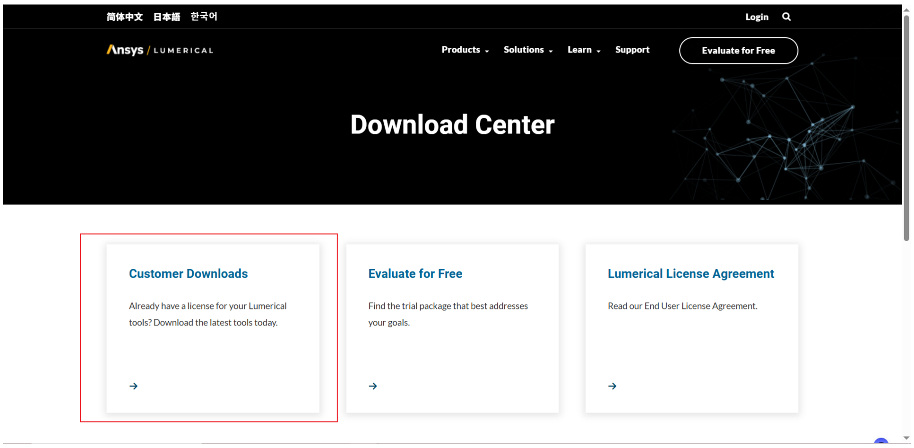
Task 2 & 3: Waveguide Mode simulations (Lumerical FDTD)

2.1. Checklist

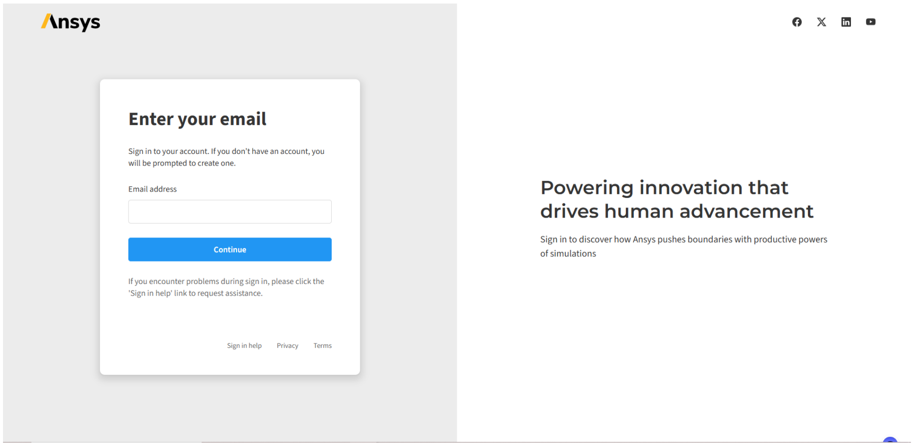
- Lumerical 2024 R2.3 is installed and activated on your PC (if nor, please follow the instructions below).

2.2. Lumerical Installation

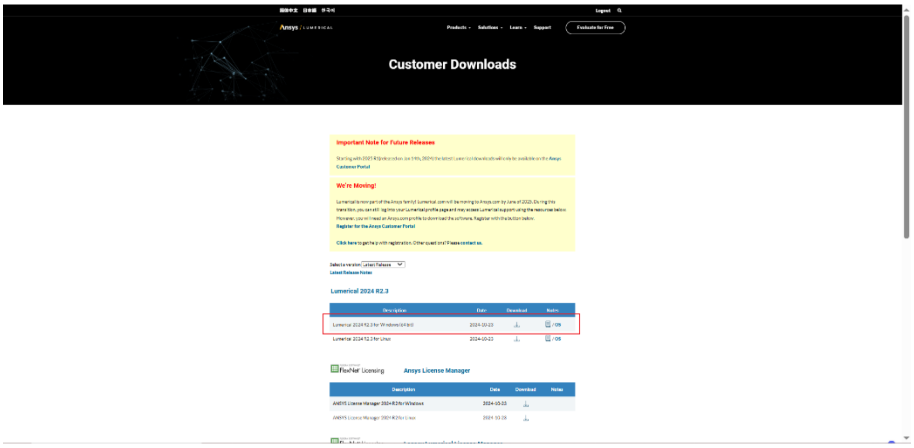
- Visit the Lumerical Download Center: https://www.lumerical.com/downloads/.



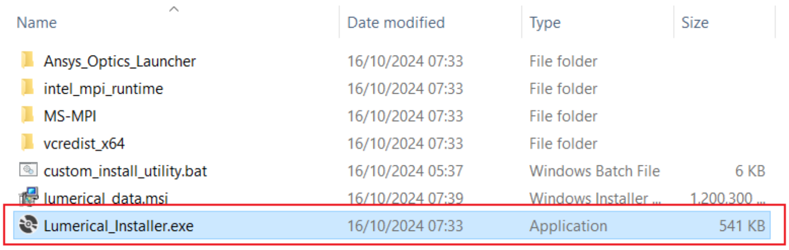
- Click on **"Customer Downloads"**, follow the instructions to create an Ansys account, and use it to log in.



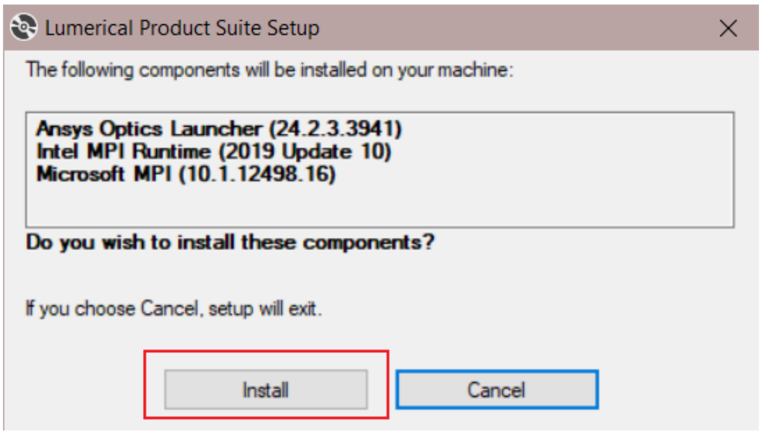
- Once logged in, you will see a list of available Lumerical software releases. Select the latest version (**Lumerical 2024 R2.3**) and click the **Download** button.



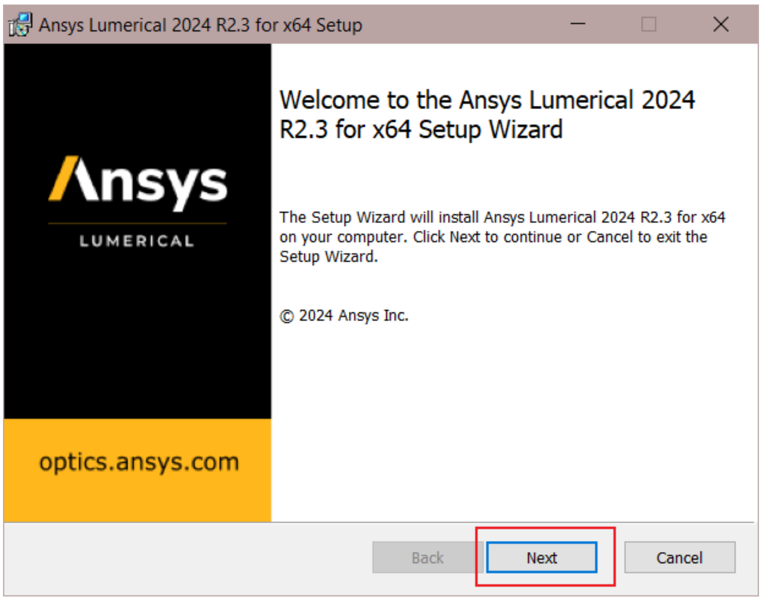
- Unzip the downloaded file and run `Lumerical_Installer.exe` inside the extracted folder.

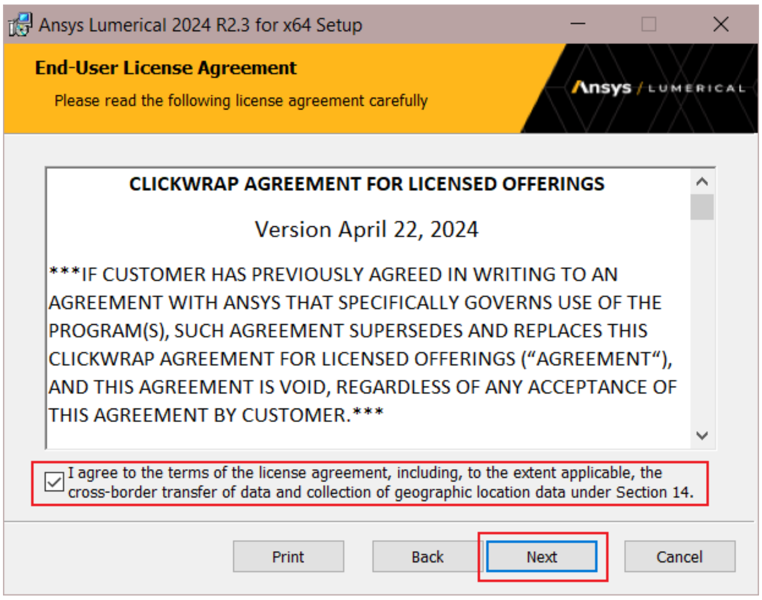


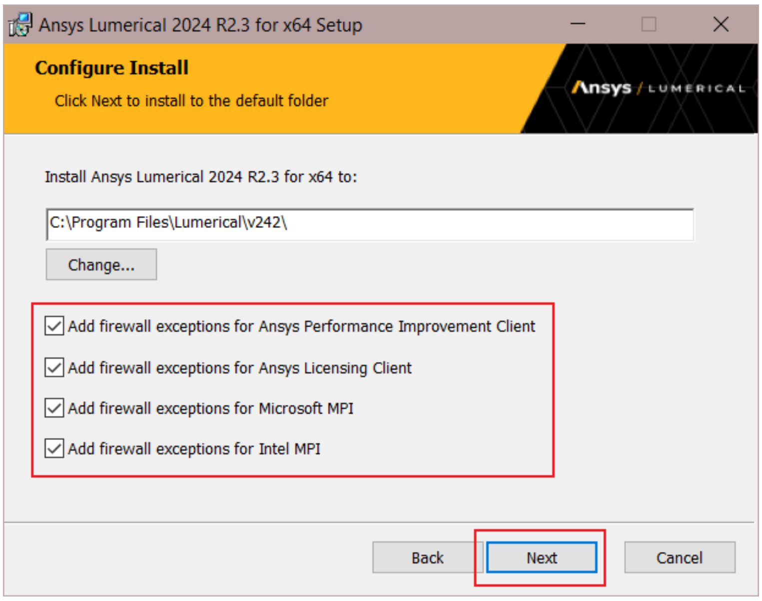
- Proceed to install all the required components.

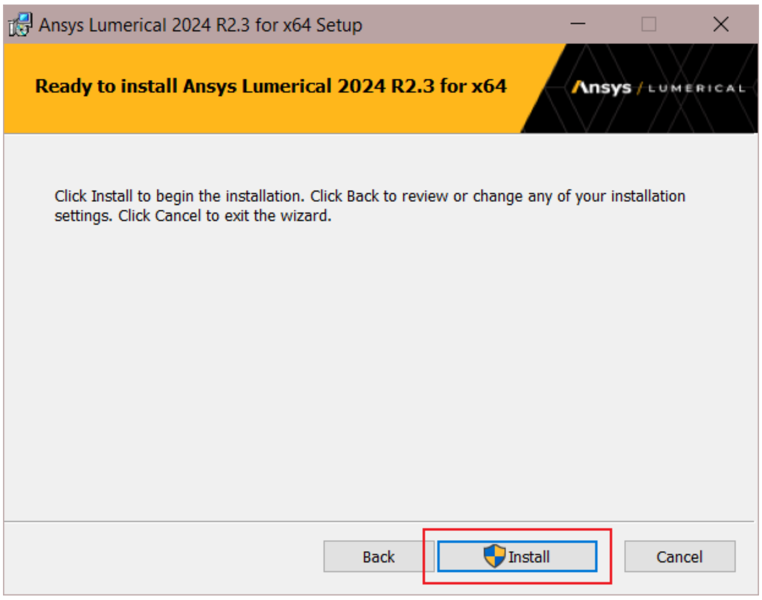


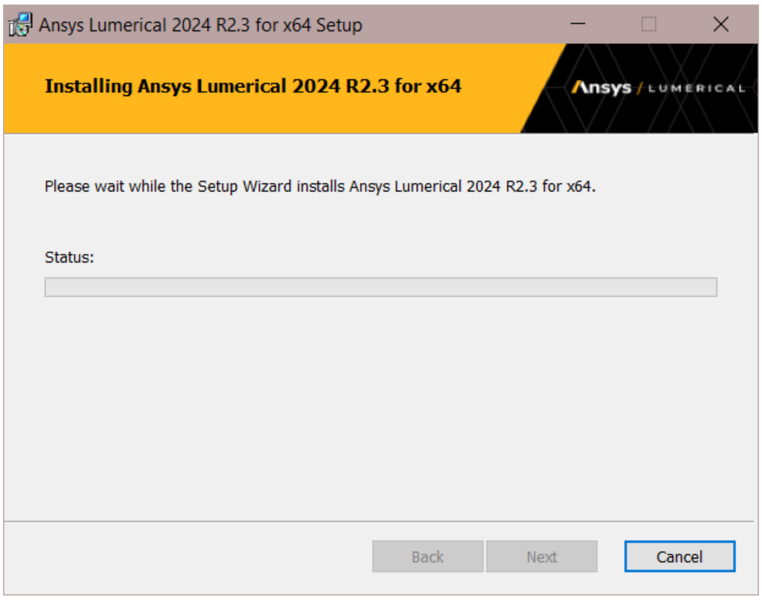
- Follow the step-by-step installation process.

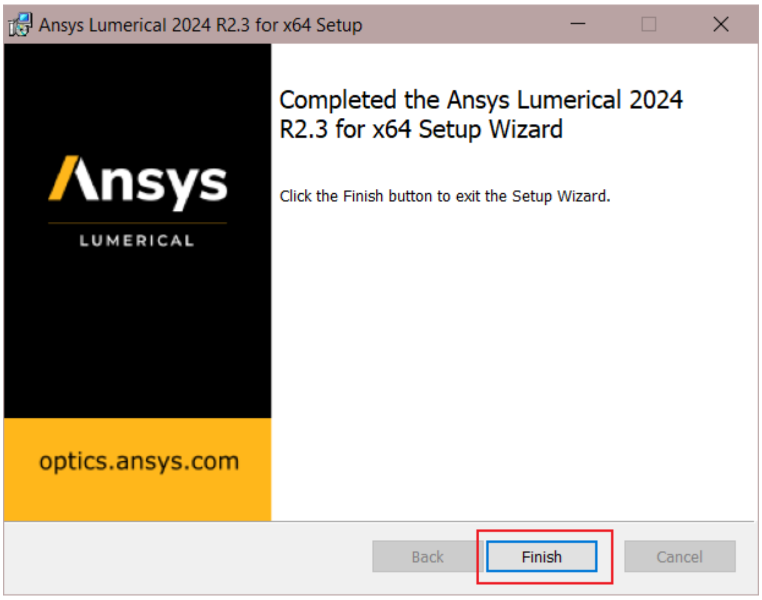




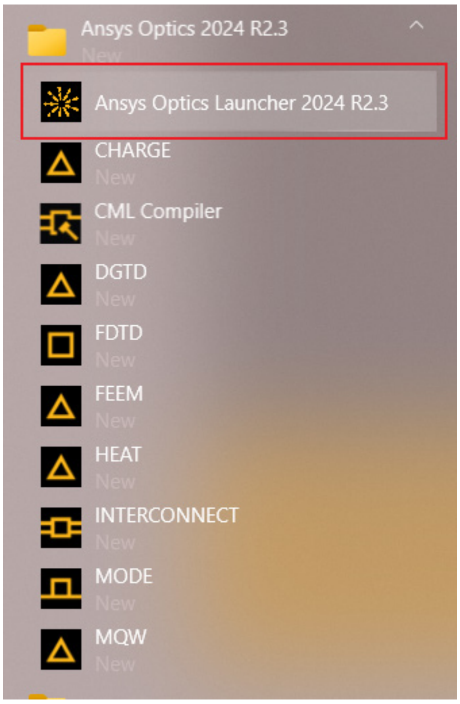



Ansys Lumerical 2024 R2.3 for x64 Setup
Ready to install Ansys Lumerical 2024 R2.3 for x64
Ansys / LUMERICAL
Click Install to begin the installation. Click Back to review or change any of your installation settings. Click Cancel to exit the wizard.
Back
Install
Cancel

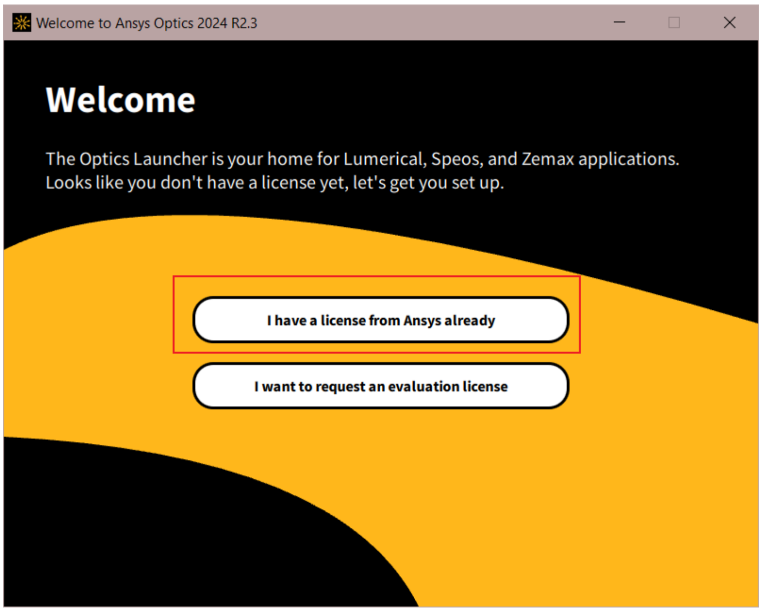

Ansys Lumerical 2024 R2.3 for x64 Setup
Installing Ansys Lumerical 2024 R2.3 for x64
Ansys / LUMERICAL
Please wait while the Setup Wizard installs Ansys Lumerical 2024 R2.3 for x64.
Status:
Back
Next
Cancel


Ansys Lumerical 2024 R2.3 for x64 Setup
Ansys
LUMERICAL
optics.ansys.com
Completed the Ansys Lumerical 2024 R2.3 for x64 Setup Wizard
Click the Finish button to exit the Setup Wizard.
Back
Finish
Cancel

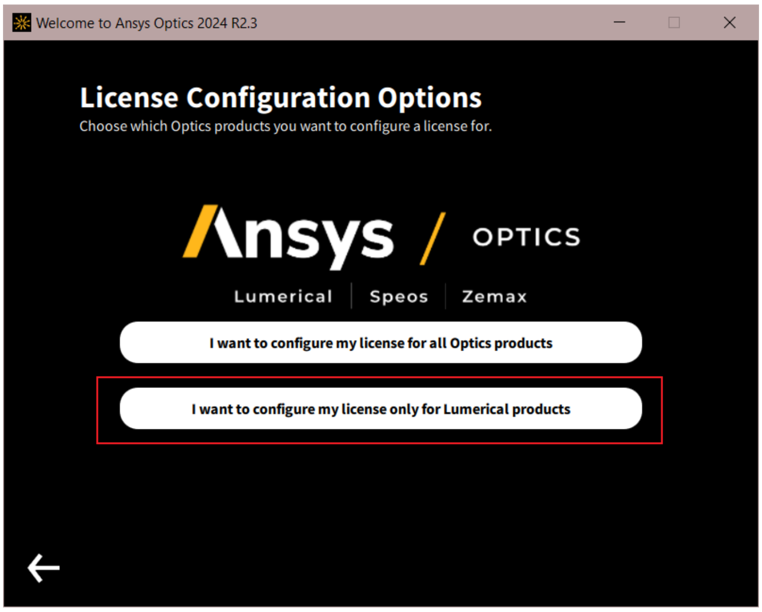
- After the installation is complete, open the **Ansys Optics Launcher** from the Start menu.



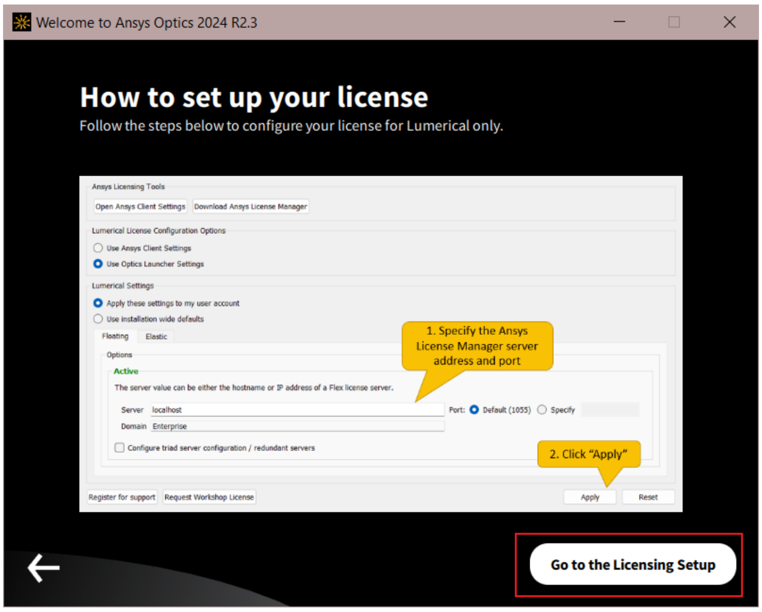
- Select **"I have a license from Ansys already."**



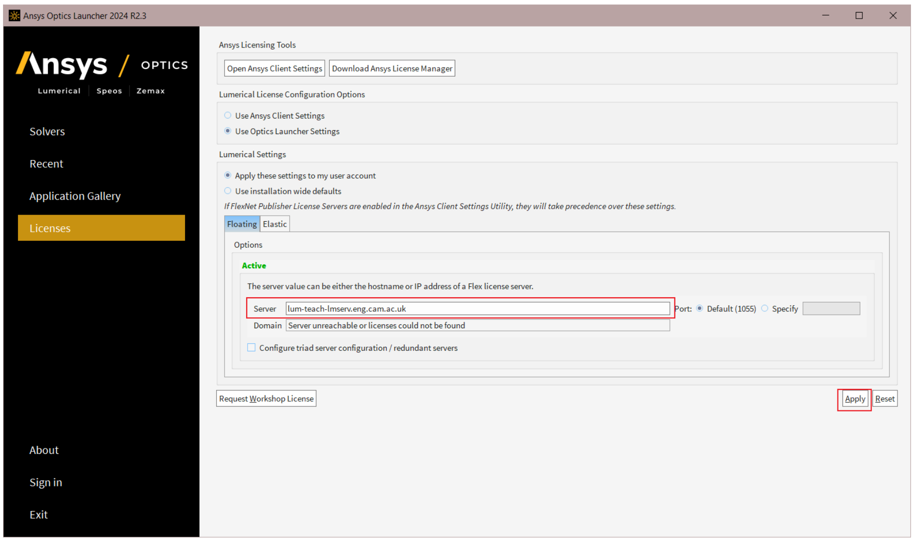
- Choose **"I want to configure my license only for Lumerical products."**



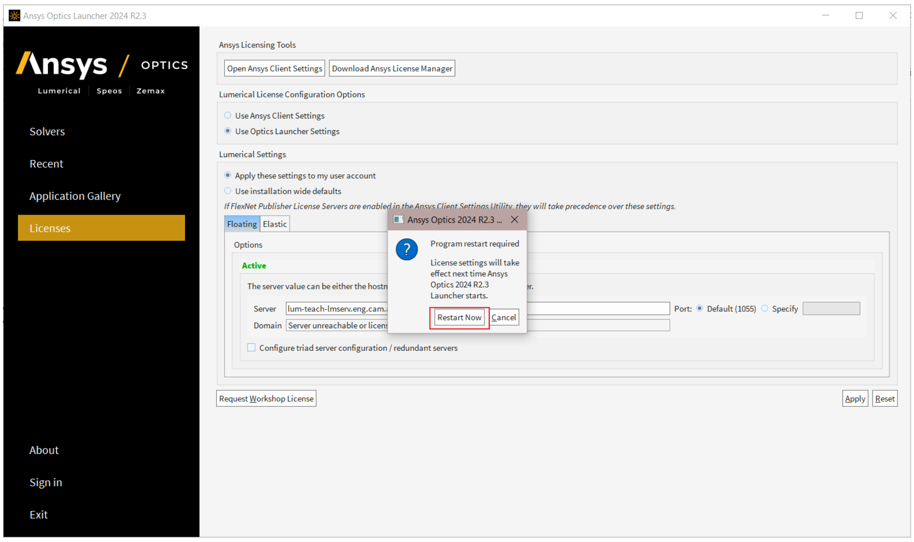
- Click on **"Go to the Licensing Setup."**

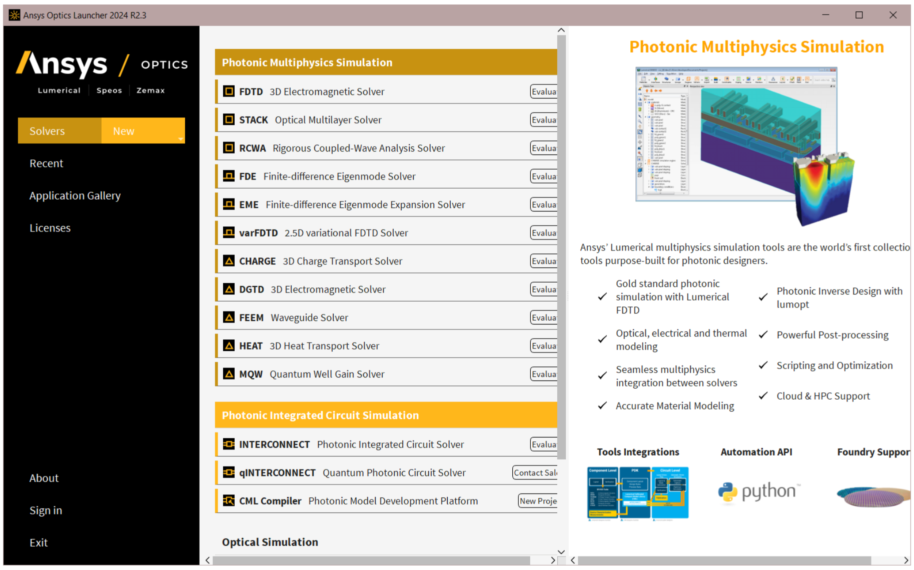


- In the license configuration window, set the **License Manager server address** to `lum-teach-lmserv.eng.cam.ac.uk`, then click **Apply**.



- Restart the program. Lumerical is now ready to use!





2.3. Coupling Analysis using Lumerical FDTD

2.3.1 Analytical Solution of Coupled-Mode Equations

- Before using the simulation tool to model the coupling process, first mathematically solve the following set of coupled-mode equations **[Include in your Report 2]**:

$$\begin{cases} \dfrac{dA_0(z)}{dz} = -i\beta A_0(z) - i\kappa A_1(z) \\ \dfrac{dA_1(z)}{dz} = -i\beta A_1(z) - i\kappa A_0(z) \end{cases}$$

Assume that initially 70% of the optical power is within Waveguide 0 at the position $z = 0$ while the rest are in Waveguide 1, i.e., $A_0(0) = 0.837\ and$ $A_1(0) = 0.548$; and assume the values of β and κ to be 9.9892 μm^{-1} and 0.107 μm^{-1}, respectively. Please determine:

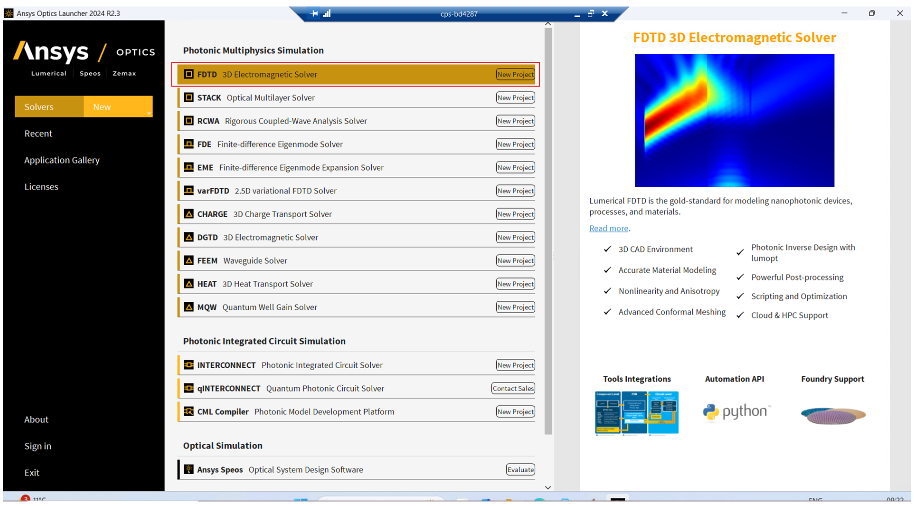
1. The analytical expressions of the field amplitudes $A_0(0)$and $A_1(0)$;
2. The distances z at which (i) the optical power is equally shared between the two waveguides, and (ii) the power in Waveguide 1 reaches its maximum, respectively.

Hint: this is a second-order linear differential system. The solutions are expected to be sinusoidal.

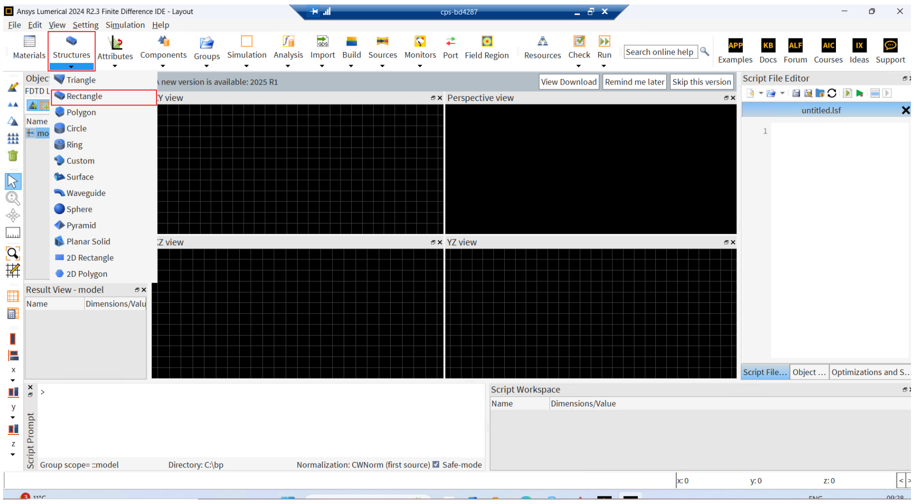
2.3.2 Numerical Simulation Using Lumerical

- In Lumerical, create a pair of identical single-mode SOI waveguides placed side by side with a small gap, and run the simulation to observe the mode coupling phenomenon between them. Below are detailed steps:

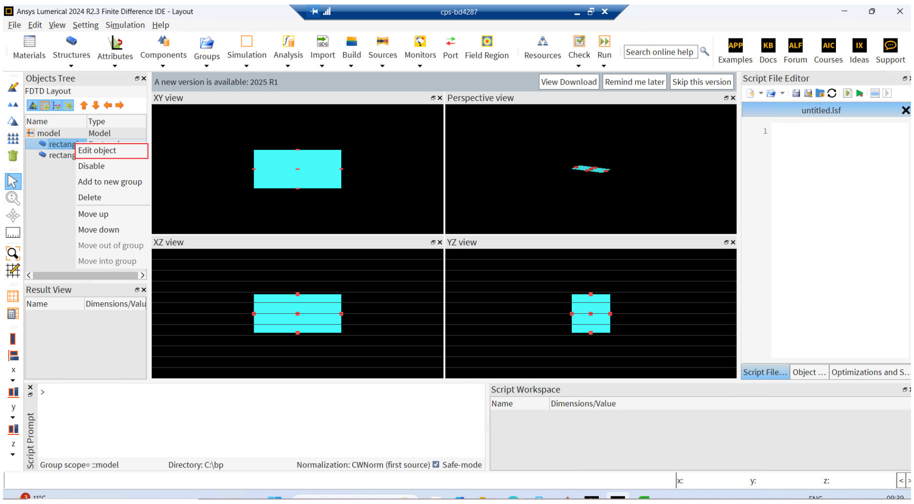
  - Launch **Ansys Optics Launcher** and open the **FDTD** solver.

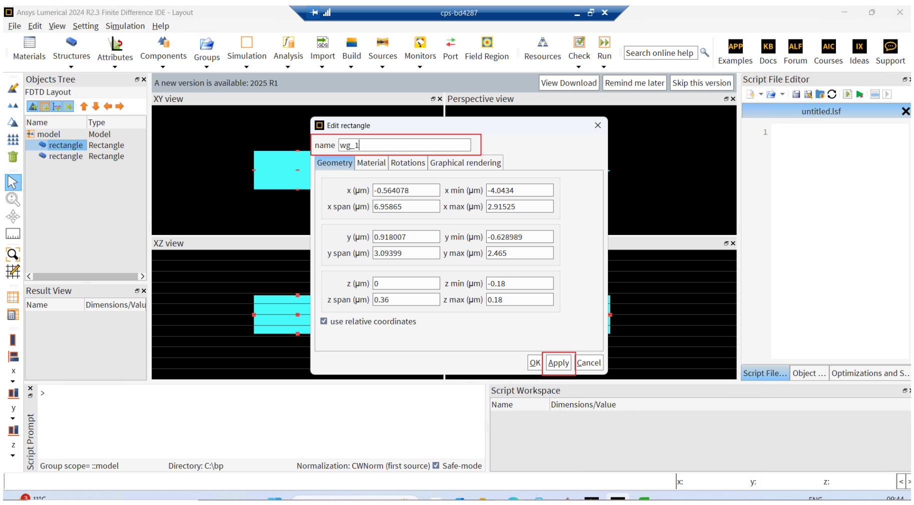


- Add two **Rectangles** to represent waveguides.

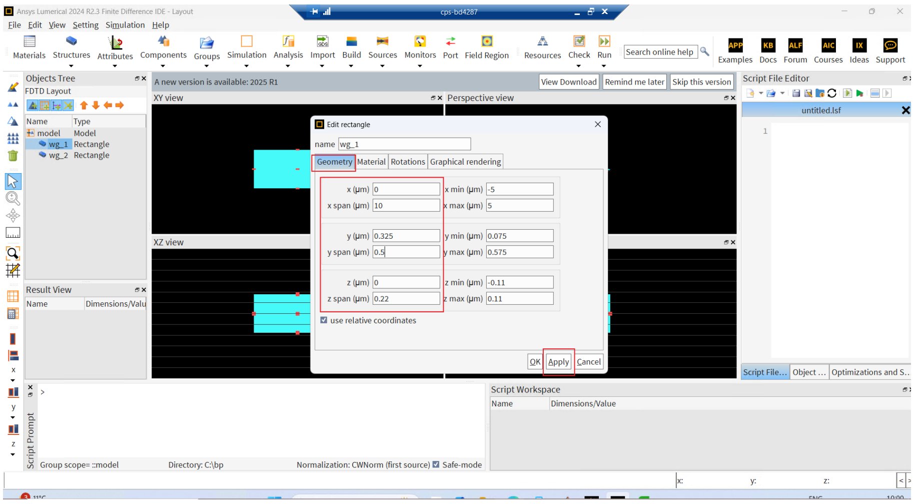


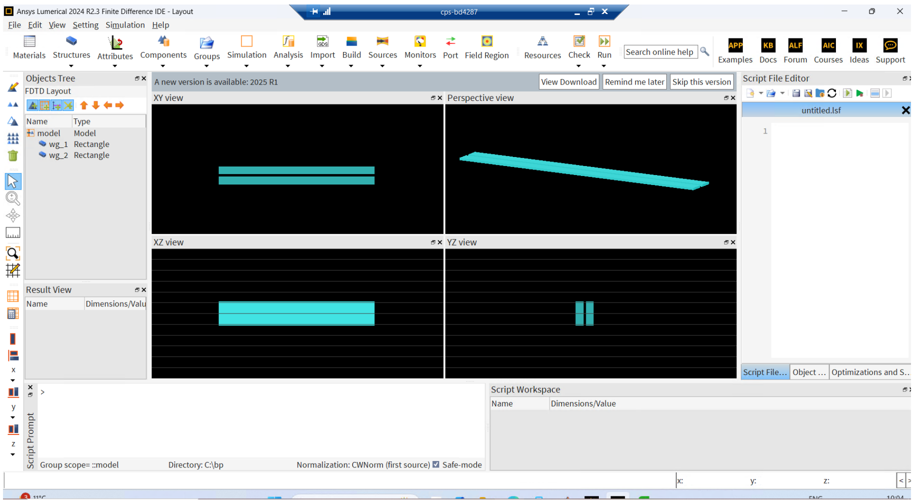
- Rename them appropriately (e.g., wg_1, wg_2).



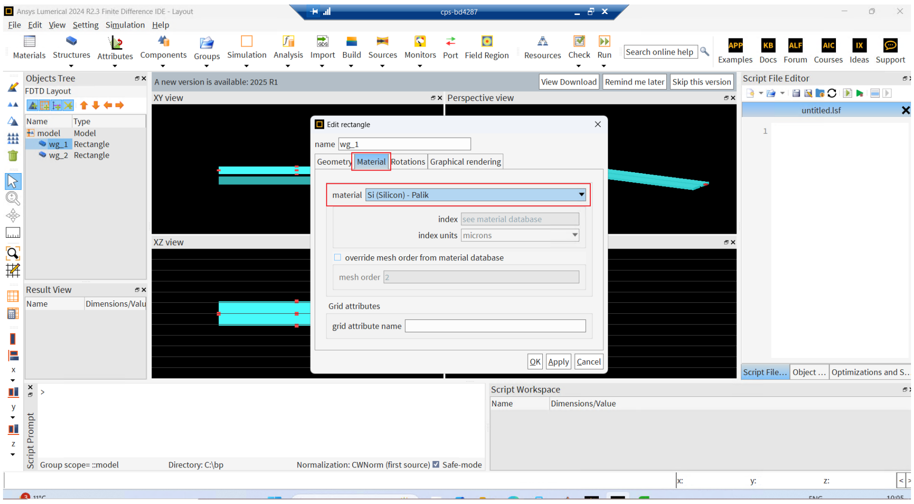


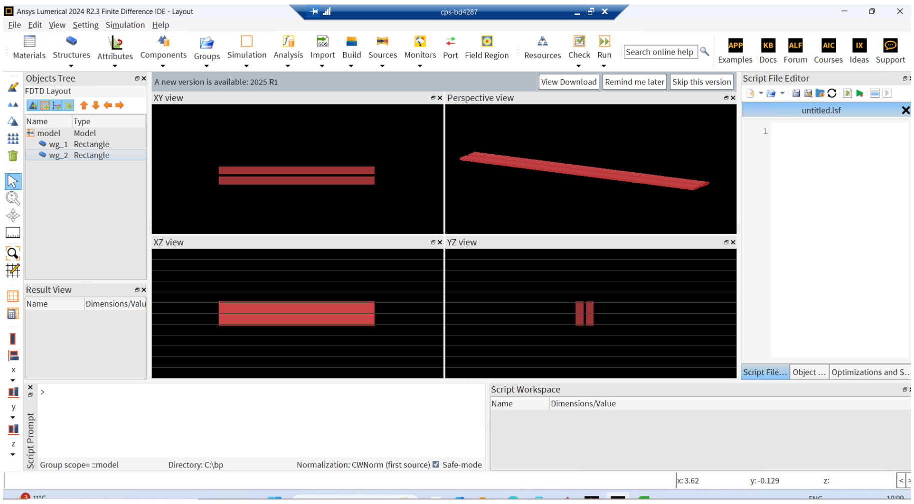
- Edit their **Geometry** so that each waveguide has dimensions of 500 nm (width) × 220 nm (thickness) × 10 µm (length), with a separation of 150 nm between them.



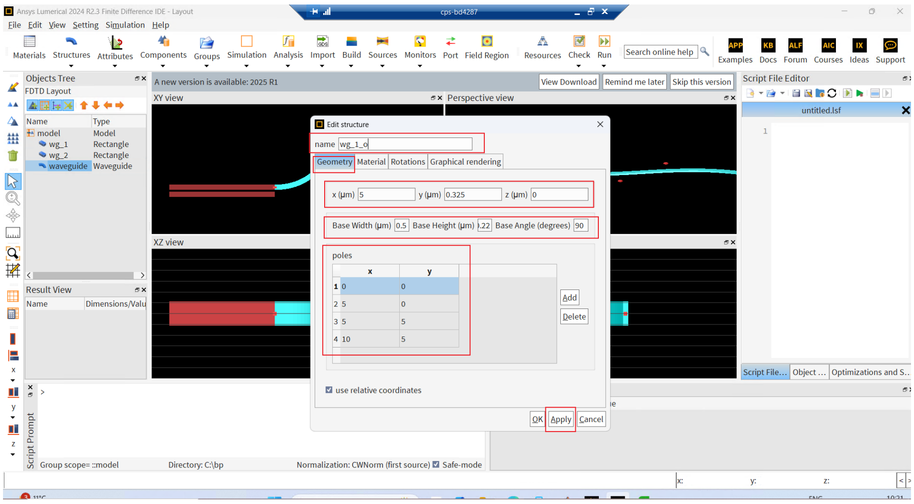


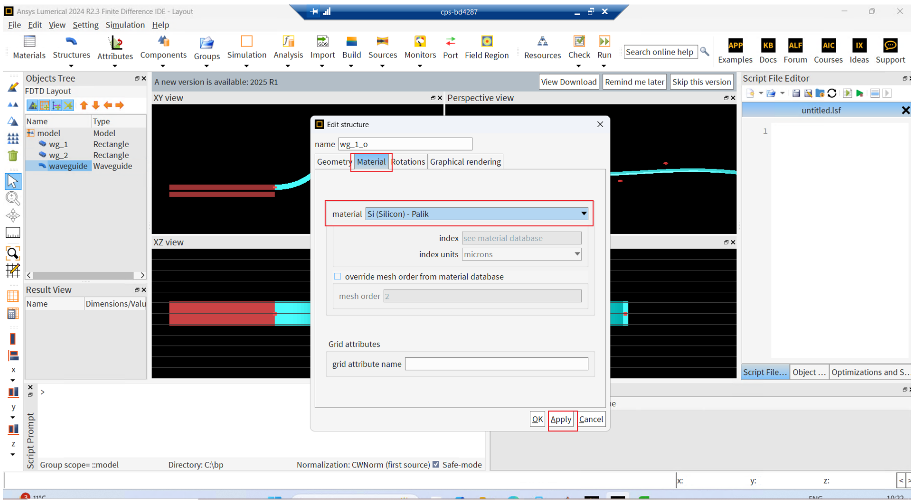
- Assign material: set to “Si (Silicon) – Palik”.

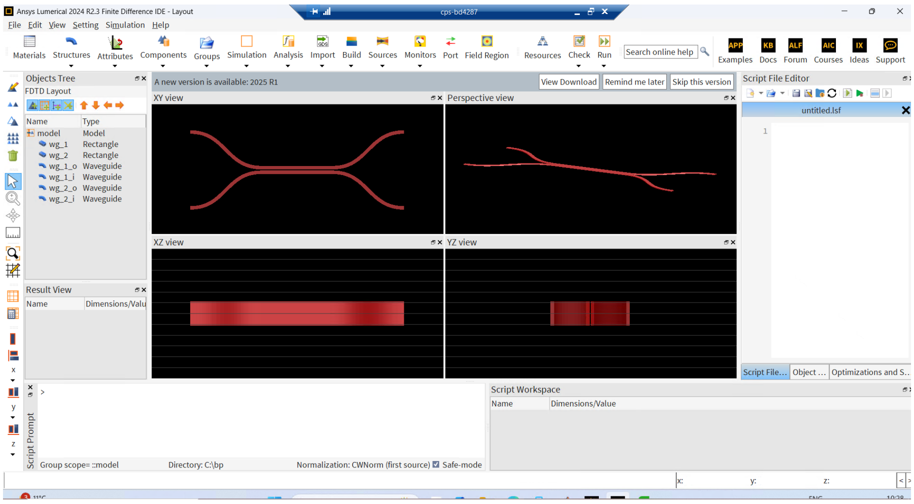




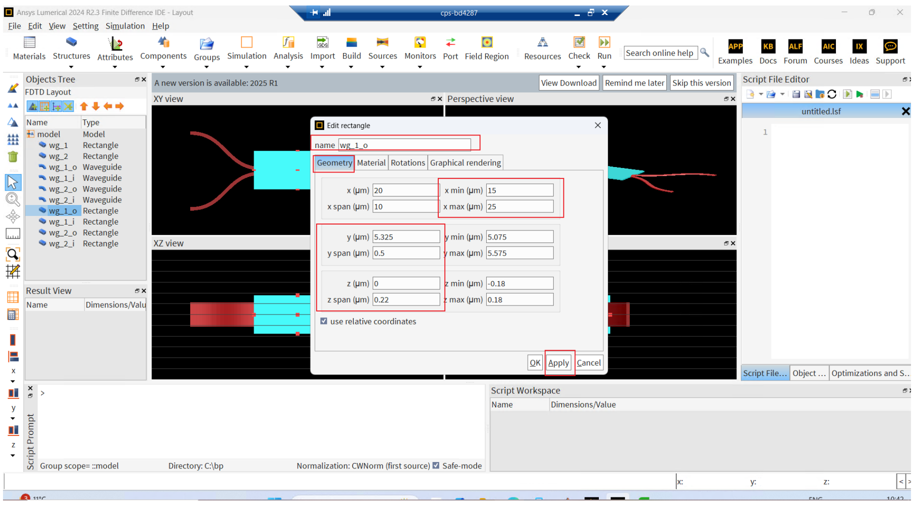
- Insert four S-bend **Waveguides** (use this guide: https://optics.ansys.com/hc/en-us/articles/360034901673-Tips-for-creating-waveguide-bends-using-the-path-object) and connect them to both ends of the two coupled waveguides. These fan-in/out S-bends bring the waveguides close together over the coupling region and separate them afterward, thereby controlling the coupling length. Rename these structures, edit their geometry, and assign appropriate materials. The exact shape of the S-bends has minimal impact on coupling but ensure that the bending radius and the separation between the fan-in/out waveguides are sufficiently large (>5 µm).

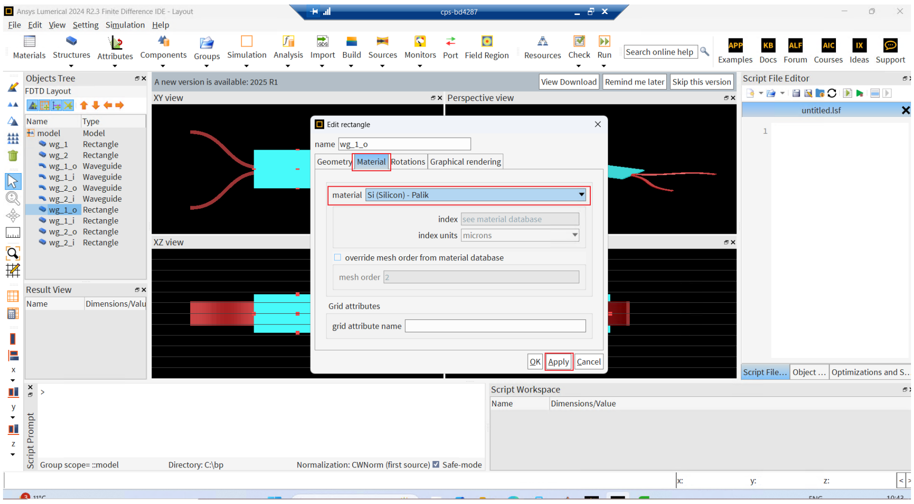


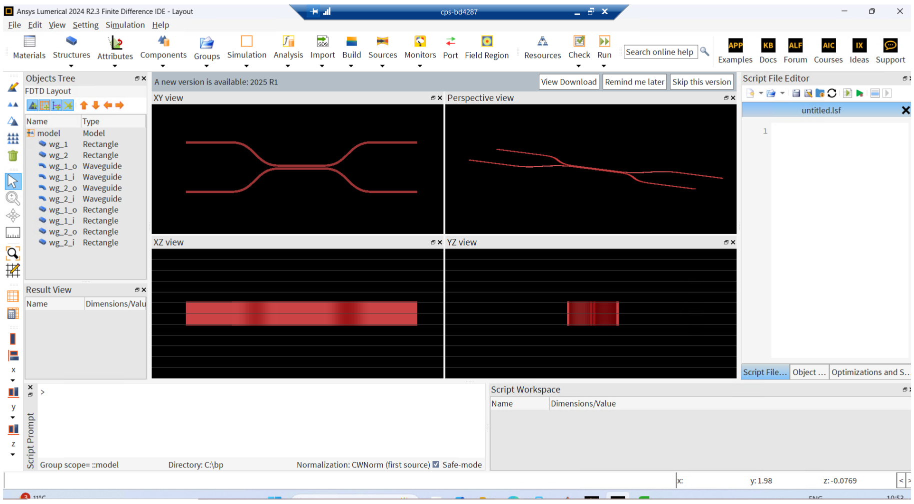




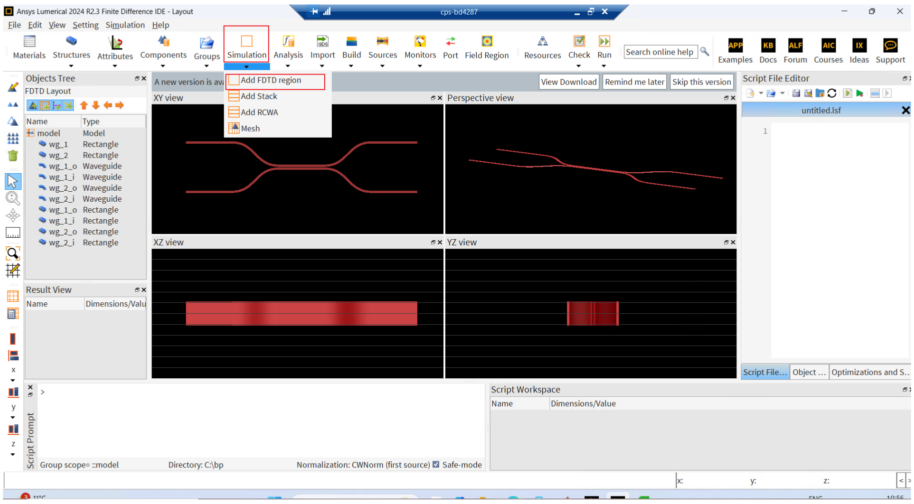
- Add another four **Rectangles** to extend the fan in/out waveguides. Make sure they are long enough (10 µm in the example).

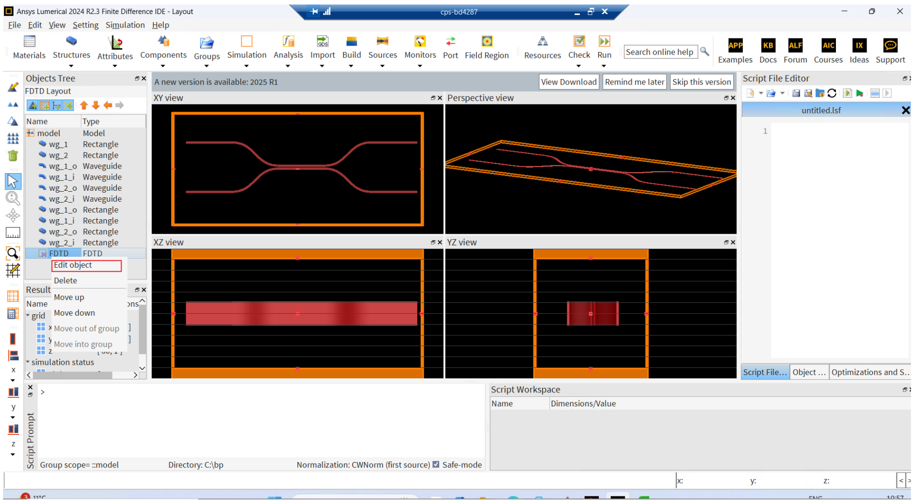


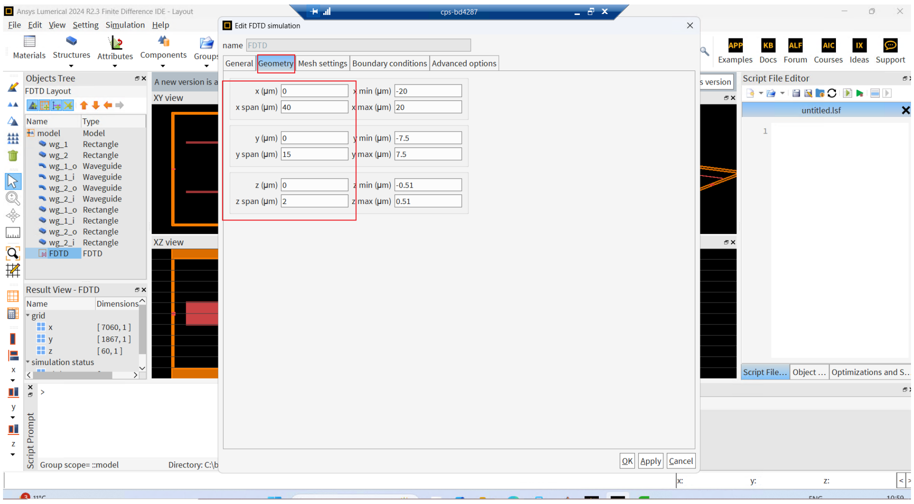




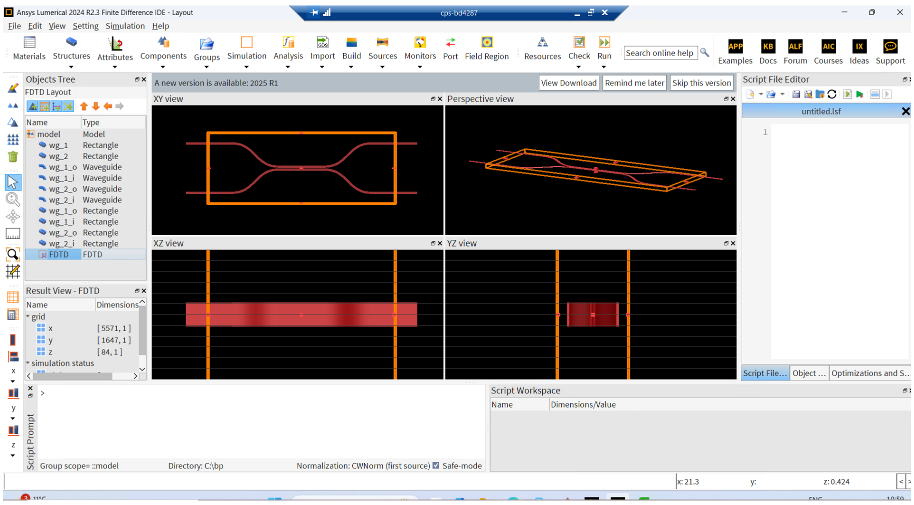
- Specify the FDTD simulation region.



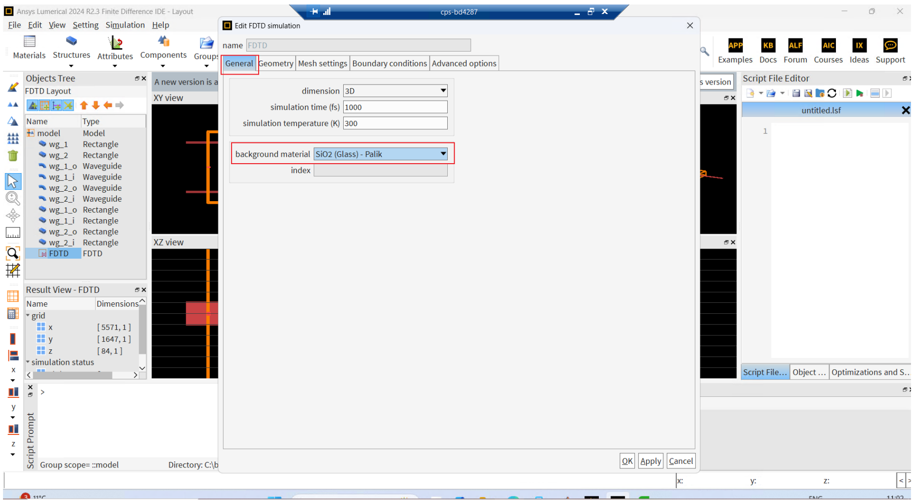




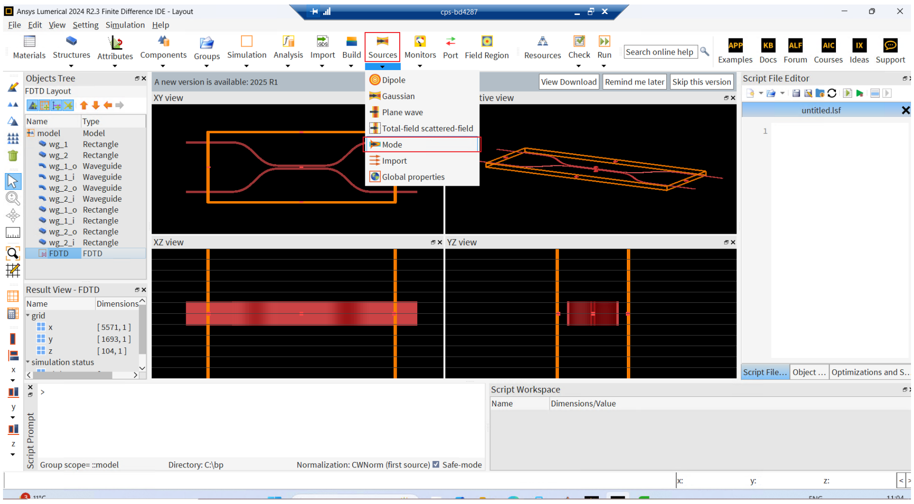
Ensure that all structures are contained within the simulation region with sufficient margin, and that the input/output waveguides extend through the region boundaries.

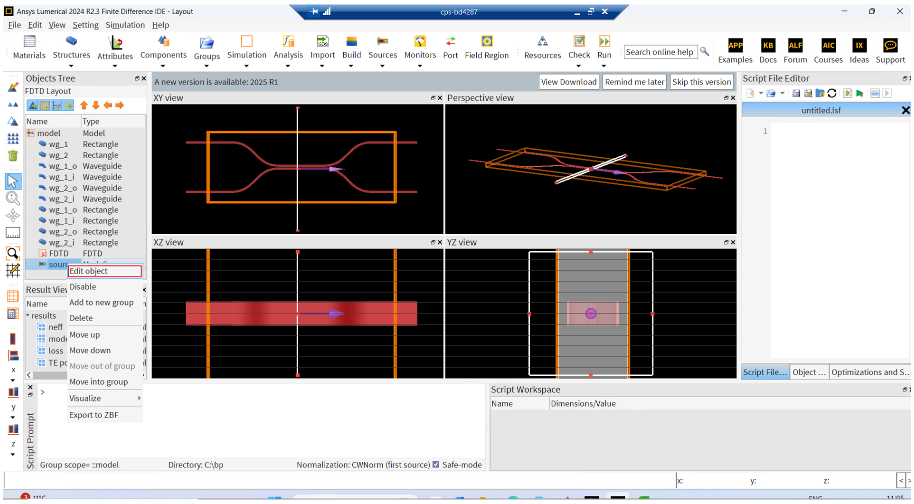


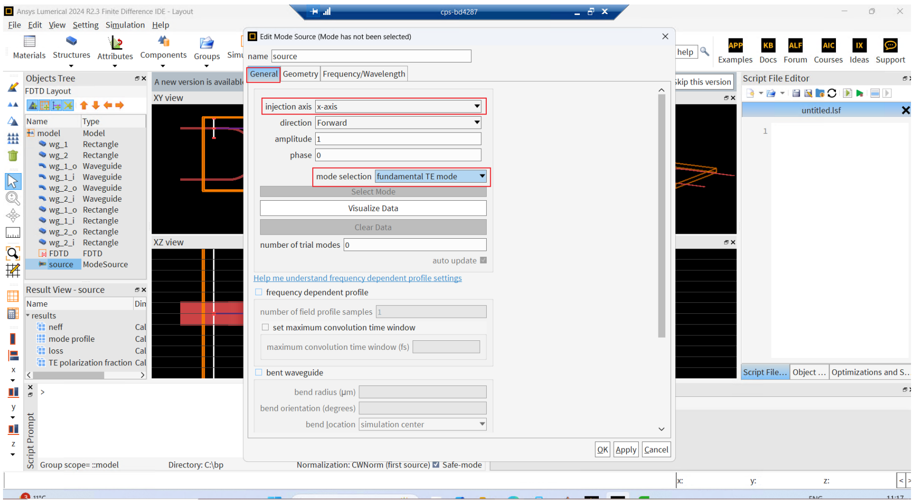
- Set the background material to “SiO2 (Glass) – Palik”.

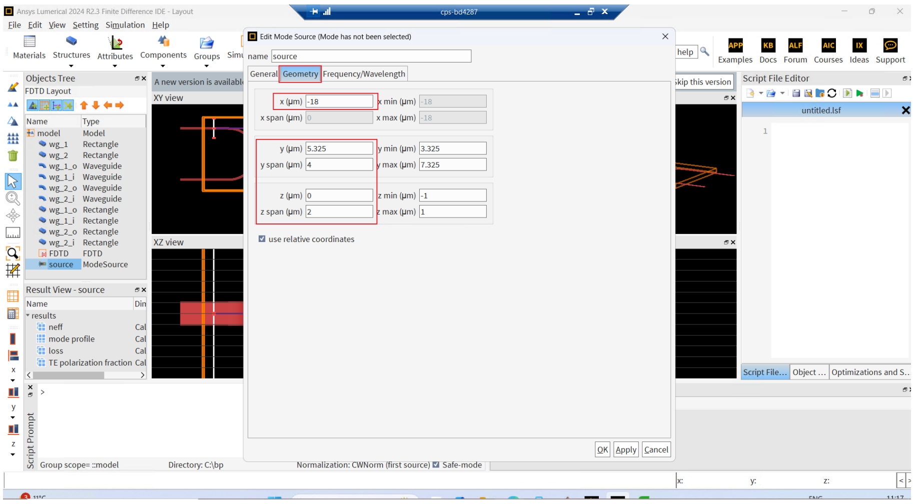


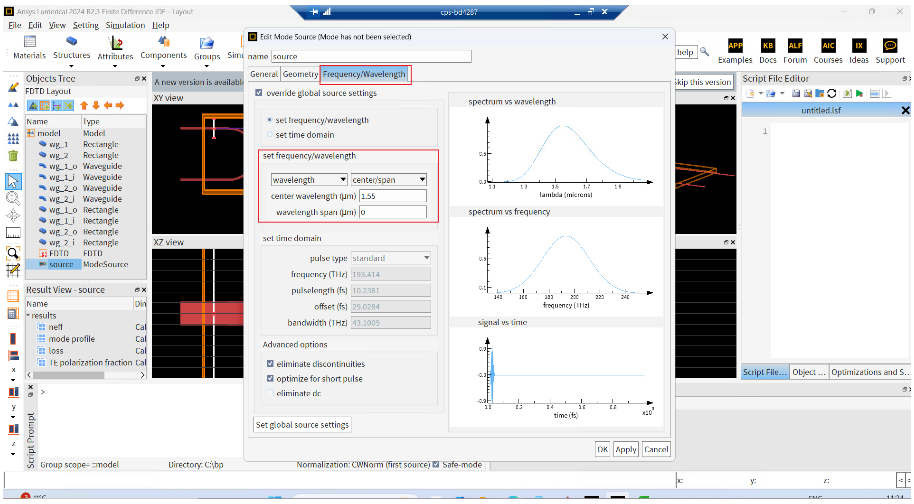
- Place a **ModeSource** at one input waveguide. Adjust its injection axis, mode, geometry, and wavelength.

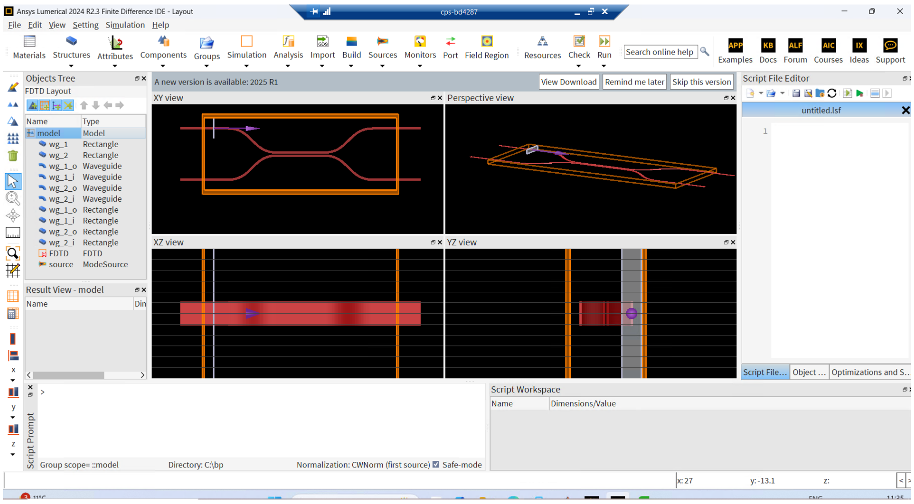




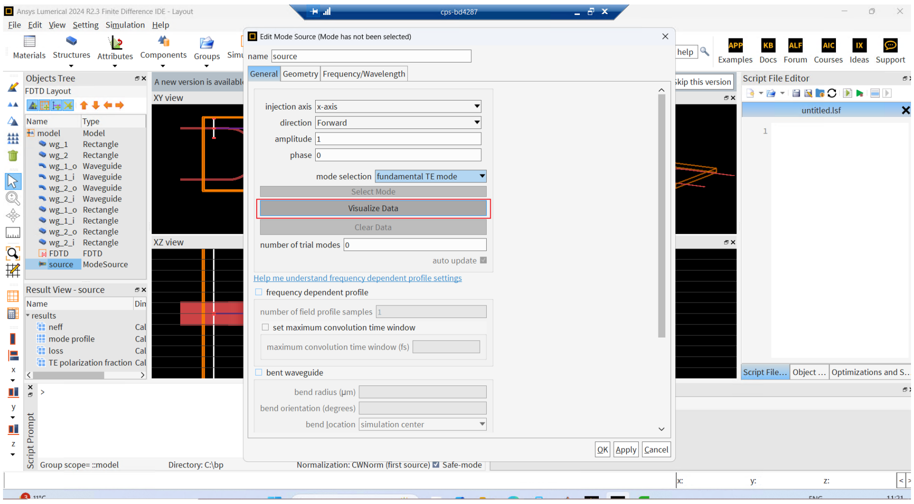

Edit Mode Source (Mode has not been selected)
name source
General Geometry Frequency/Wavelength
injection axis x-axis
direction Forward
amplitude 1
phase 0
mode selection fundamental TE mode
Select Mode
Visualize Data
Clear Data
number of trial modes 0
auto update
Help me understand frequency dependent profile settings
frequency dependent profile
number of field profile samples 1
set maximum convolution time window
maximum convolution time window (fs)
bent waveguide
bend radius (μm)
bend orientation (degrees)
bend location simulation center
OK Apply Cancel

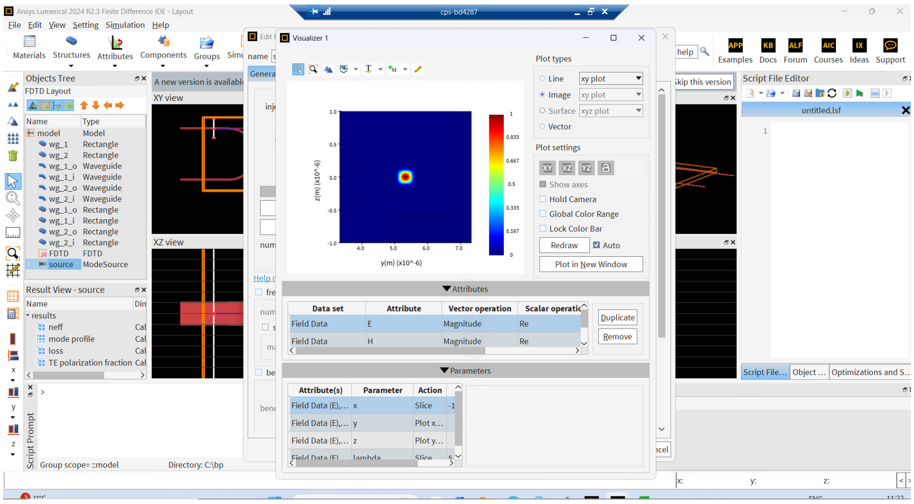

Edit Mode Source (Mode has not been selected)
name source
General Geometry Frequency/Wavelength
x (μm) -18
x min (μm) -18
x span (μm) 0
x max (μm) -18
y (μm) 5.325
y min (μm) 3.325
y span (μm) 4
y max (μm) 7.325
z (μm) 0
z min (μm) -1
z span (μm) 2
z max (μm) 1
use relative coordinates
OK Apply Cancel


Edit Mode Source (Mode has not been selected)
name source
General Geometry Frequency/Wavelength
override global source settings
set frequency/wavelength
set time domain
set frequency/wavelength
wavelength
center/span
center wavelength (μm) 1.55
wavelength span (μm) 0
set time domain
pulse type standard
frequency (THz) 193.414
pulselength (fs) 10.2381
offset (fs) 29.0284
bandwidth (THz) 43.1009
Advanced options
eliminate discontinuities
optimize for short pulse
eliminate dc
Set global source settings
spectrum vs wavelength
lambda (microns)
spectrum vs frequency
frequency (THz)
signal vs time
time (fs)
OK Apply Cancel

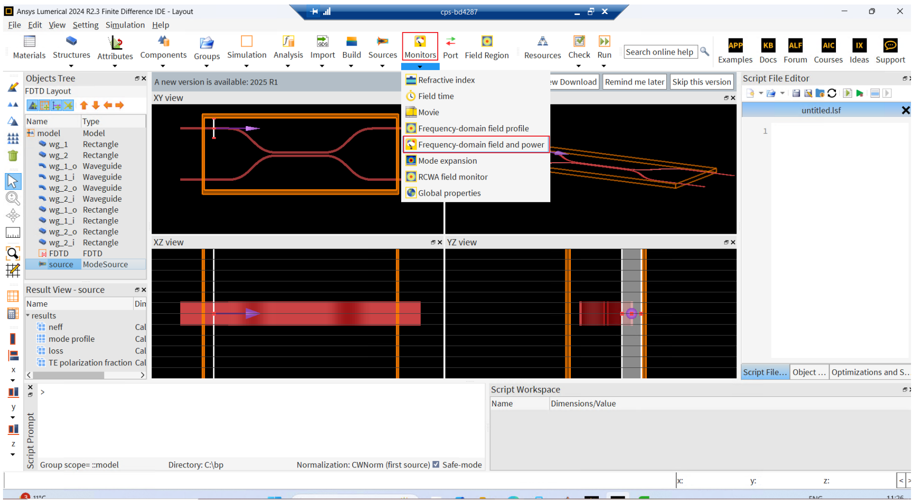


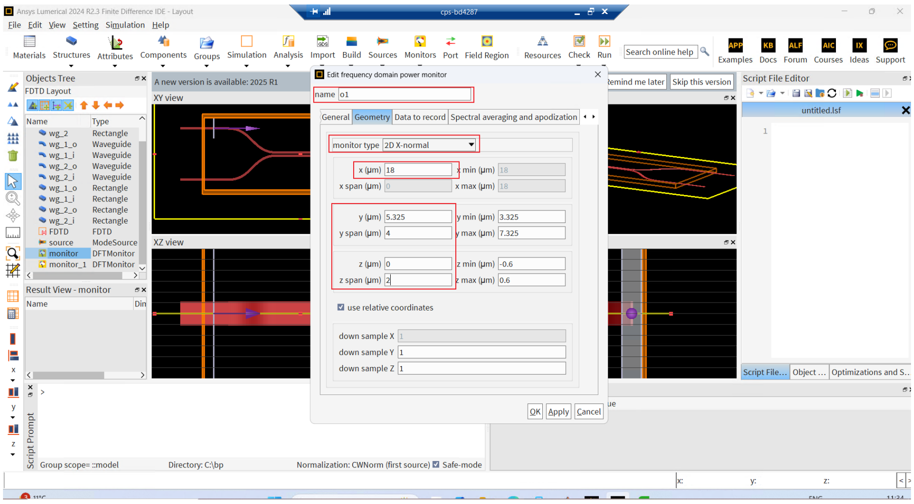
Verify the mode source covers the entire optical power distribution. This can be checked through visualizing the input mode profile.

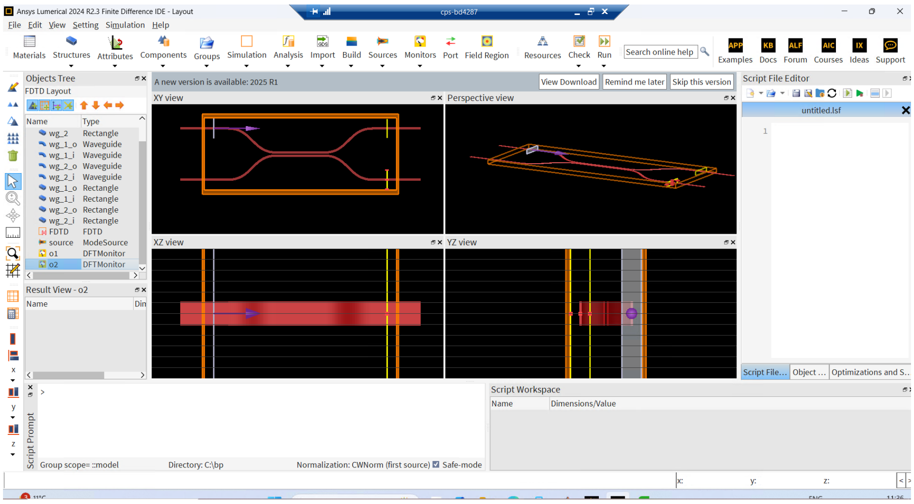




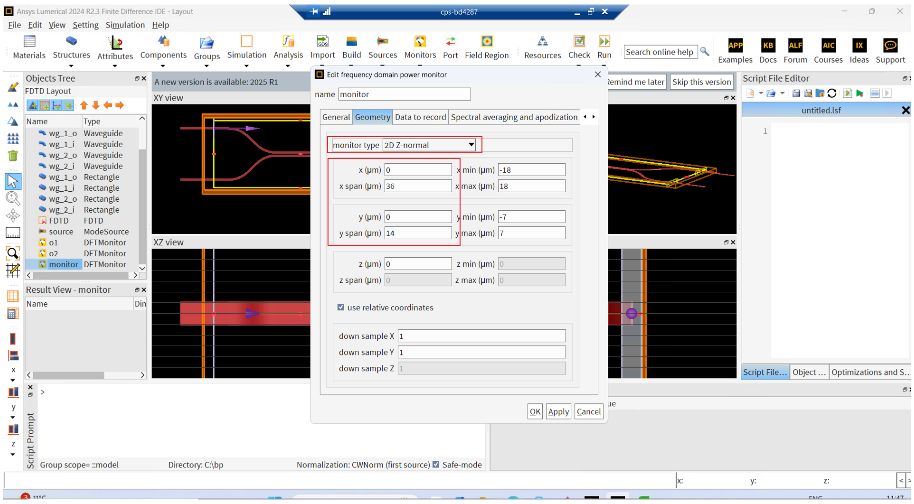
- Add two **DFTMonitors** at both output waveguides to measure transmitted intensity. Position monitors normal to propagation direction and ensure their size fully captures the output mode.

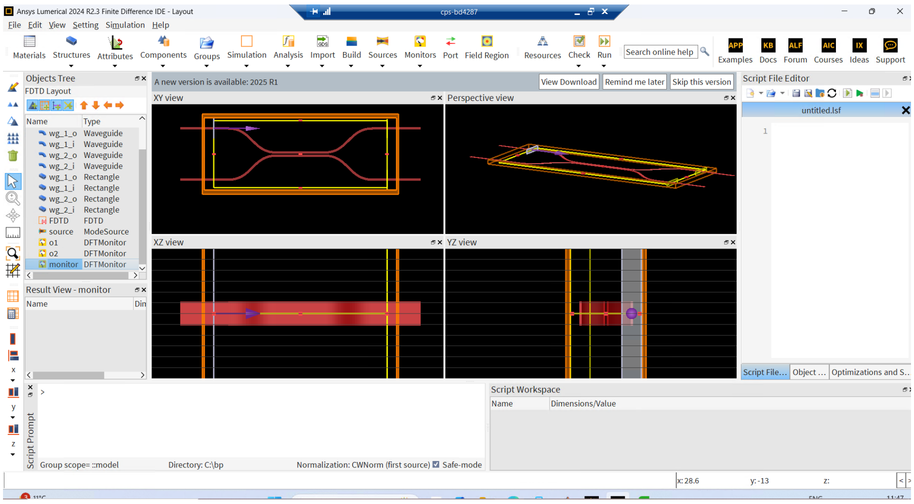




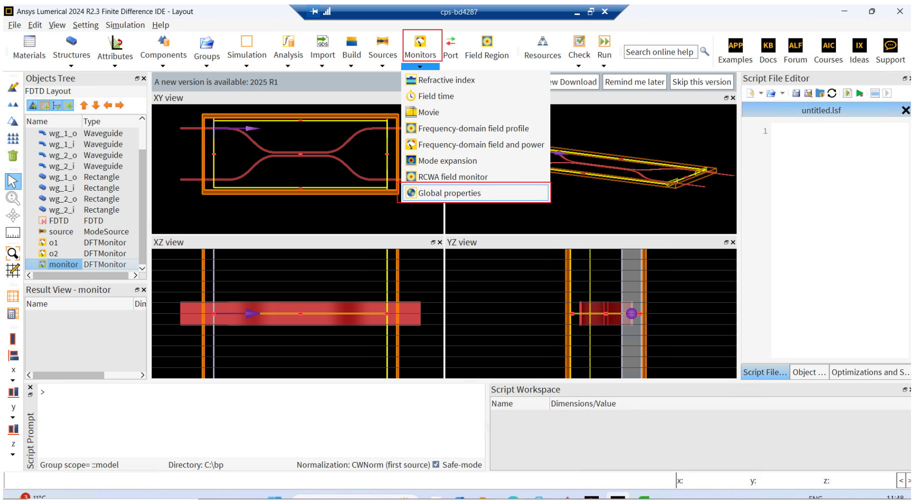


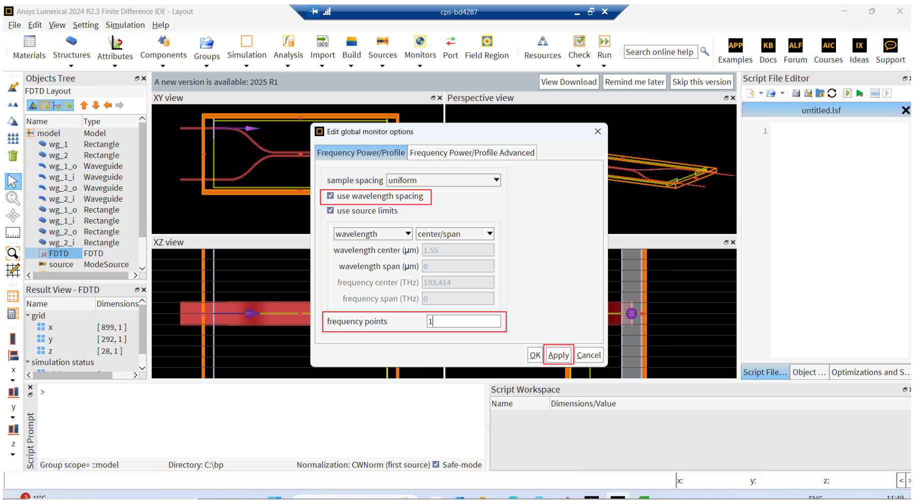
- Insert an additional **DFTMonitor** in the XY-plane to visualize electric field coupling clearly.



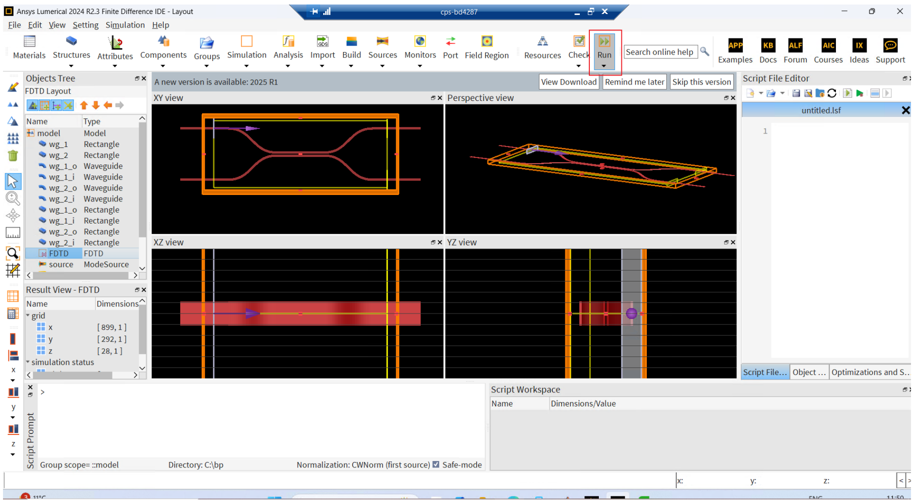


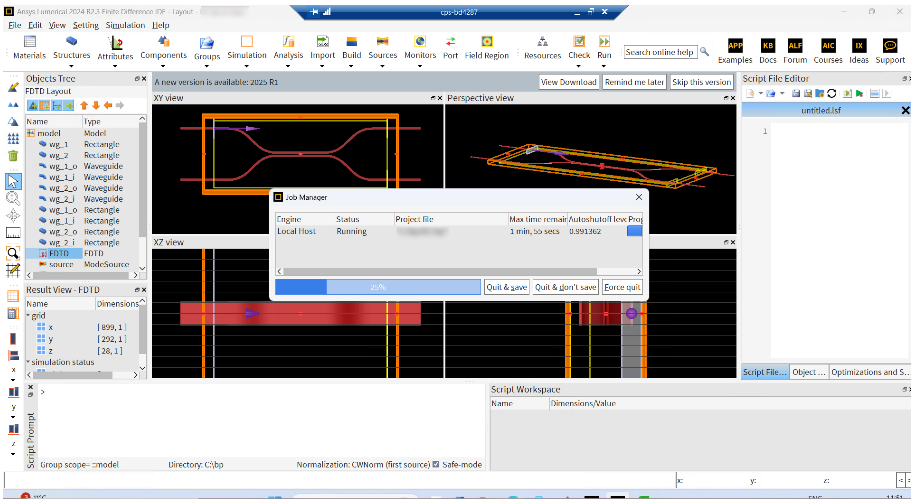
- Define the simulation bandwidth.



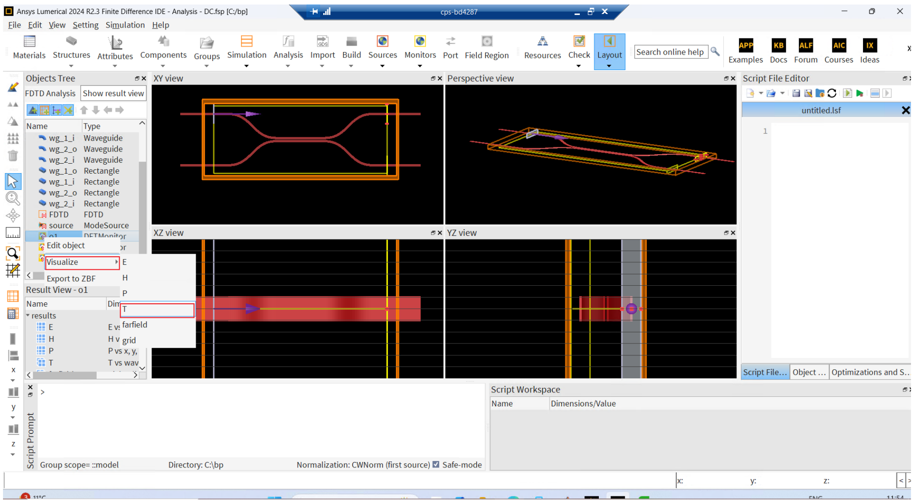


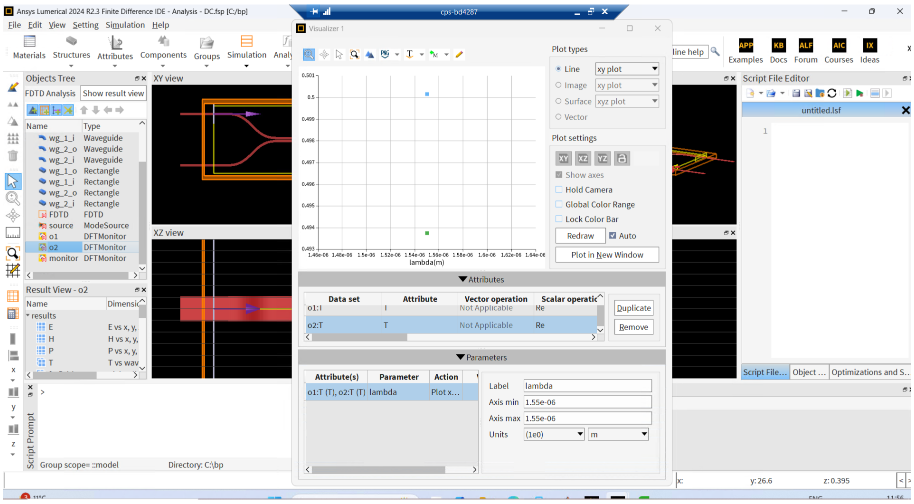
- Run the simulation.

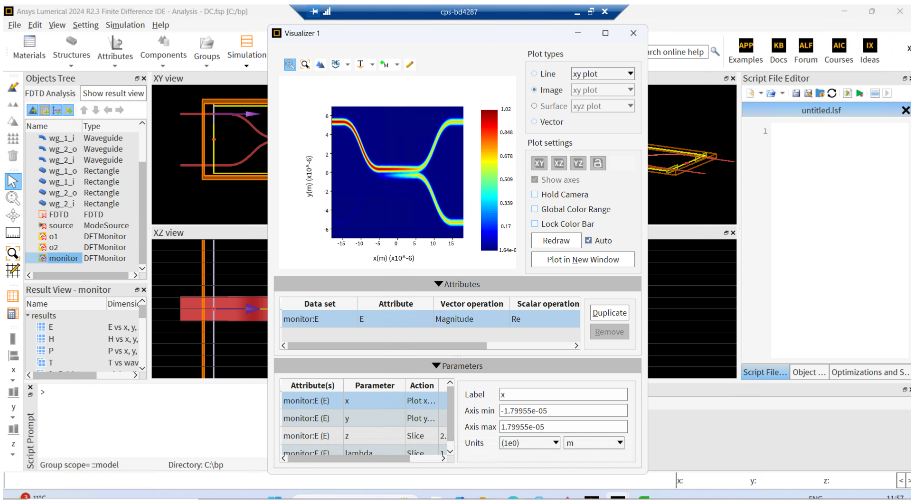




- Once finished, visualize the results.







Find the coupling length when approximately half/full optical power is transferred from one waveguide to the other. **[Include in your Report 3]**

Further explorations:

- Vary the waveguide width and the separation between them to study how these parameters affect the coupling strength. After modifying these parameters, make sure to update the geometry of the fan-in/out waveguides accordingly, and adjust the positions of the mode source and monitors as needed. For convenience, you can use Lumerical's scripting language (https://optics.ansys.com/hc/en-us/categories/360001998954-Scripting-Language) to define and modify objects such as Rectangles, Waveguides, FDTD regions, Mode Sources, and DFT Monitors. **[Include in your Report 3]**

- Based on your findings, design and optimize two directional couplers that achieve complete power transfer (>99%) of the fundamental TE_0 mode from one waveguide to the other (centred at 1550 nm). Start by selecting suitable waveguide widths and separations, then sweep the coupling length to maximize the transferred power. Note that, in practice, the minimum allowable gap between waveguides is typically 150 nm due to fabrication constraints. Note that in your simulation, make sure to set a wavelength range (rather than a single wavelength) to evaluate how dispersion influences the coupling performance across the operational bandwidth.
  Also, as an extension, briefly discuss how the coupler design would change if the platform were switched from SOI to other material systems such as SiN (e.g., consider the impact on device size and gap control). **[Include in your Report 3]**

- Try designing an asymmetric directional coupler, where the two coupled waveguides have different widths. Observe whether it is still possible to achieve 100% power transfer of the TE_0 mode between the waveguides in this case. Additionally, consider how to enable coupling between different mode orders in such an asymmetric structure — for example, from TE_0 to TE_1 — i.e., designing a mode order converter. (Hint: Since the effective index depends on the waveguide width and mode order, you can achieve index matching between different orders of modes by carefully adjusting the waveguide dimensions, thereby…) **[Include in your Report 3]**