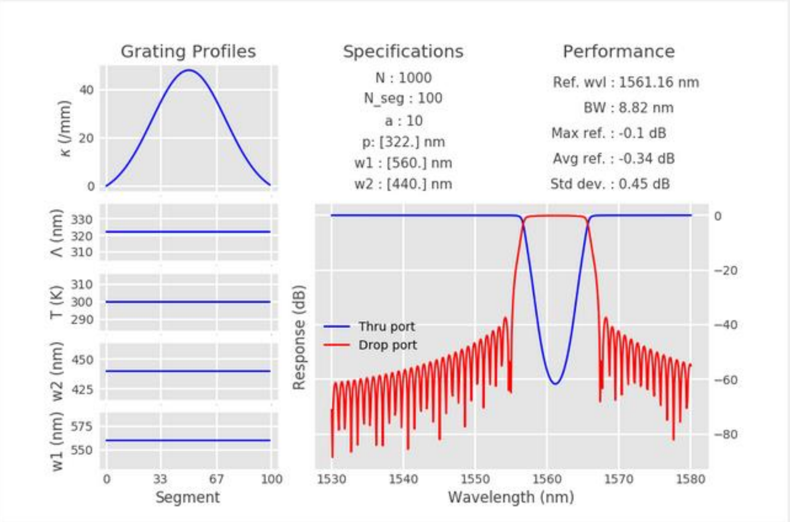
- The out-of-the-box program is valid for a subset of devices:
  - Silicon on silica
  - E-Beam process
  - 100-nm gap
  - 550 nm < w1 < 570 nm
  - 430 nm < w2 < 450 nm

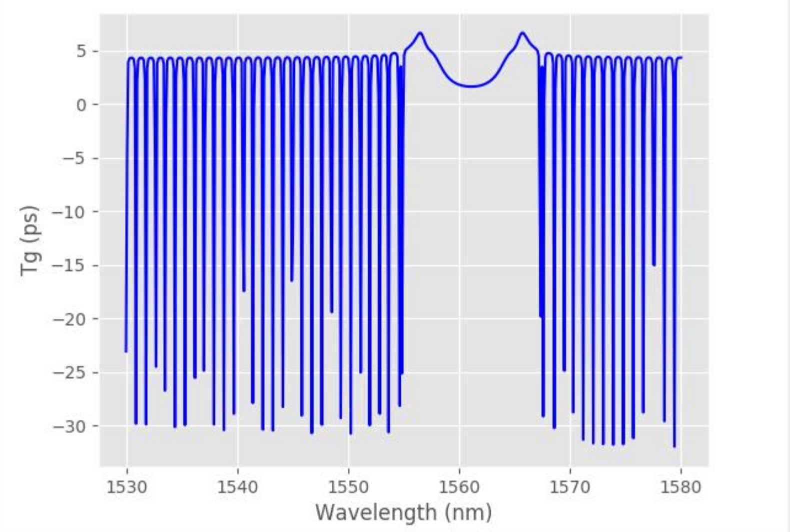
- Many MODE simulations where performed for this subset, which makes interpolation possible. You can build your own database



EXAMPLE 1: CONTRA-DC "HELLO WORLD"

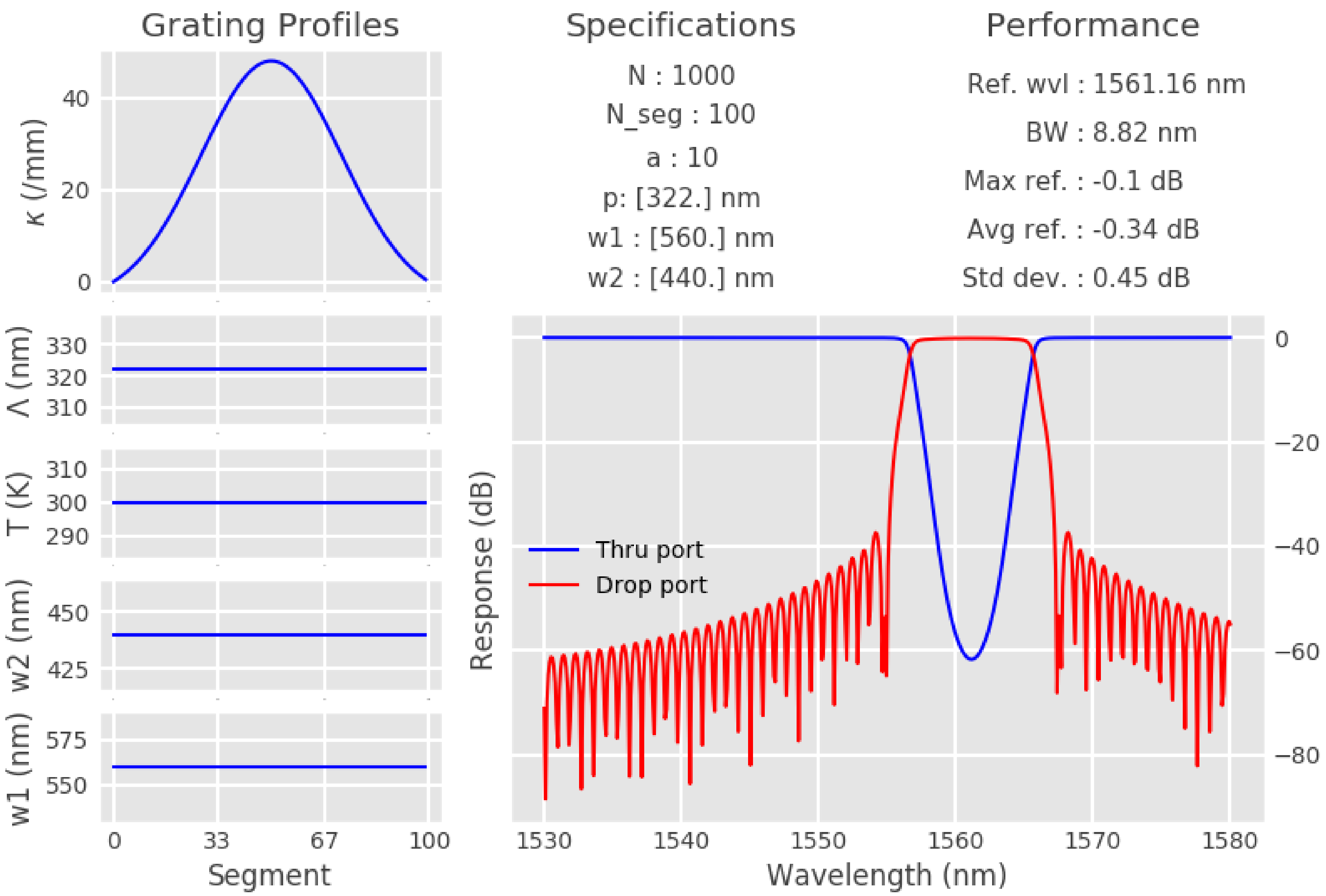
```python
""" Example 1: regular SOI Contra-DC """

# instantiate, simulate and show result

device = ContraDC().simulate().displayResults()

# calculate the group delay
device.getGroupDelay()

# plot group delay
plt.figure()
plt.plot(device.wavelength*1e9, device.group_delay*1e12)
plt.xlabel("Wavelength (nm)")
plt.ylabel("Tg (ps)")

plt.show()
```





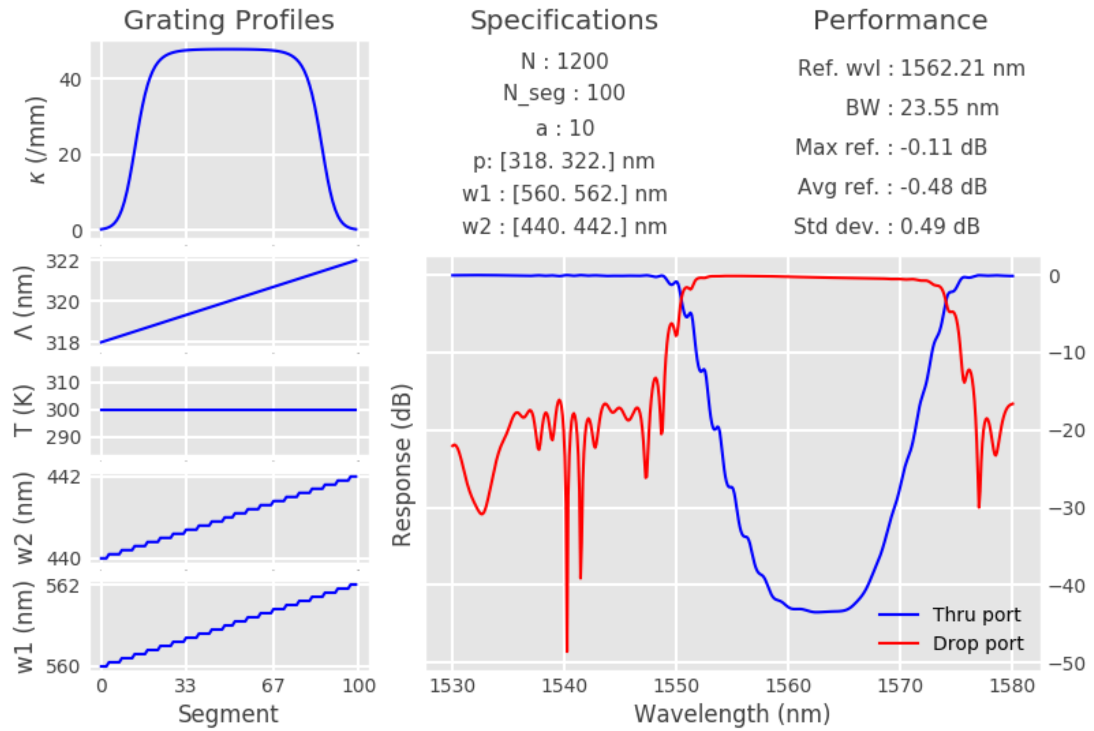
PERFORMANCE INTERFACE

`ContraDC.displayResults()`



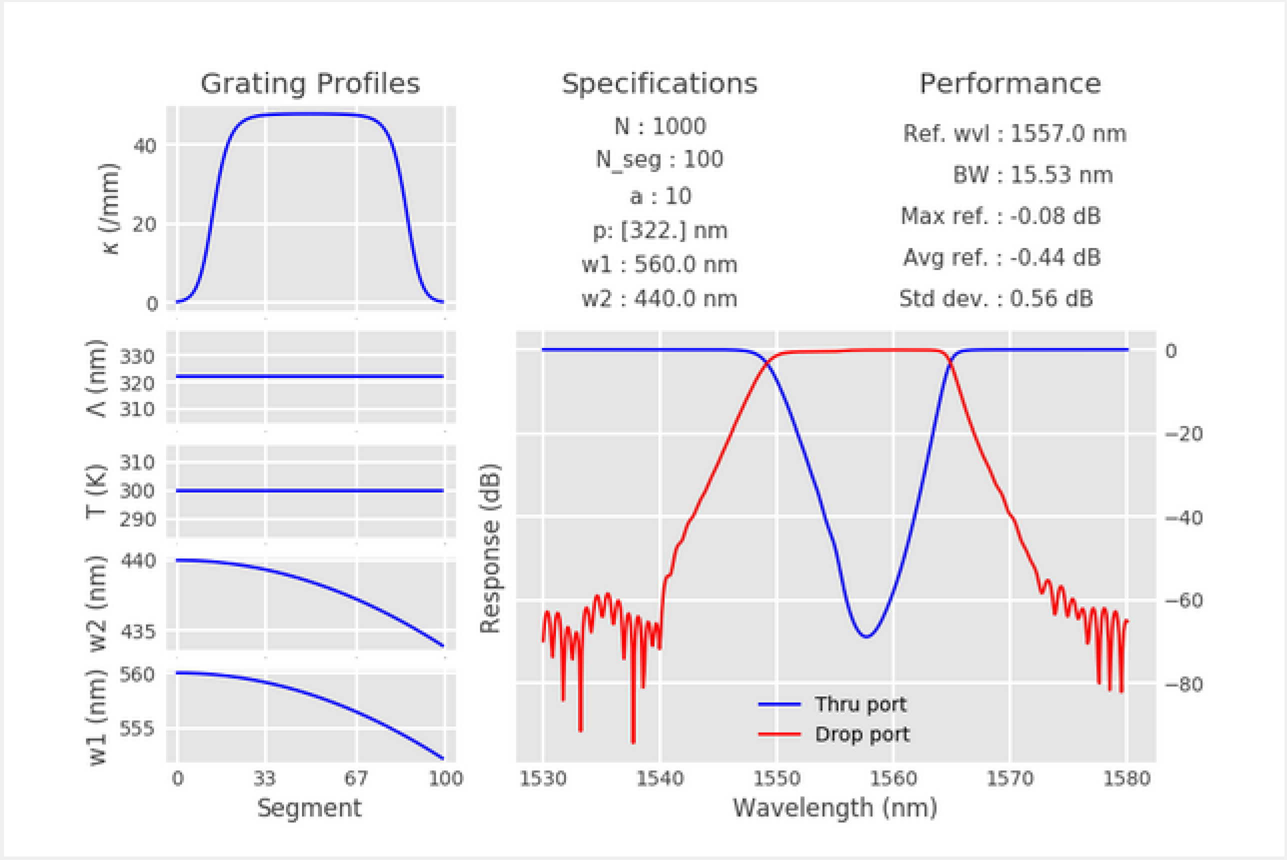
EXAMPLE 2: CHIRPED DESIGN

```python
""" Example 2: Full chirped example.
        Create a CDC with chirped w1, w2, period, temperature.
"""

# Waveguide chirp
w1 = [.56e-6, .562e-6]
w2 = [.44e-6, .442e-6]
w_chirp_step = .1e-9

# Period chirp
period = [318e-9, 322e-9]

# apod shape
apod_shape = "tanh"

N = 1200

device = ContraDC(N=N, w1=w1, w2=w2, apod_shape=apod_shape,
                                     w_chirp_step=w_chirp_step, period=period)

device.simulate().displayResults()
```



EXAMPLE 3: CUSTOM CHIRP

```python
""" Example 3: defining custom chirp profiles """

device = ContraDC(apod_shape="tanh")

z = np.linspace(0, device.N_seg, device.N_seg)
device.w1_profile = device.w1*np.cos(z/600)
device.w2_profile = device.w2*np.cos(z/600)

device.simulate().displayResults()
```

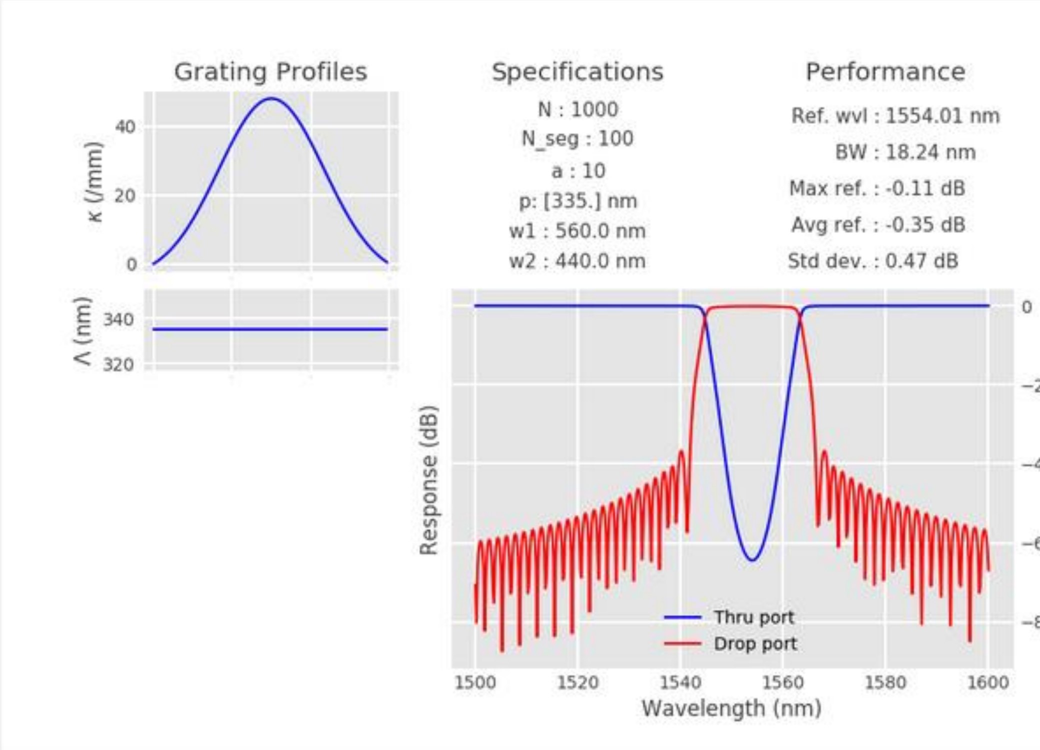


EXAMPLE 4: CUSTOM PLATFORM

```
polyfit.txt
1.5e-06,1.6e-06,1.97004,-201040,1.98997,-257755
```

How to get polyfit.txt? **See waveguides-> waveguide coupler**

```python
""" Example 4: using custom supermode indices.
      You might want to use this if you are designing
      with silicon nitride, of using other waveguide specs than
      SOI, 100-nm gap.
"""

device = ContraDC(polyfit_file="polyfit.txt", period=335e-9)
device.simulate().displayResults()
```



EXAMPLE 5: LUMERICAL-ASSISTED

- Lumerical Generate S-parameters

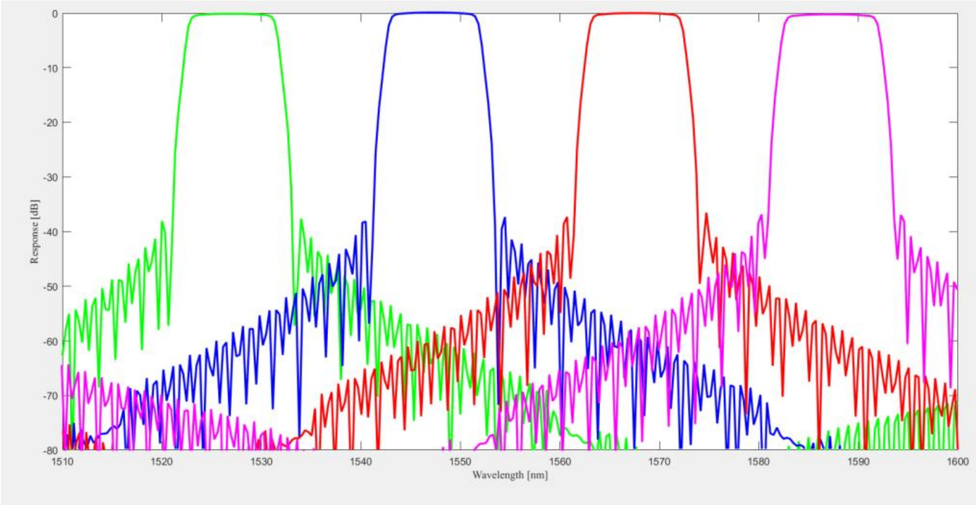
- Lumerical imports S-parameters into INTERCONNECT

ACKNOWLEDGEMENTS

- Keysight Technologies for their financial support on these projects.
- The Natural Sciences and Engineering Research Council (NSERC) of Canada and Canadian Microsystems Corporation (CMC).
- EBeam Fabrication was done at Applied Nanotools and the University of Washington Microfabrication/Nanotechnology User Facility, a member of the NSF National Nanotechnology Infrastructure Network (NNIN). Optical lithography was done at the Institute of Microelectronics (IME)/ Advanced Micro Foundry (AMF) at Singapore through Keysight Technologies.

DESIGN ACTIVITIES

ACTIVITY 1



- Design a 4-channel CWDM (de)multiplexer
  - Around the C-Band
  - Full 3-dB bandwidth: 13 nm
  - channel spacing: 20 nm
- Plot your channel responses in a single figure
- Think about how to connect each channel to its neighboring channel.
  - Input waveguide: wide? Narrow? Think about the self-reflection
  - Reduce cross-talk: Apodization? Cascaded filters?
- 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

ACTIVITY 2

- Design a C-band optical add-drop filter
  - C-band bandwidth 1530 nm – 1565 nm
  - Think of the best way to design a filter with such bandwidth.