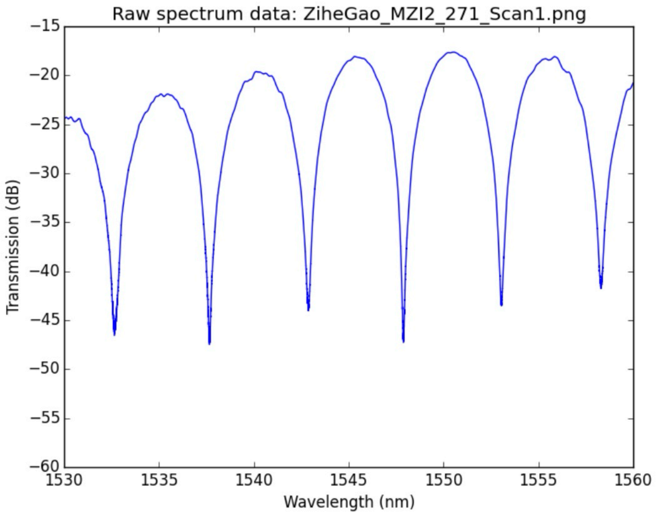
Chip 1 / Project 1

Goal: design a Mach-Zehnder Interferometer, MZI (w/ 2 outputs)
w/ 25 GHz spacing, ~ 1310nm wavelength

will connect commercially tunable laser to the interferometer to test
Why? don't know if it works unless we test

aiming to get a diagram w/ sinusoidal shape



note: dB = log scale to measure output signal relative to input

0 dB ⟹ output = input, i.e. no loss

$-\infty$ dB ⟹ complete loss, 0 output

$+\infty$ dB ⟹ infinite gain

dB < 0 ⟹ loss relative to input

dB > 0 ⟹ gain relative to input

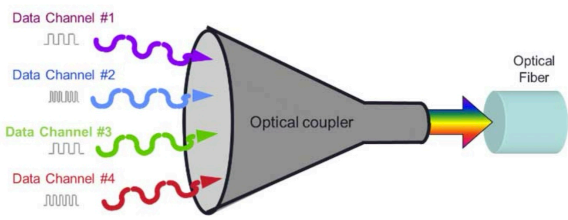
$$dB = 20\log_{10}\left(\frac{A_{out}}{A_{in}}\right)$$

this graph shows the constructive/destructive interference pattern of the MZI
peaks = max. constructive, neg. transmission dB is result of losses in system
valleys = complete destructive interference, should go off to $-\infty$

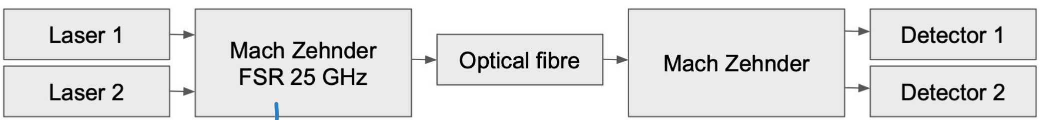
Why an MZI?

wavelength division multiplexing (WDM):

- technique to transmit multiple data signals (multiple wavelengths) in a single optical fibre cable
- allows for more efficient data transmission



MZI's can be used for WDM:



how? not sure...

Aside: also could be that MZI splits 1λ to 2λ's, as seen by interference, so this is like de-muxing, & bc reciprocity can do 2λ's → 1λ

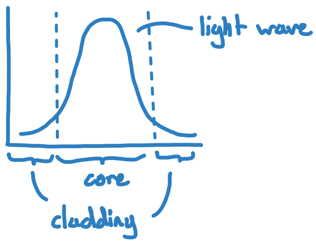
DeepSeek: MZI = wavelength-selective filter, when combine Laser 1, 2 w/ a directional coupler, output is a mix of λ_1, λ_2, so use MZI to restrict output to strictly λ_1 & λ_2 (not mix w/ other λ's?)

How does a MZI work?

- have light travelling in wave guide

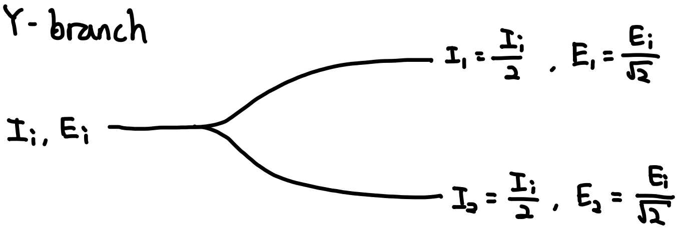
$$E = E_0 e^{i(\omega t - \beta z)}$$ for plane wave travelling in z-dir

$$\beta = \frac{2\pi n_{eff}}{\lambda}$$ wave number, k for the wave guide

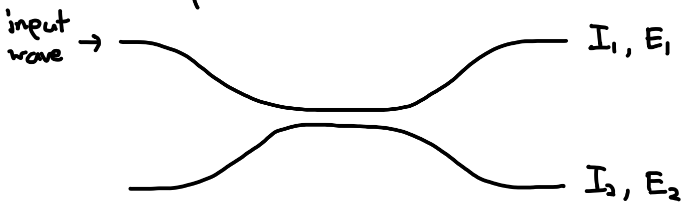


n_{eff} = effective index of refraction of wave guide (b/c wave travels in combo. of core & cladding)

- split it into two w/ 50/50 splitter using either
  - Y-branch



  - directional coupler



part of wave goes here b/c some of wave in other wave guide travels outside the guide & so leaks over into this one

Note: layout for this project uses directional coupler instead of Y-branch b/c ∄ Y-branch component for 1310nm (I think... TA said to use coupler)

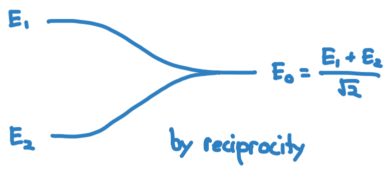
- 2 waves travel in wave guides of different lengths, some ΔL path difference

"imbalanced interferometer"

$$E_1 = \frac{E_i}{\sqrt{2}} e^{i(\omega t - \beta L_1)} \qquad E_2 = \frac{E_i}{\sqrt{2}} e^{i(\omega t - \beta L_2)}$$

- waves then recombine using another Y-branch/directional coupler

$$E_o = \frac{1}{\sqrt{2}}\left(E_1 + E_2\right) = \frac{E_i}{2}\left(e^{i(\omega t - \beta L_1)} + e^{i(\omega t - \beta L_2)}\right)$$



true when $E_2 = 0$, some light gets coupled to higher order modes not supported by wave guide

$$I_o = |E_o|^2 = \frac{I_i}{4}\left|e^{i(\omega t - \beta L_1)} + e^{i(\omega t + \beta L_2)}\right|^2$$

$$= \ldots$$

$$= \frac{I_i}{2}\left(1 + \cos(\beta \Delta L)\right)$$

- this is what gives the interference its sinusoidal shape

- spacing b/w constructive ($\cos(\beta\Delta L)=1$) & destructive ($\cos(\beta\Delta L)=-1$) is given by the period of this $\cos(\beta\Delta L)$ term "Free Spectral Range (FSR)"
- doing the math... (see FSR doc. for details)

$$\Delta\nu = \frac{c}{\Delta L\, n_g} \quad \text{for } \Delta\nu \text{ in Hz}$$

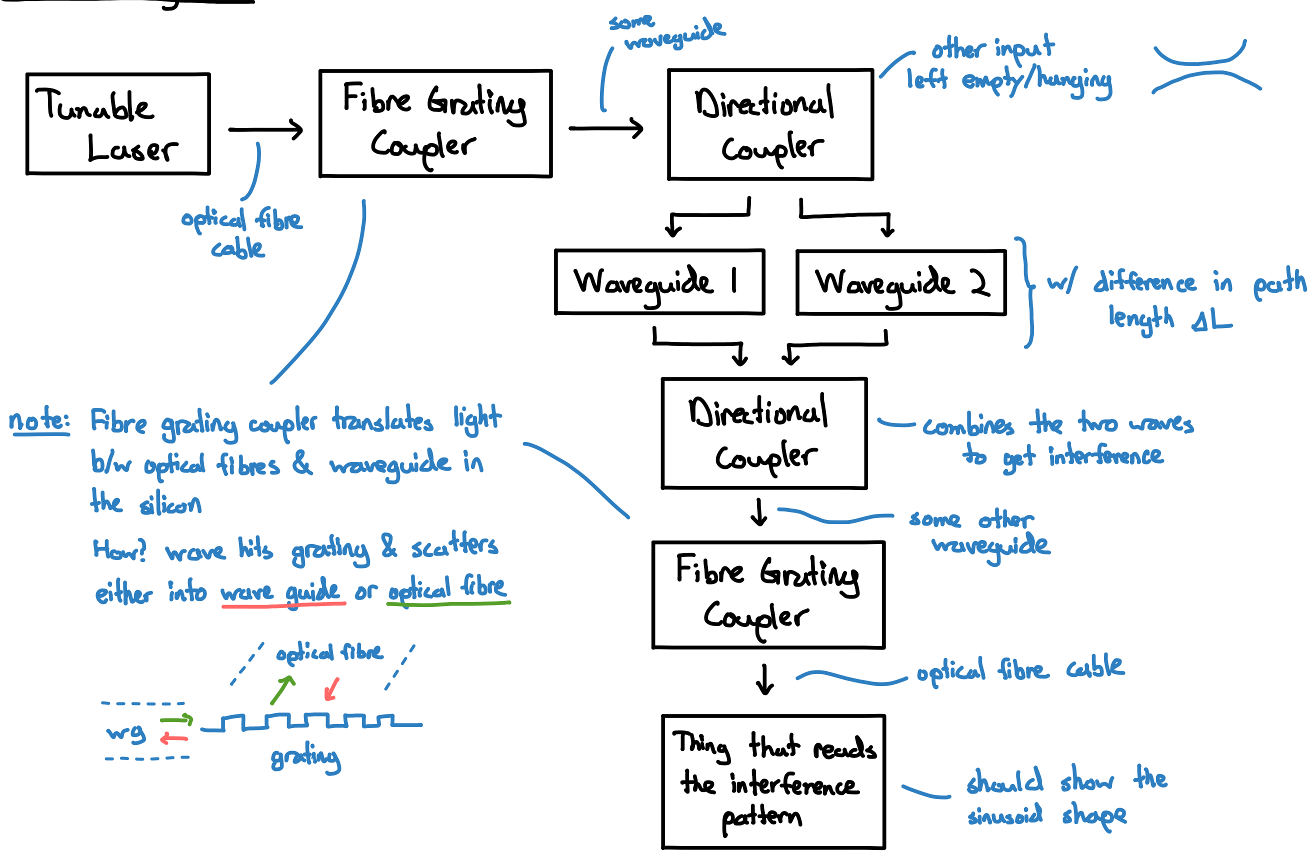
- so to calculate required ΔL for $\Delta\nu = 25\,\text{GHz}$, need n_g

  n_g: group index, how energy (envelope) propogates in wave guide

  distinct from phase velocity (n_{eff}) – how fast the mode moves

- to get n_g, need to run Lumerical MODE simulation

Block Diagram:



Process:

① Simulate wave guide in Lumerical MODE to get group index

- setup w/ the following:

  SiO_2 cladding – 4 μm × 4 μm

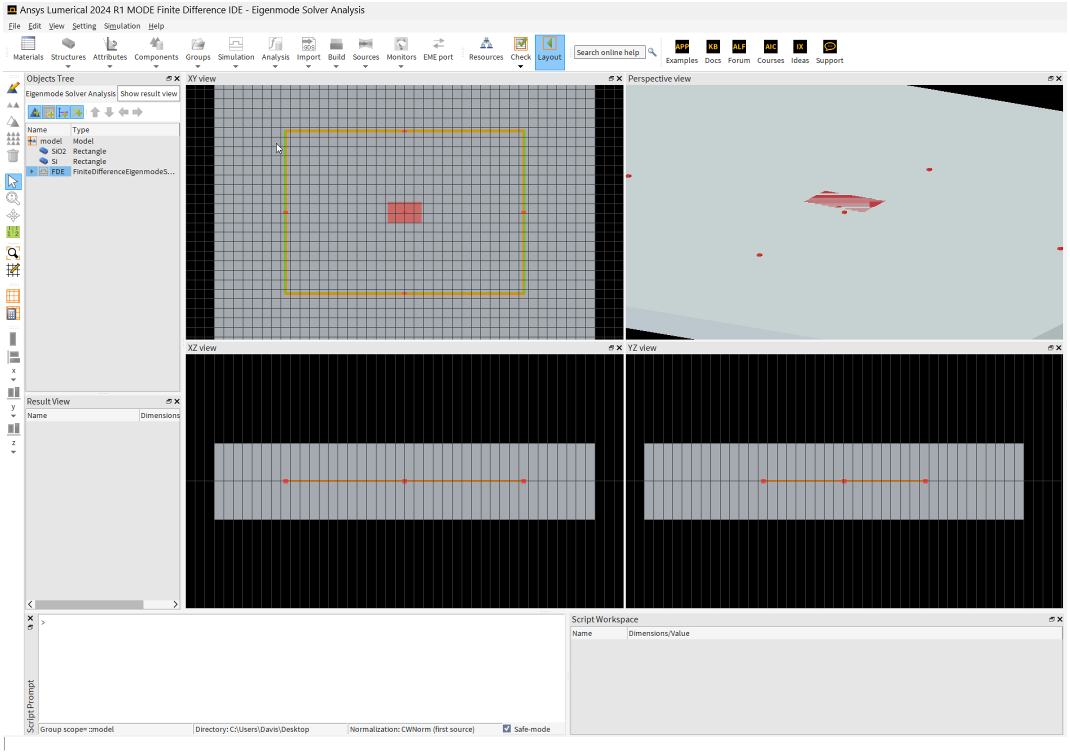
  Si core – 350 nm × 220 nm (dimensions given by components to use in layout)

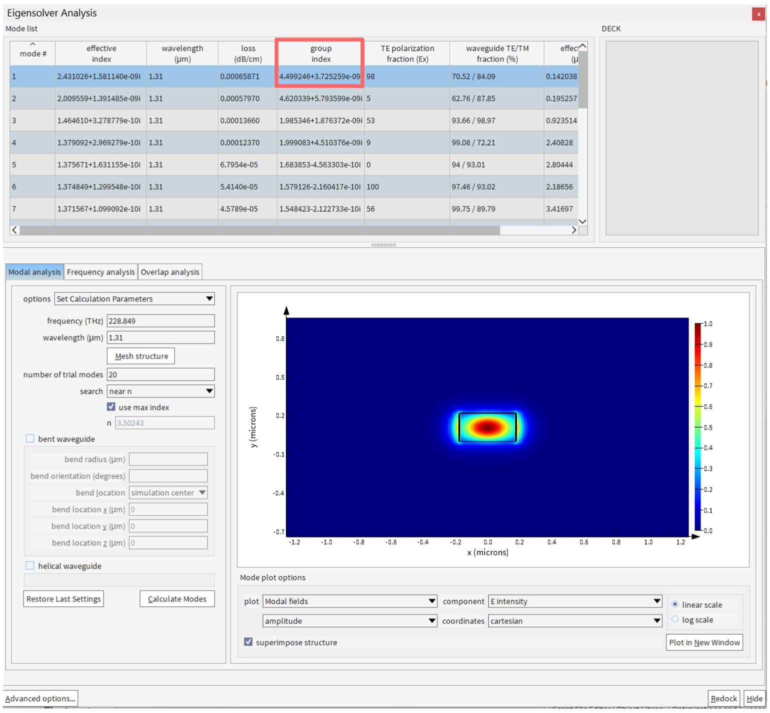
  Finite Difference Eigenmode Solver – 2.5 μm × 1.7 μm, 200 mesh cells in x & y, metal BCs

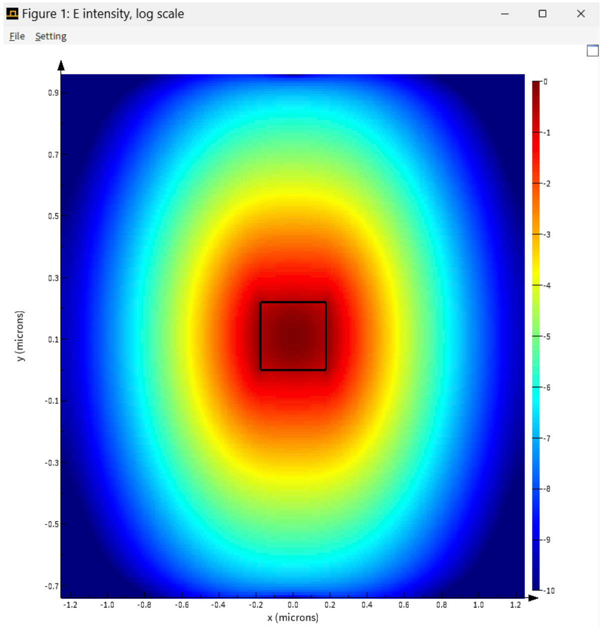
- eigensolver analysis done w/ wavelength, $\lambda = 1310\,\text{nm}$, yielding a group index of

  $\boxed{n_g = 4.499246}$ for TE polarization

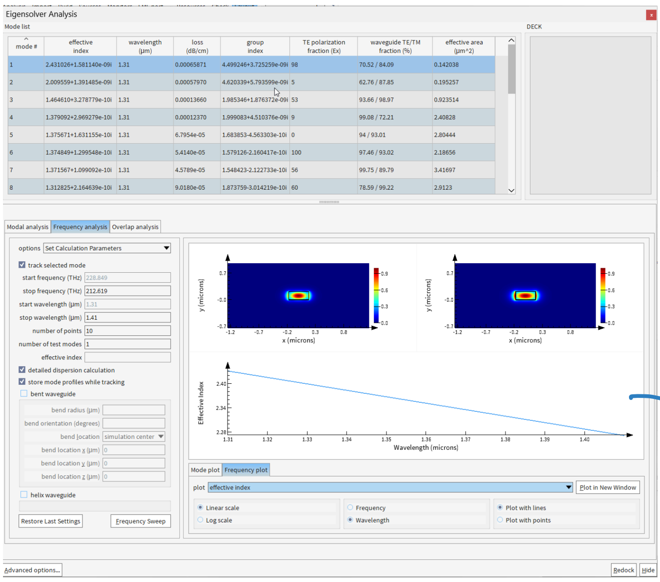
  note: E-field intensity was confirmed to decay

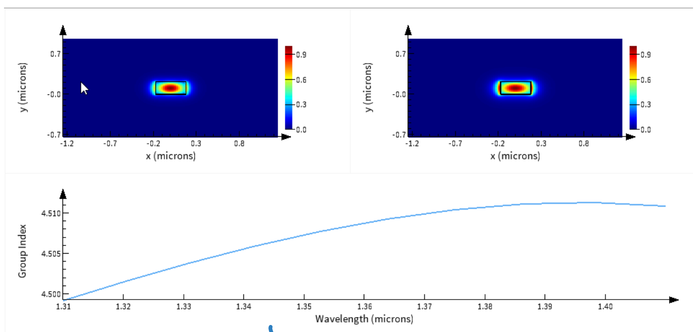






- wavelength sweep was performed from 1310–1410nm
  results were saved & exported for use in circuit simulation





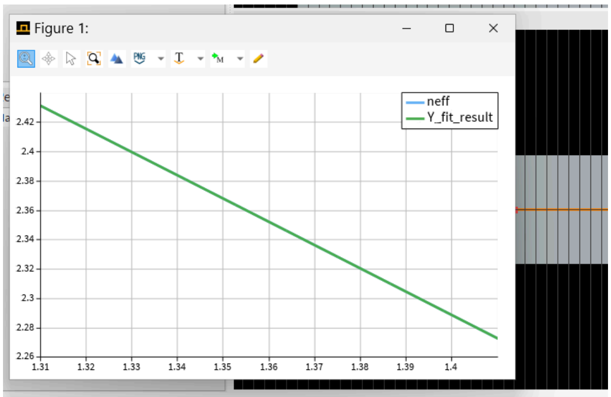
group index ~ increases w/ λ

confirming n_{eff} decreases w/ λ

• compact wave guide model was also found by curve fitting in Lumerical MODE using the given script

$$n_{eff}(\lambda) = 2.04903 - 1.60275(\lambda - 1.31) - 0.045979(\lambda - 1.31)^2$$

note: not sure if this is needed... will see later

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# This is the polynomial equation:
Y_fit_result = a_fit(1) + a_fit(2)*(lambda-lambda0) + a_fit(3)*(lambda-lambda0)^2;

plot (lambda, neff, Y_fit_result);  # plot the result;
result:
2.04903
-1.60275
-0.045979
>
```

② Calculate required ΔL given the n_g found from simulation

$$\Delta\nu = \frac{c}{\Delta L\, n_g} \implies \Delta L = \frac{c}{\Delta\nu\, n_g} = \frac{(3.8\times10^{8}\ \text{m/s})}{(25\times10^{9}\ \text{1/s})(4.449246)}$$

$$= 2.665\ \text{mm}$$

③ Complete the layout of the MZI w/ $\Delta L = 2.665$ mm

• using the following components (as specified on piazza)

fibre grating coupler: GC_TE_1310_8degOxide_BB

wave guide: 350 nm × 220nm @ 1310nm

directional coupler: ebeam_splitter_swg_assist_te1310

• important design parameters / considerations:

floorplan size = 605 μm × 410 μm

fibre grading coupler spacing of 127 μm

minimize wave guide length & bends to reduce loss

minimize floorplan area usage (?)

• going w/ two designs to vary parameters - mainly loss

(i) create ΔL w/ spiral paperclip

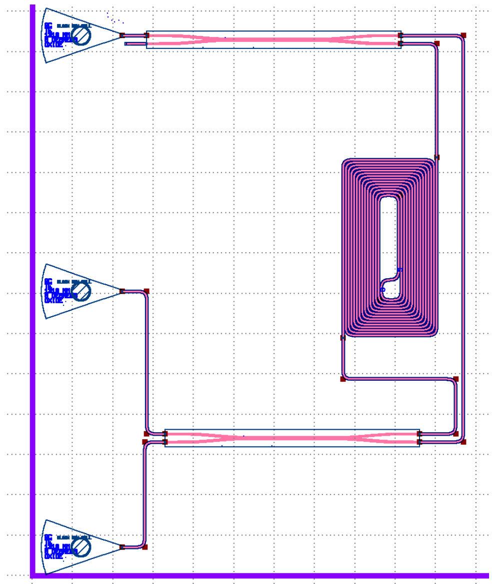
- area efficient
- but lots of bends (more loss)

note: bends have more optical loss than straight wave guide

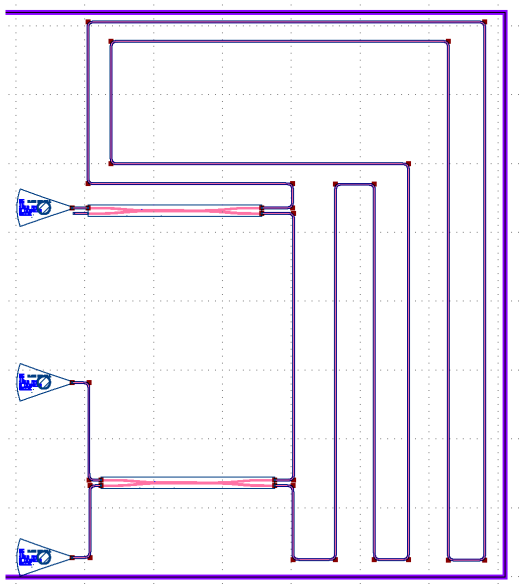
(ii) create ΔL w/ regular path waveguides

- takes up more area/physical space
- less bends, less loss

(i)

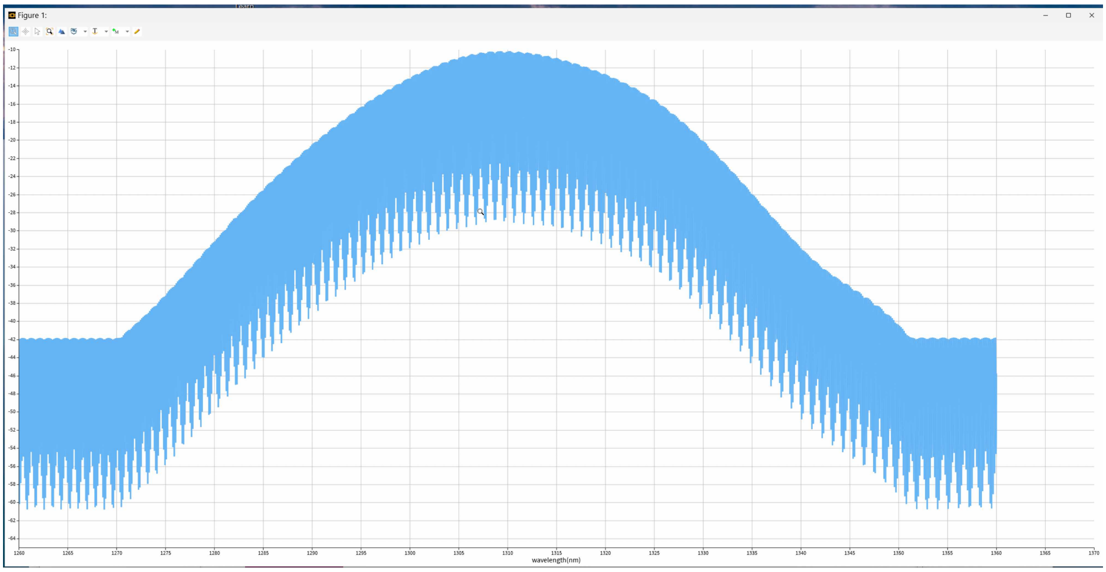


(ii)



- functional verification run & passing

④ Confirm operation of circuit w/ Lumerical INTERCONNECT simulation



in progress...