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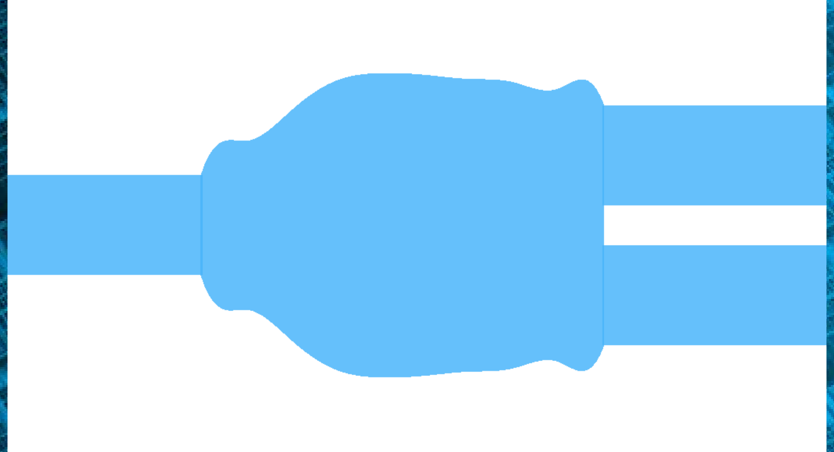
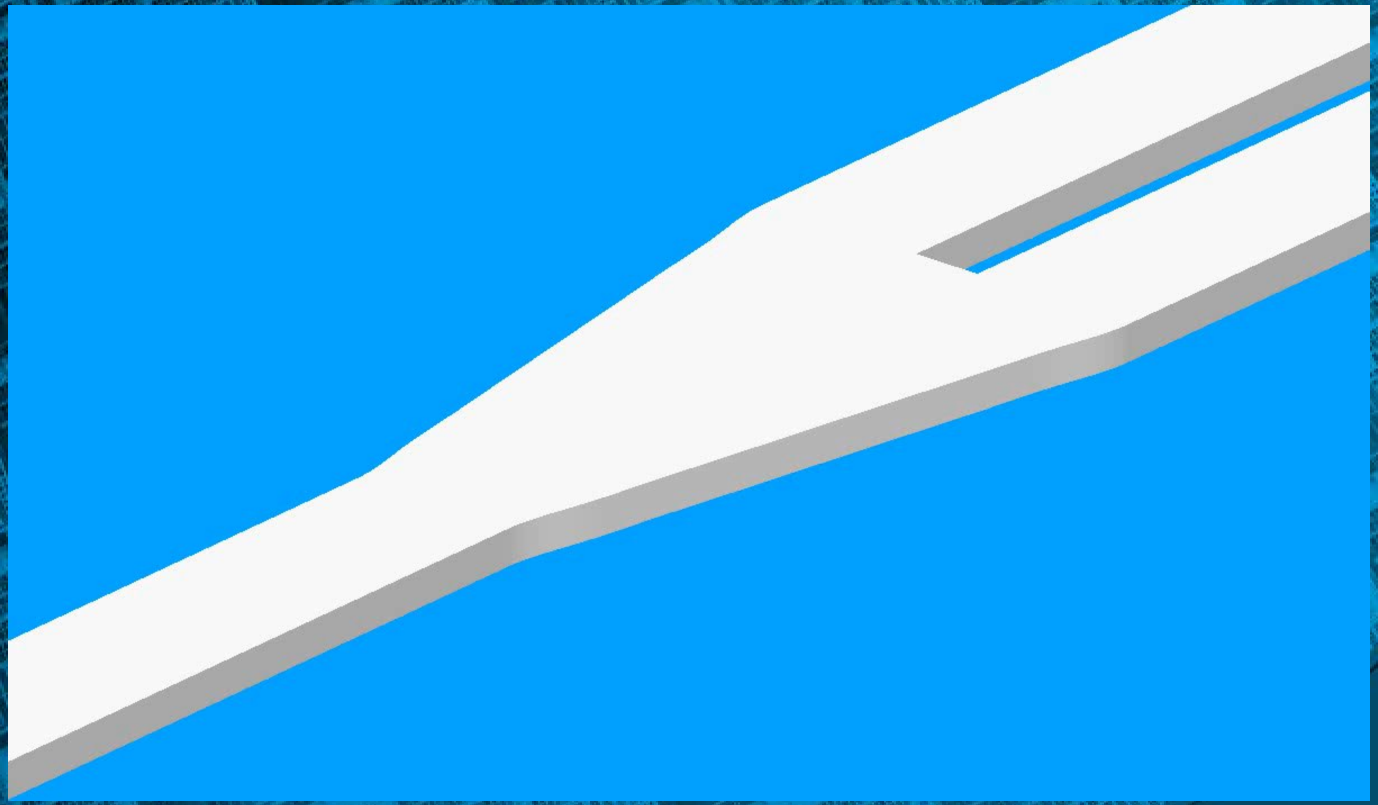
Photonic Inverse Design using the Adjoint Method





Adam Reid - Co-founder and VP Engineering

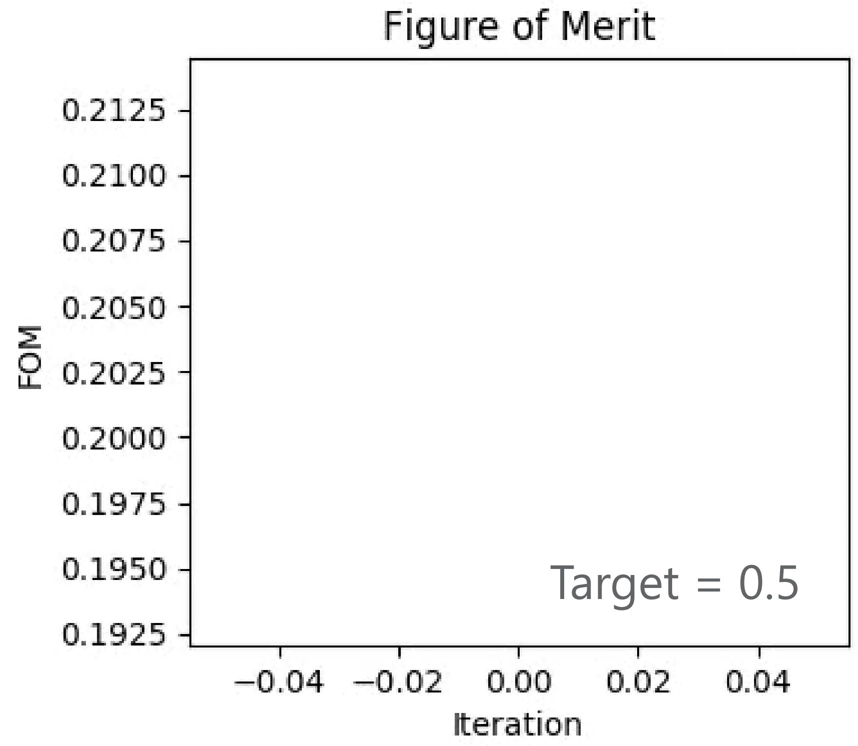
Lumerical Inc.
March 2, 2019

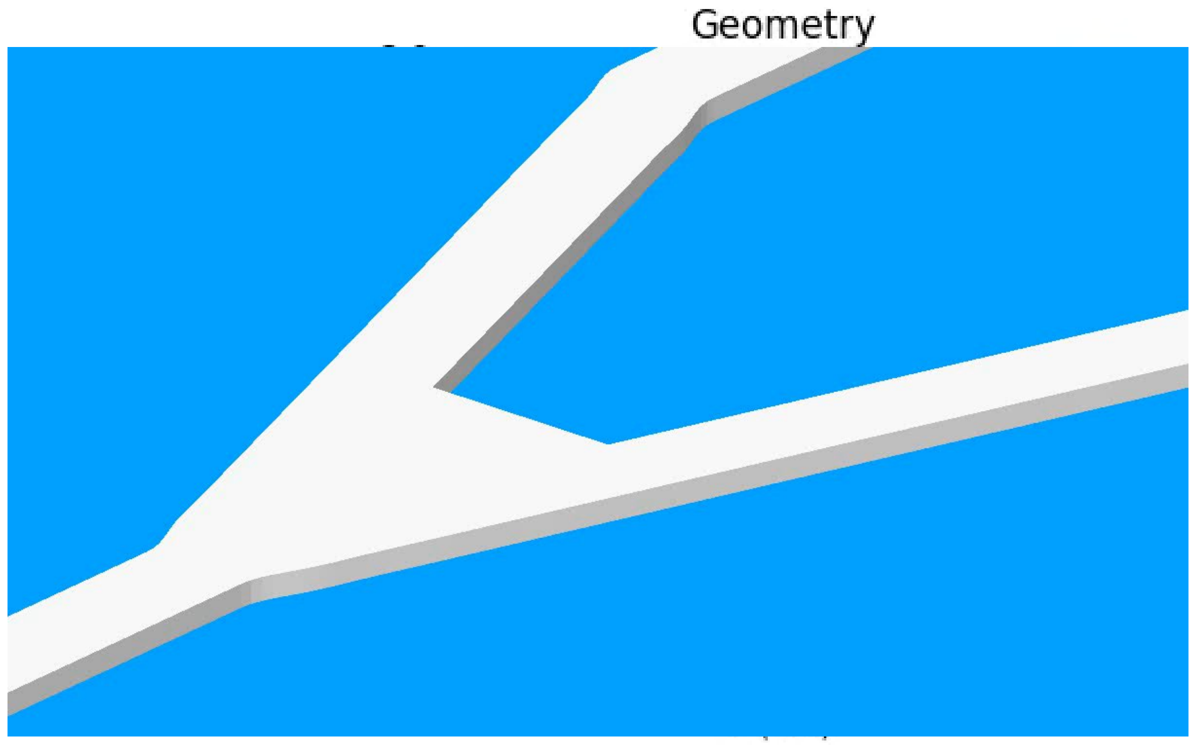
Photonic Inverse Design Using the Adjoint Method

See more @Booth 5438

+ Lumopt[1] Python module for adjoint sensitivity analysis
+ FDTD Solutions for 2D/3D simulation
+ SciPy gradient based optimization algorithms

= Highly efficient optimization of photonic components



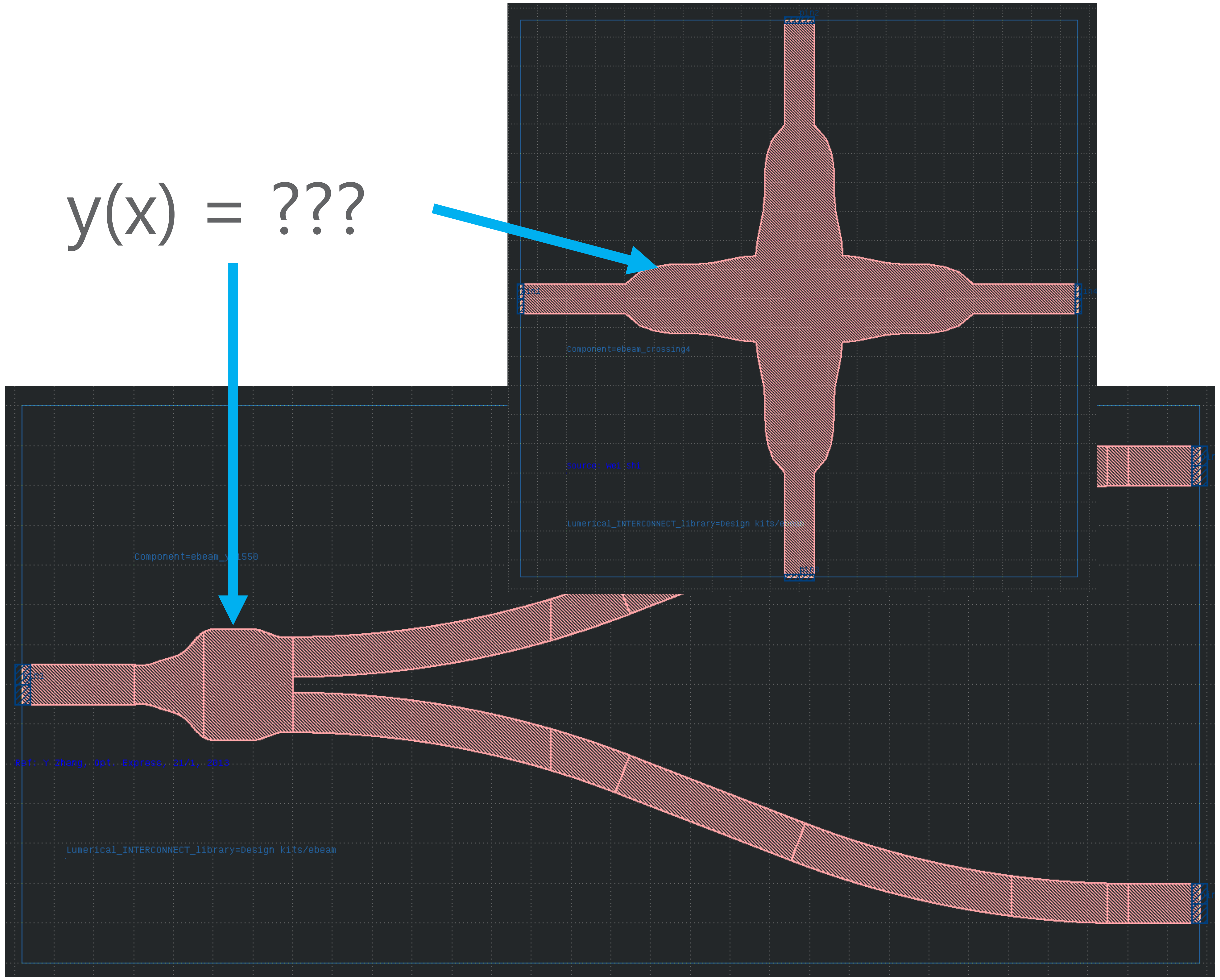


Try yourself: Examples and software

lumeri.ca/ofc

Motivation

- Component design challenging, even for basic components
- We would like a lot:
    - No reflections
    - No loss
    - Insensitive to manufacturing imperfections
    - Works for range of wavelengths
    - Works at different temperatures
- Usually no analytic solution
- Good solutions using PSO
    - Zhang, Y., Yang, S., Eu-Jin Lim, A., Lo, G-Q., Galland, C., Baehr-Jones, T., and Hochberg, M., "A compact and low loss Y-junction for submicron silicon waveguide," Optics Express 21, 1310-1316 (2013).
- Can we do better with adjoint methods?



https://github.com/lukasc-ubc/SiEPIC_EBeam_PDK

Lumerical's Suite of Simulation Tools for Photonics

Optical Simulation

FDTD Solutions
Nanophotonic Design Environment

MODE Solutions
Waveguide Design Environment

Multiphysics

DEVICE
Multiphysics Photonics Design Platform

- Charge Transport Solver
- Discontinuous Galerkin Time-Domain Solver
- Heat Transport Solver
- Finite Element Eigenmode Solver

Circuit & System

INTERCONNECT
PIC Design and Simulation Platform

- System Element Library Extension
- Laser Element Library Extension
- EDA Interoperability
- Foundry PDKs

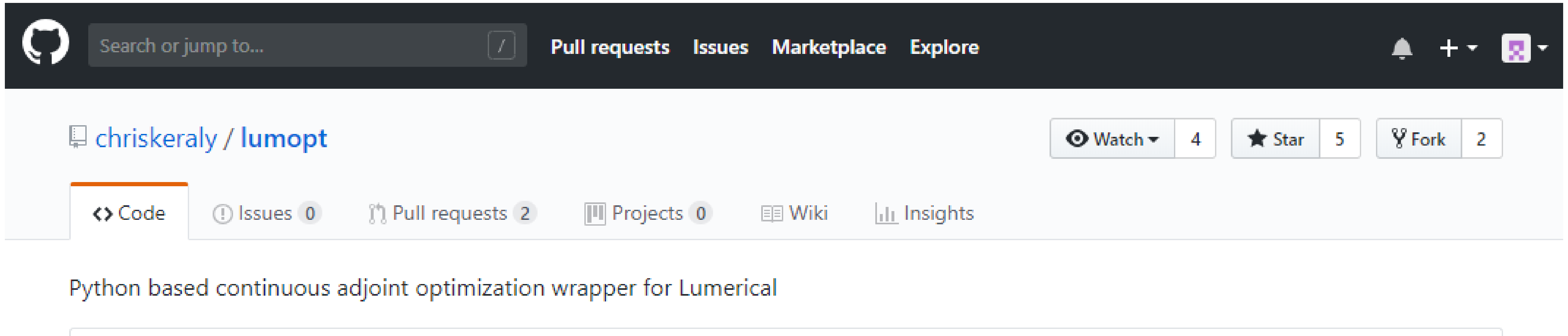
Data Exchange: Lumerical Scripting | MATLAB API | Python API

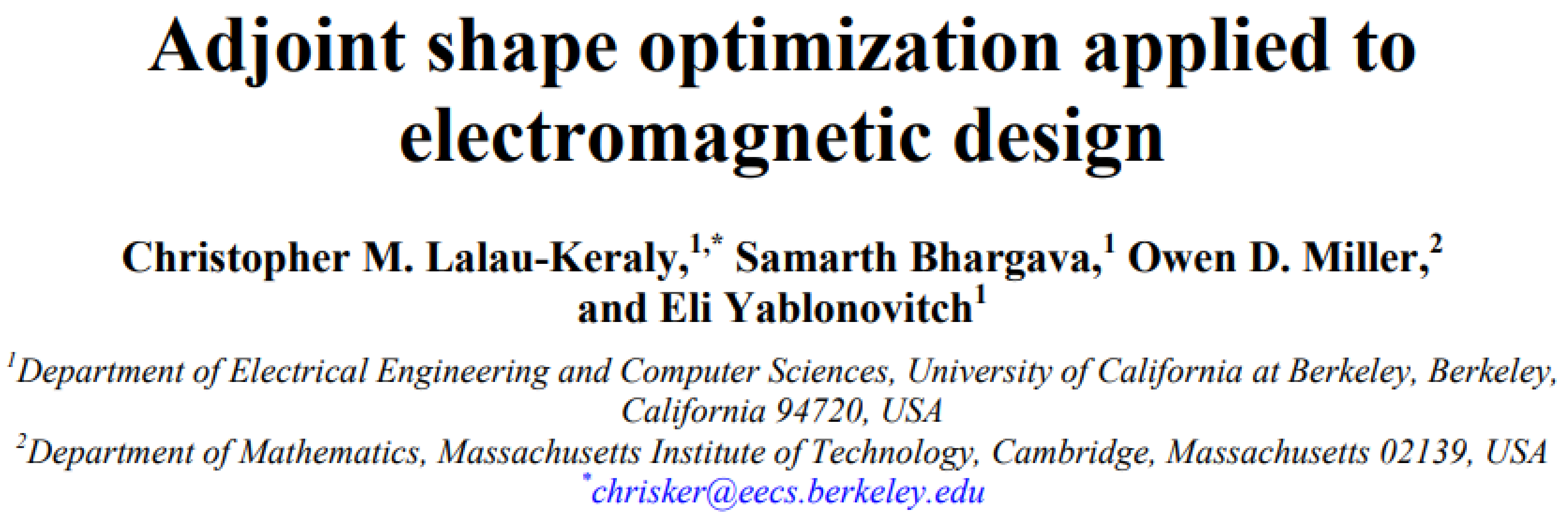
This demo uses FDTD simulation automated via Python API

Lumopt: Python Based Inverse Design for Lumerical FDTD

- Lumopt: open source adjoint sensitivity analysis
- Collaboration with Lumerical over past year
- Targets integrated photonics
- **Now included with FDTD Solutions**

https://github.com/chriskeraly/lumopt





Adjoint shape optimization applied to electromagnetic design

Christopher M. Lalau-Keraly,[1,*] Samarth Bhargava,[1] Owen D. Miller,[2] and Eli Yablonovitch[1]

[1]*Department of Electrical Engineering and Computer Sciences, University of California at Berkeley, Berkeley, California 94720, USA*

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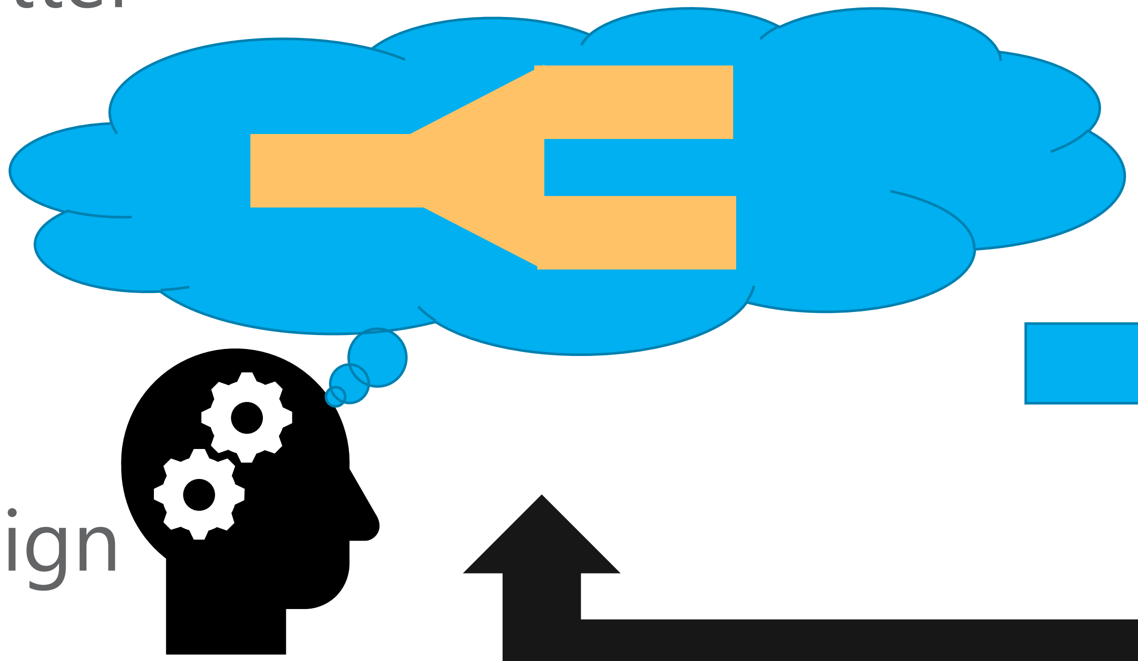
Optics Express, Vol 21, Issue 18, 2013
https://www.osapublishing.org/oe/abstract.cfm?uri=oe-21-18-21693

Inverse Design vs Forward Design

3dB Power Splitter



Traditional Design

FDTD Solutions
NANOPHOTONIC MAXWELL'S SOLVER

FOM
IL = 0.3dB

Costly Iterations

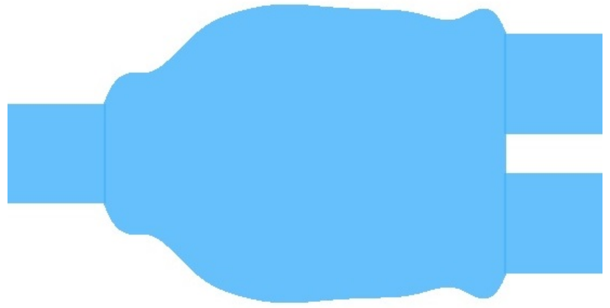
Inverse Design

FOM
IL = 0.1dB

Lumopt

FDTD Solutions
NANOPHOTONIC MAXWELL'S SOLVER

Adjoint optimization tool



Parametric Shape based adjoint optimization

Parametric shape

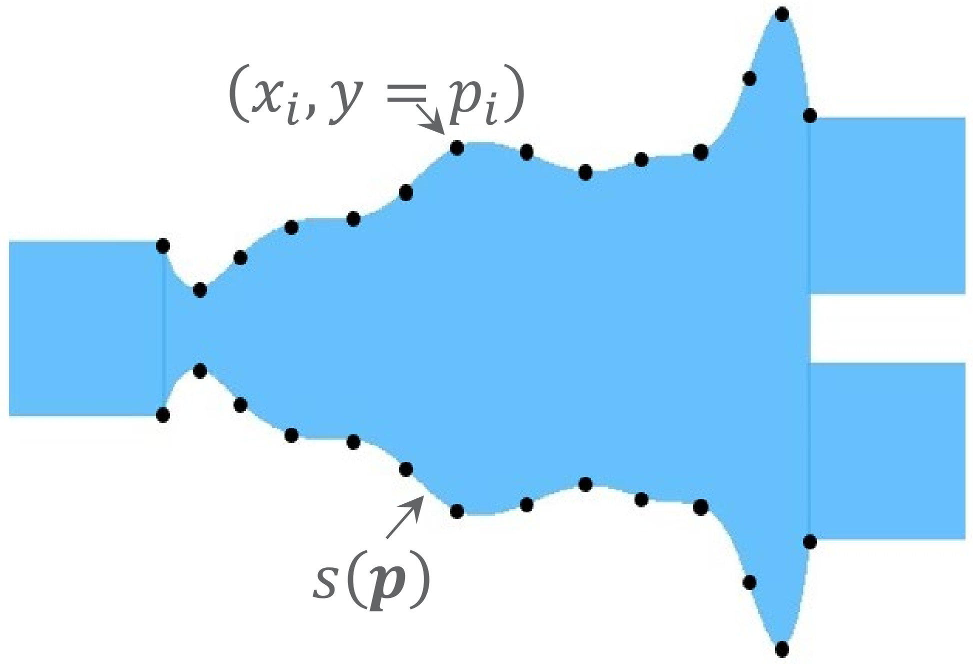
- Defines design space
- Optimization parameters

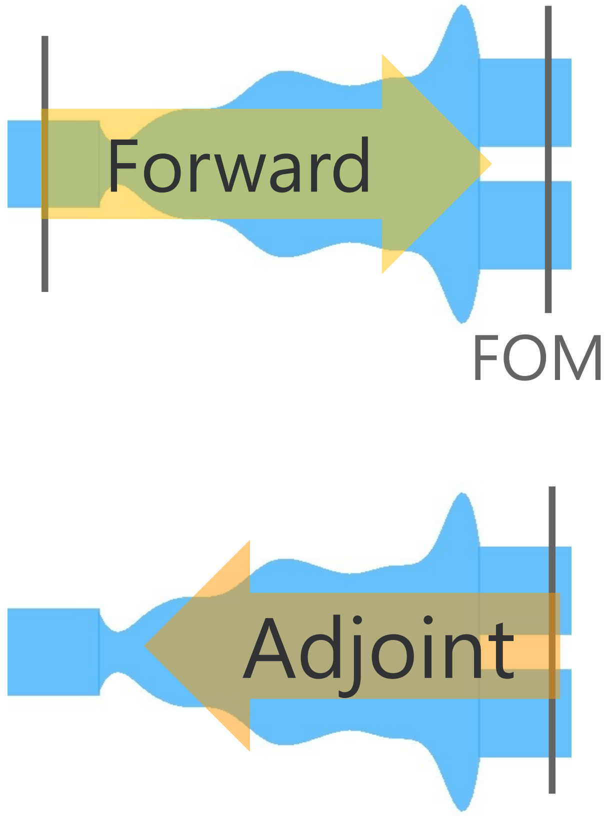
Adjoint sensitivity analysis

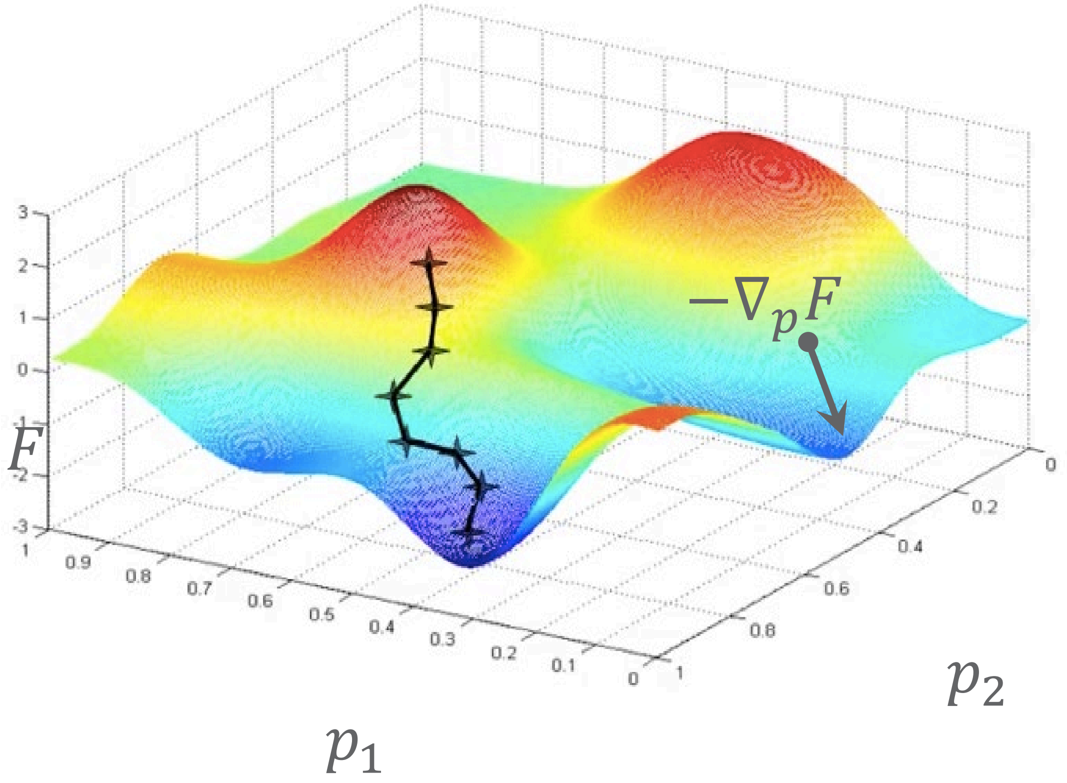
- Efficiently compute gradient
- 2 FDTD simulations
- Independent of # parameters

Gradient based optimization

- Highly efficient optimization
- Uses more physics of device







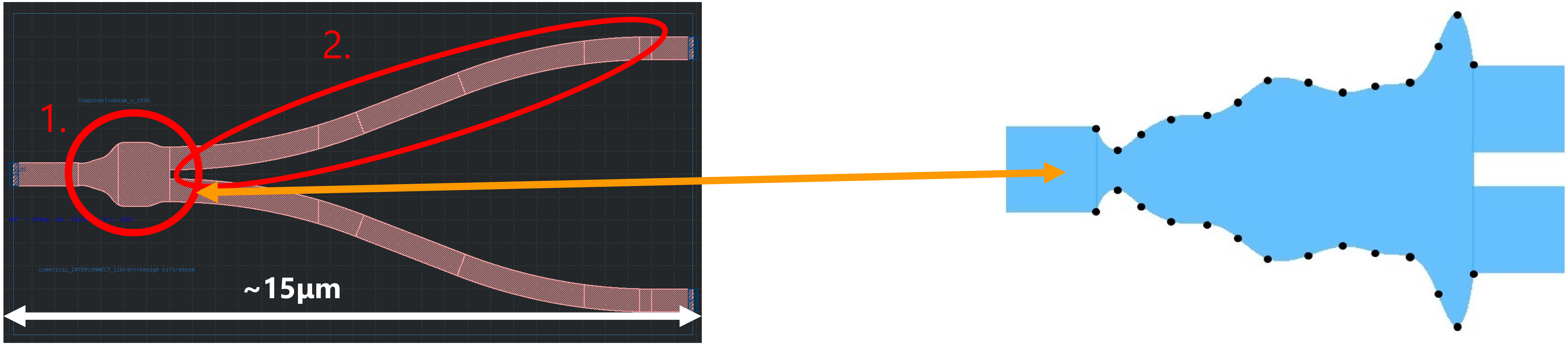
https://hackernoon.com/gradient-descent-aynk-7cbe95a778da

Example: Full component design flow for Y-Branch

Lumopt in Action

Full component design flow for Y-Branch

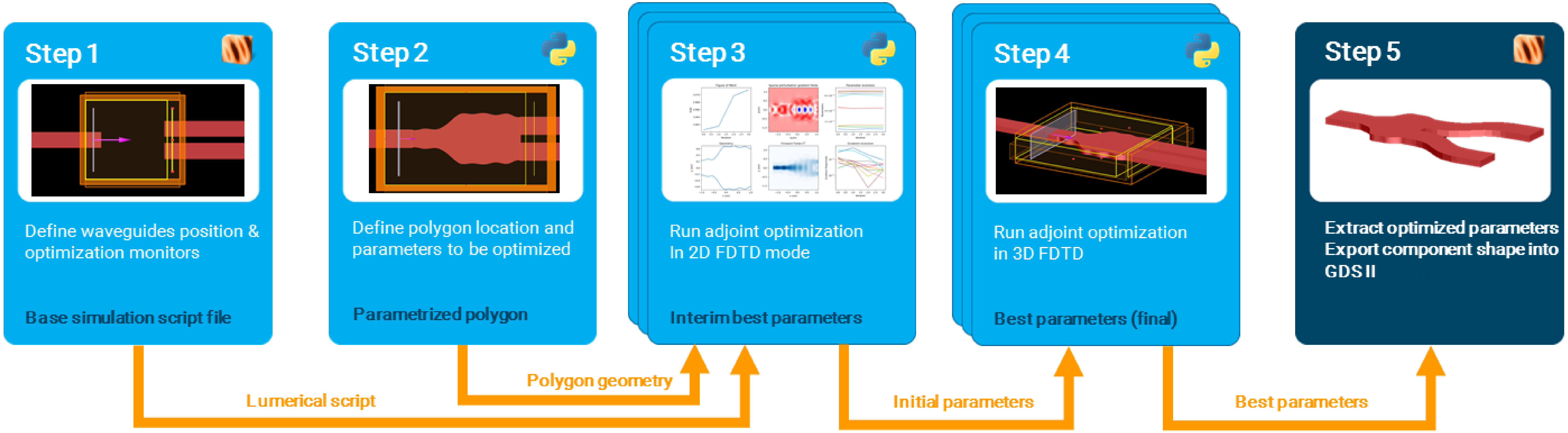
- Objective: build a splitter like prior art below
- Use inverse design to build splitter section (1)
- Add waveguide offset arms (2) post-optimization



https://github.com/lukasc-ubc/SiEPIC_EBeam_PDK

A compact and low loss Y-junction for submicron silicon waveguide
Yi Zhang, et al, Optics Express Vol. 21, Issue 1, pp. 1310-1316 (2013)

An Inverse Design Flow



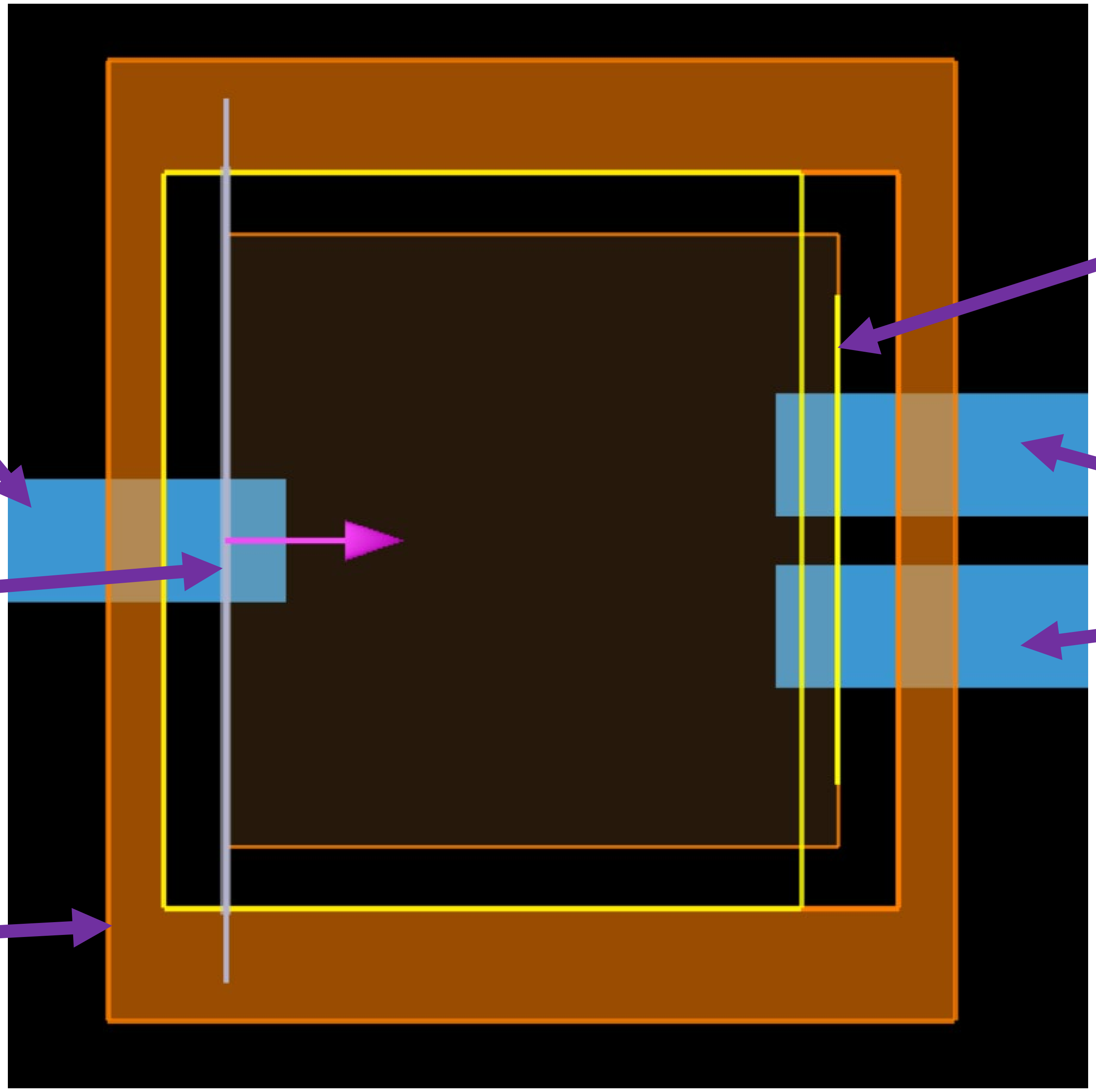
Step 1: Define base simulation

2D simulation
- Uses an effective index for waveguide
- Good approximation
- Fast simulation

Input waveguide

TE Source mode

FDTD simulation region



- Figure of merit measurement
- TE Mode

Output waveguides

Base simulation is defined by Lumerical Script (lsf)

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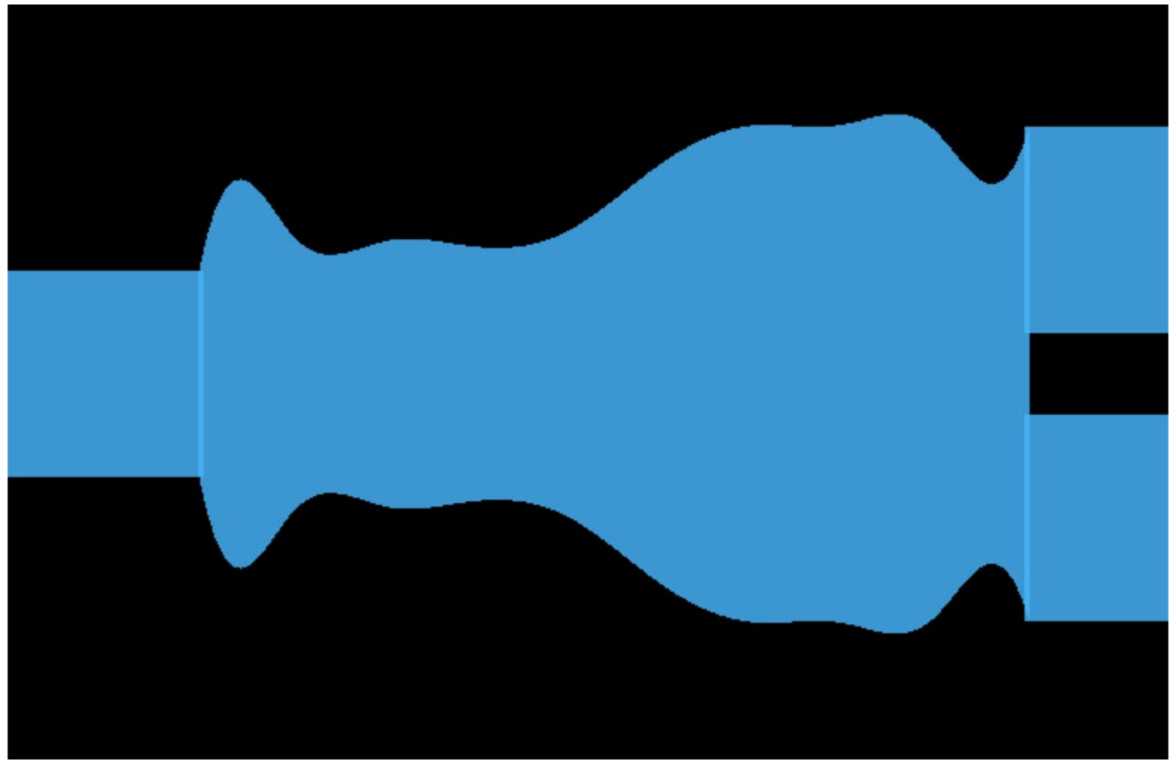
Step 2: Define parametric shape

- Parametric shape defined as Python function
- Function argument is list of parameters
- Function returns list of polygon vertices

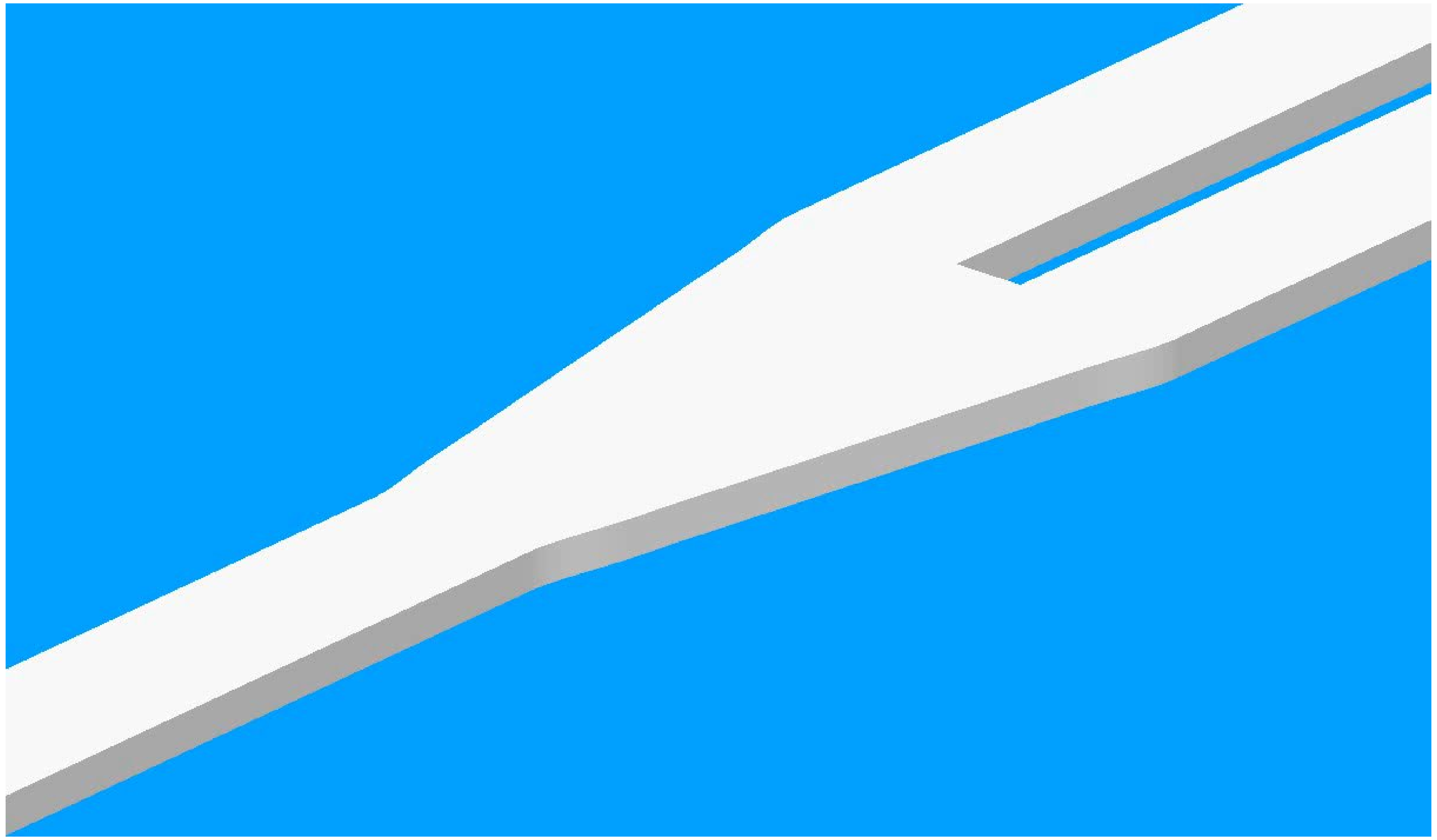


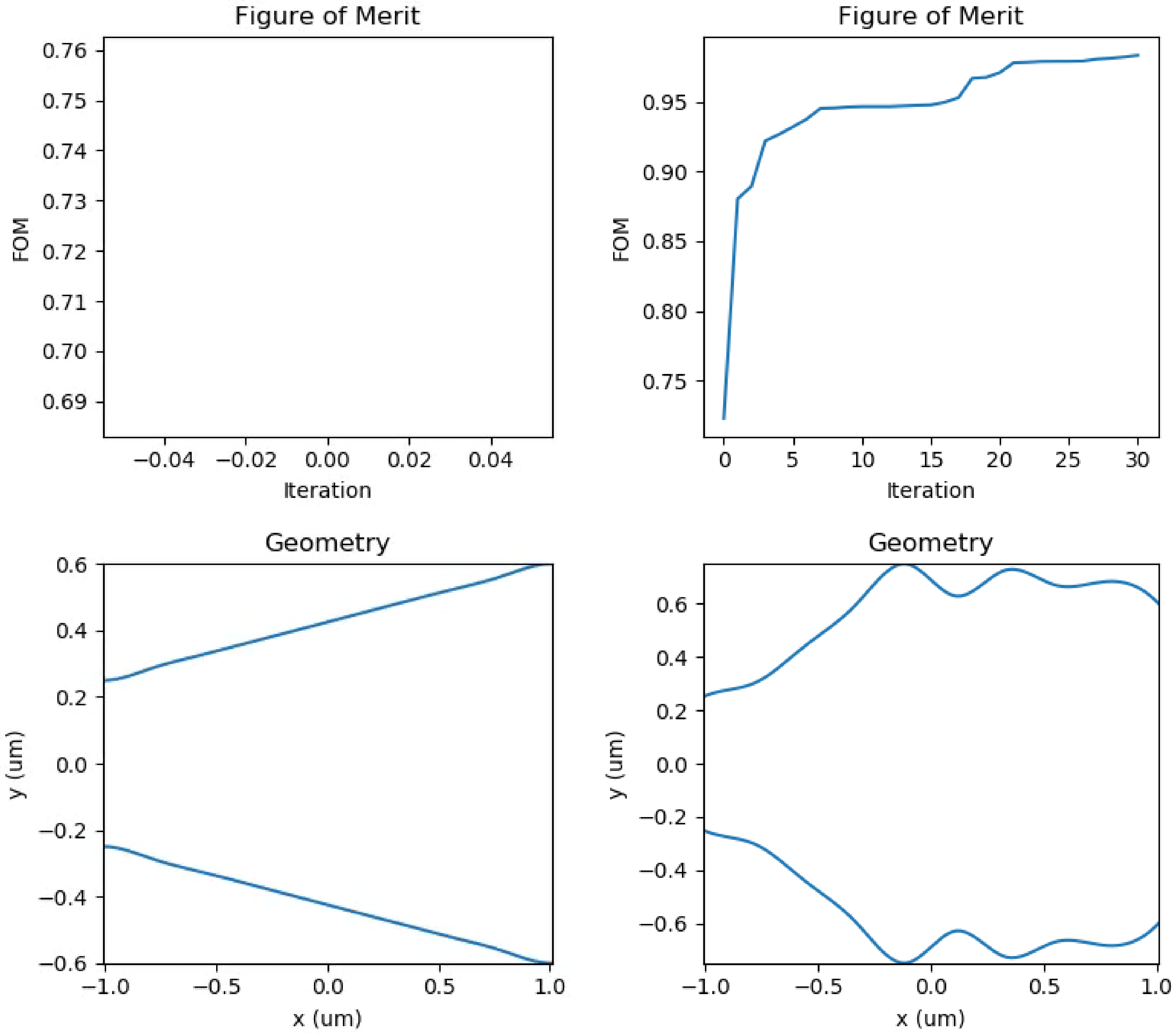
```
def taper_splitter(params = np.linspace(0.25e-6, 2e-6, 20)):
    ''' Defines a taper where the paramaters are the y coordinates of the nodes of a cubic
    points_x = np.concatenate(([-2.51e-6], np.linspace(-2.5e-6,2.5e-6,20), [2.51e-6]))
    points_y = np.concatenate(([0.25e-6], params, [2e-6]))
    n_interpolation_points = 100
    px = np.linspace(min(points_x), max(points_x), n_interpolation_points)
    interpolator = sp.interpolate.interp1d(points_x, points_y, kind = 'cubic')
    py = interpolator(px)
    py = np.minimum(2.5e-6, py)
    py = np.maximum(np.concatenate((np.ones(50)*0.2e-6, np.ones(50)*0.53e-6)), py)

    px = np.concatenate((px, px[40::][::-1]))
    py = np.concatenate((py, py[40::][::-1]-0.5e-6))
    polygon_points_up = [(x, y) for x, y in zip(px, py)]
    polygon_points_down = [(x, -y) for x, y in zip(px, py)]
    polygon_points = np.array(polygon_points_up[::-1] + polygon_points_down)
    return polygon_points
```

Step 3: Run fast 2D optimization

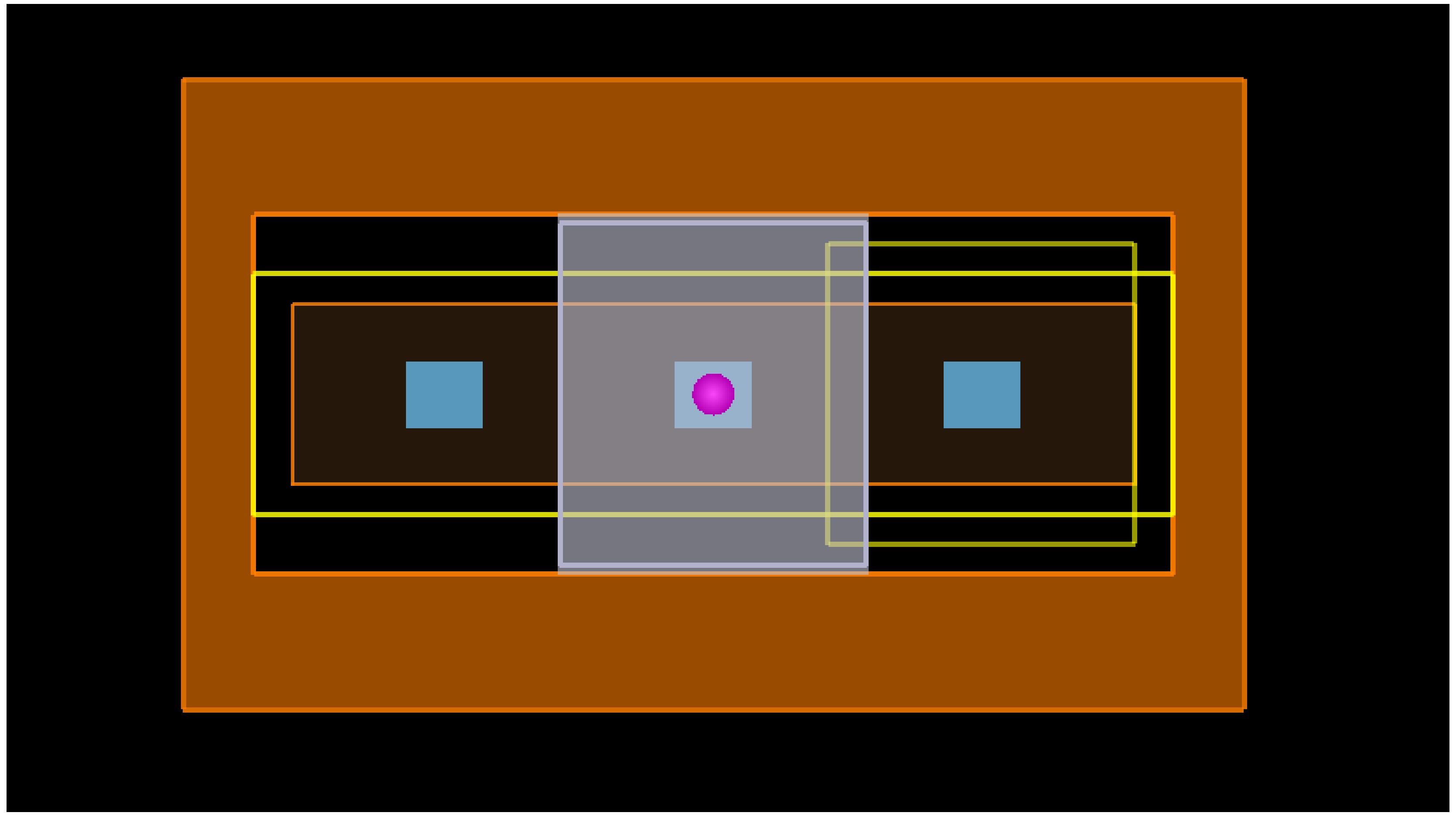
This optimization runs in 20-30 minutes

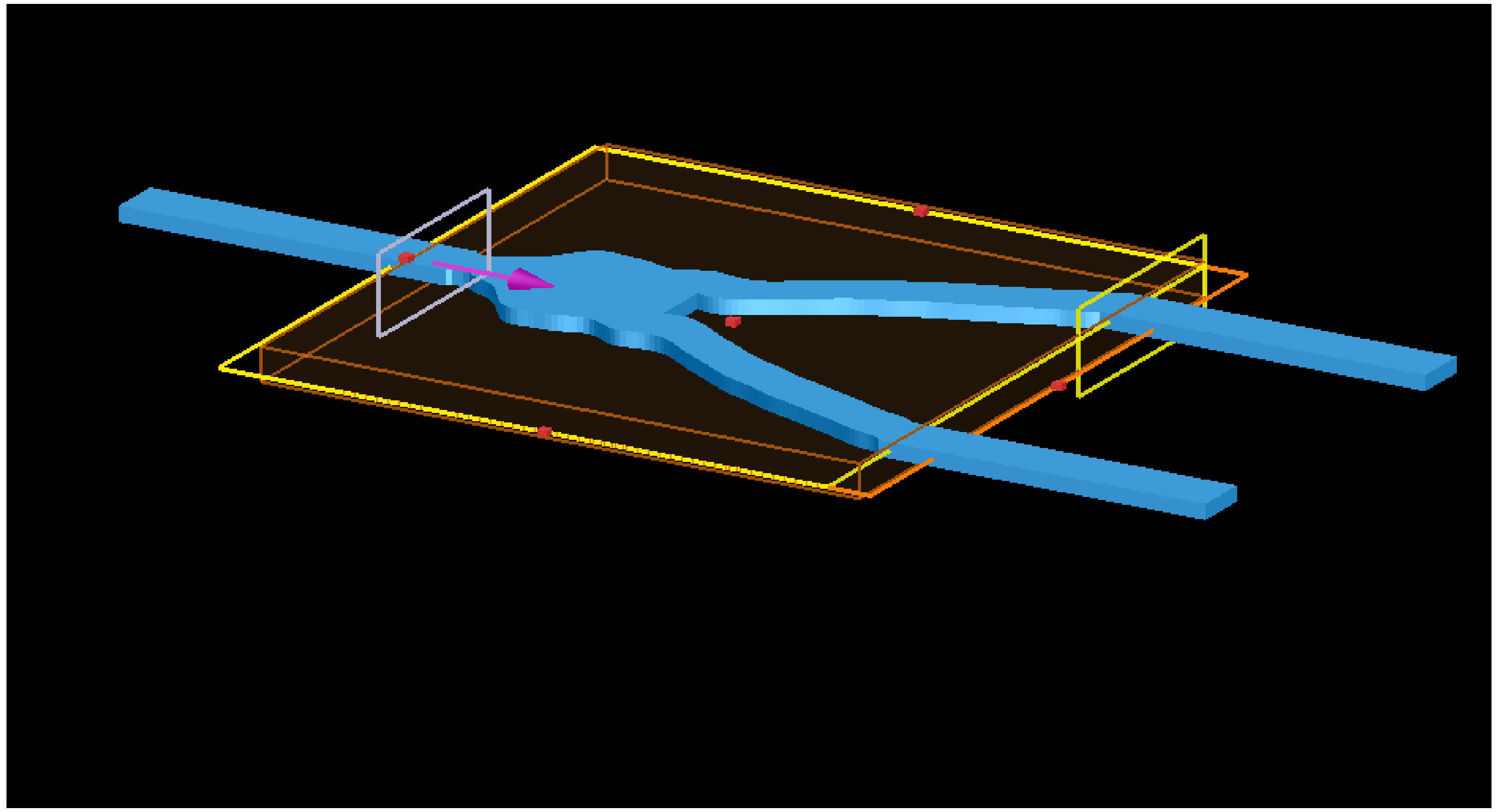




Step 4: Refine with 3D optimization

- This step is largely the same as 2D simulation
- Takes a bit longer to run
- Should complete with few iterations if **seeded with 2D solution**

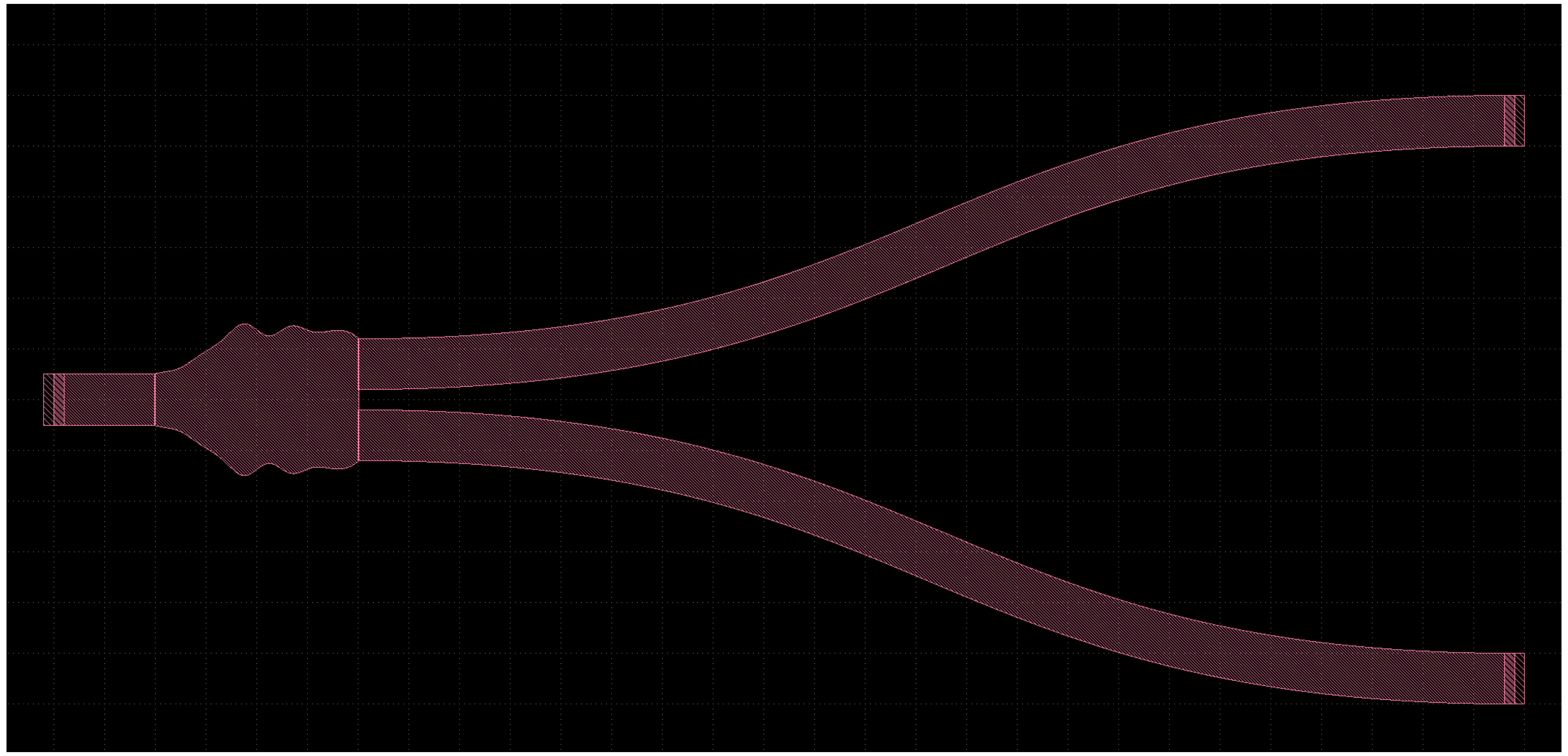




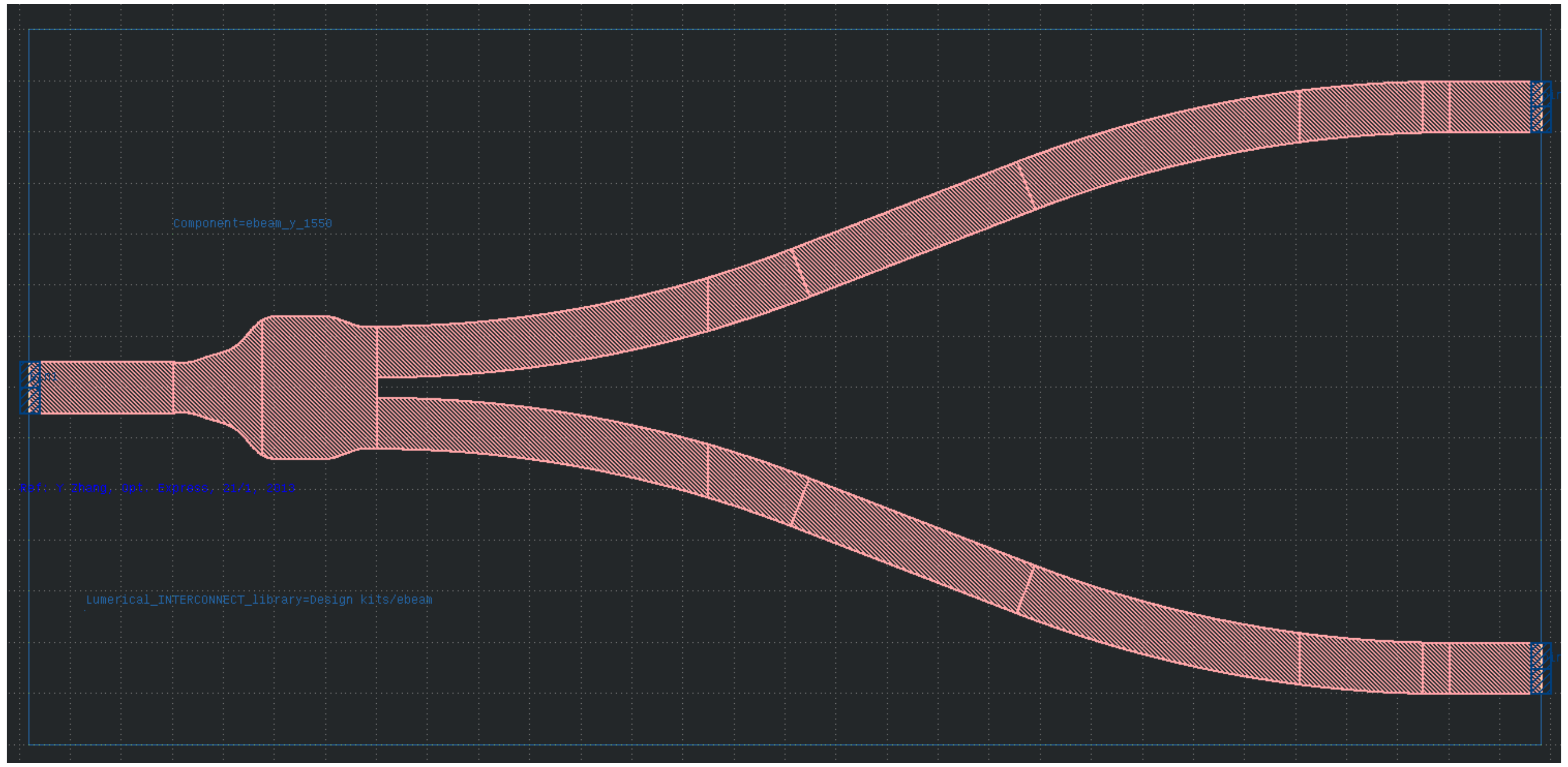
Step 5: Save design to GDSII

- Optimized shape and output arms saved to GDSII
- Similar to prior art, but has a few ripples!

Example design



Prior art



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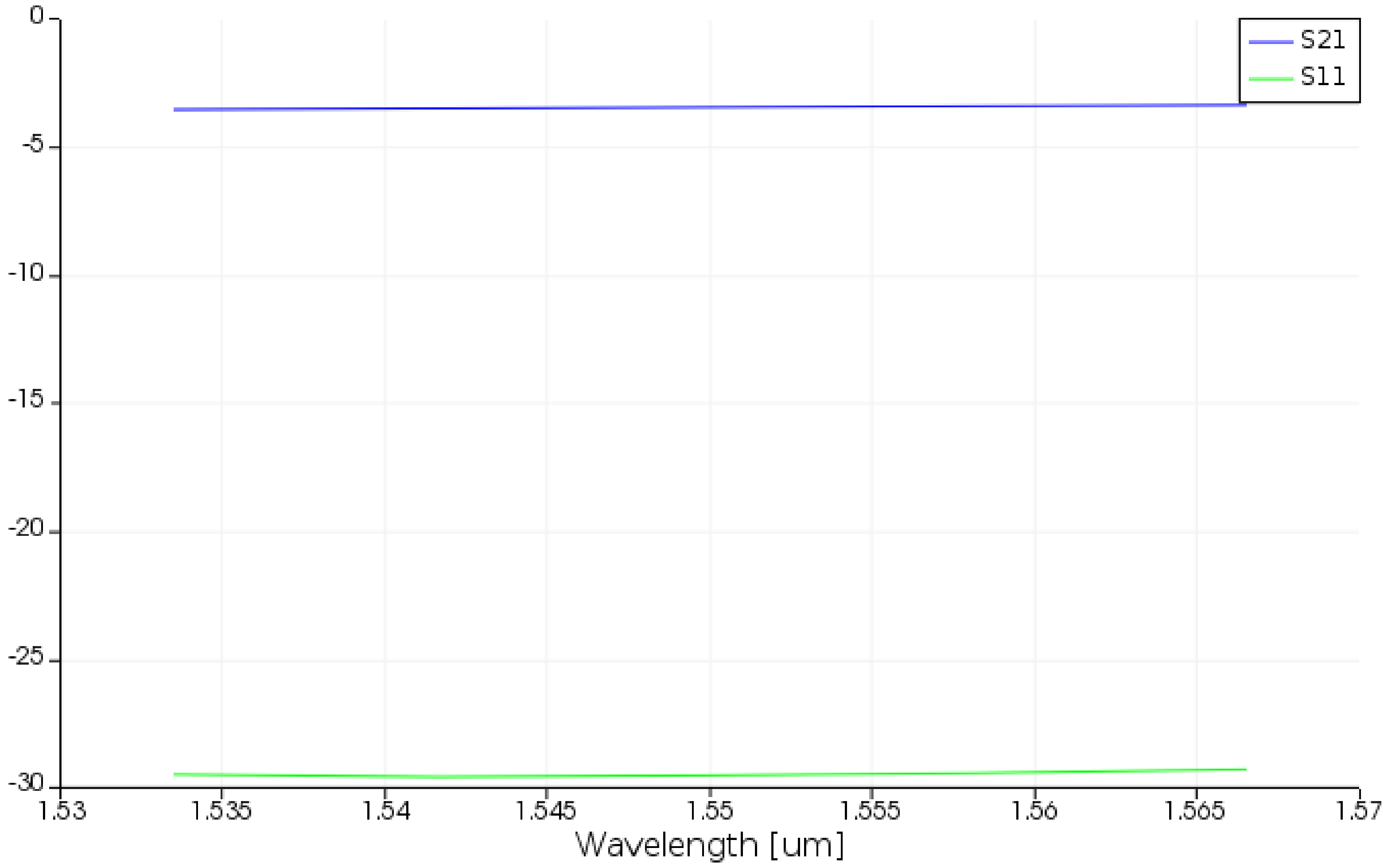
Step 5: Y splitter example: Compact model extraction from layout

- Import the final GDSII mask into 3D simulation
- Define ports
- Extract the S-parameters
- Save to data file for INTERCONNECT circuit simulation



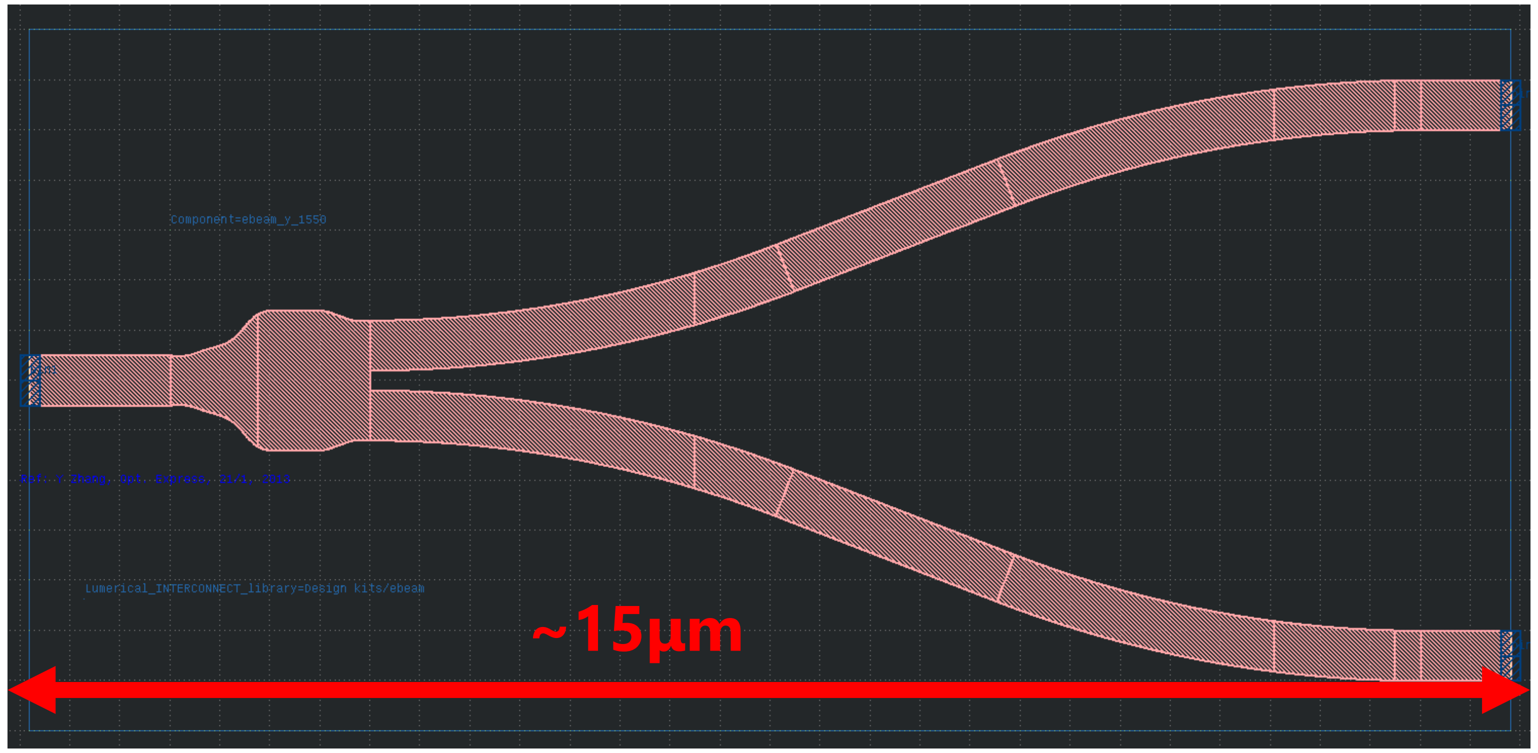
Example: Broadband & Compact Y-Branch

Lumopt in Action

Broadband & Compact Splitter

- Can we make a smaller splitter?
- Can we ensure broadband?

- Parametric shape with output waveguides, 20 parameters
- 5x5 footprint footprint
- FOM taken over C+L bands



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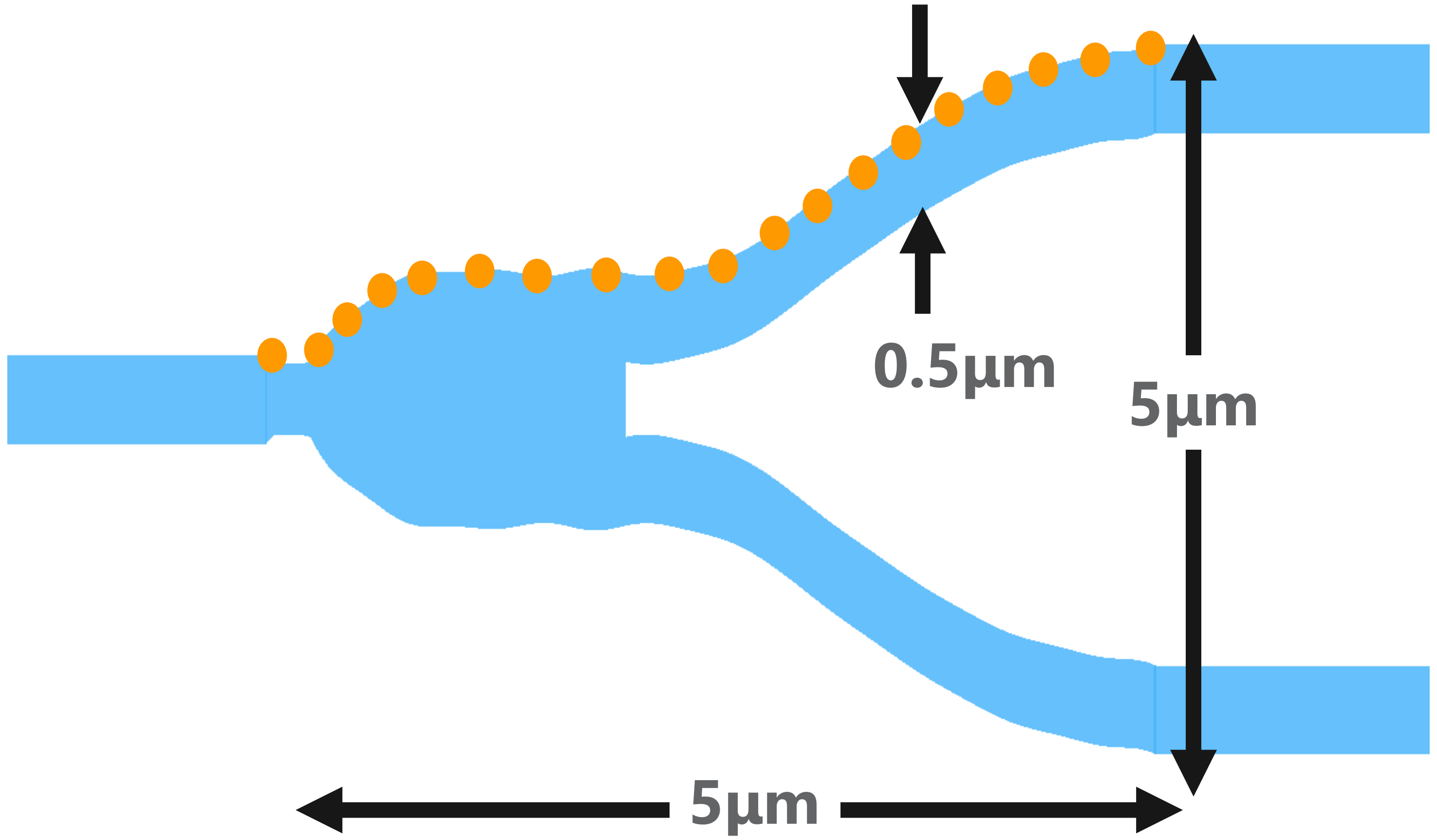

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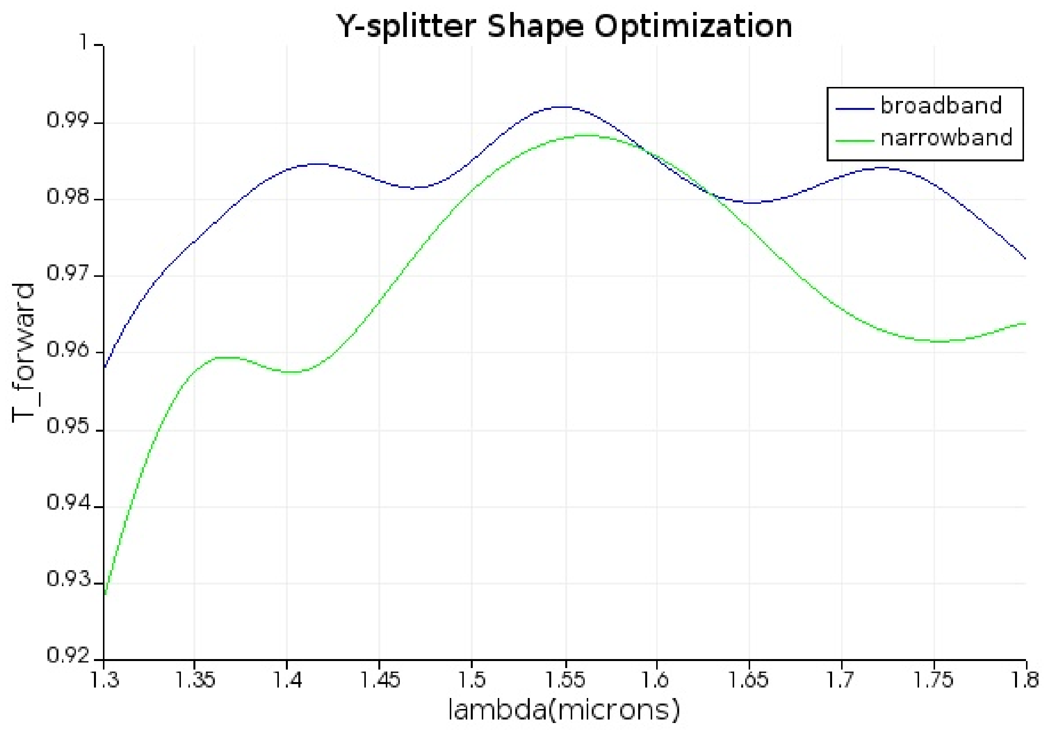
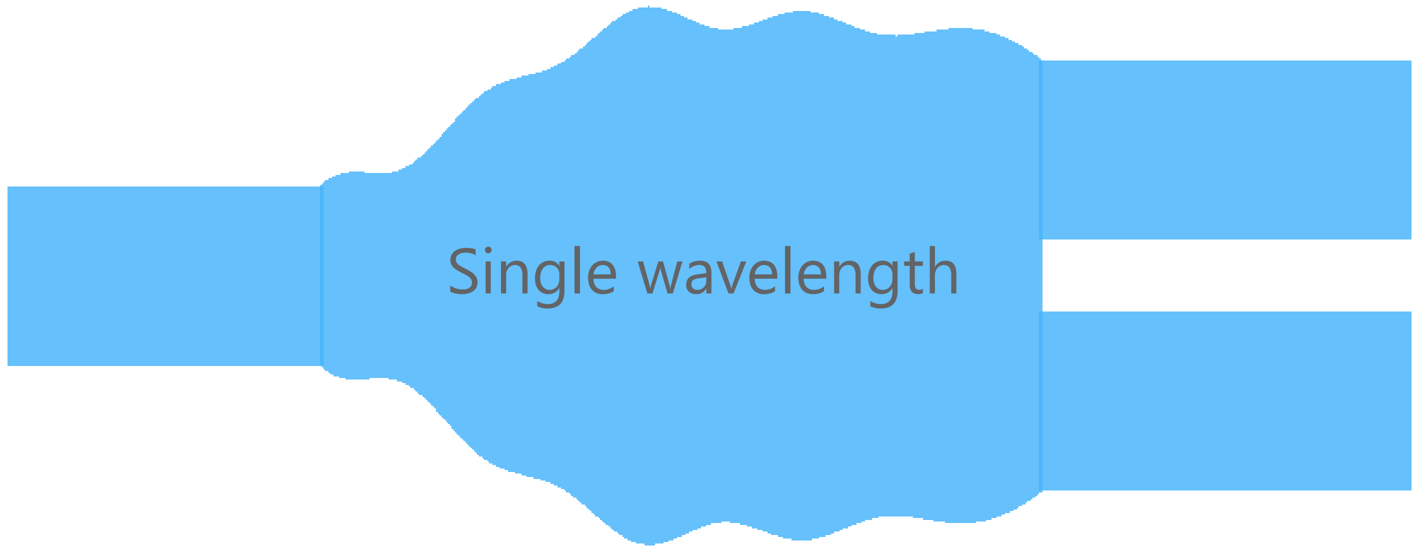
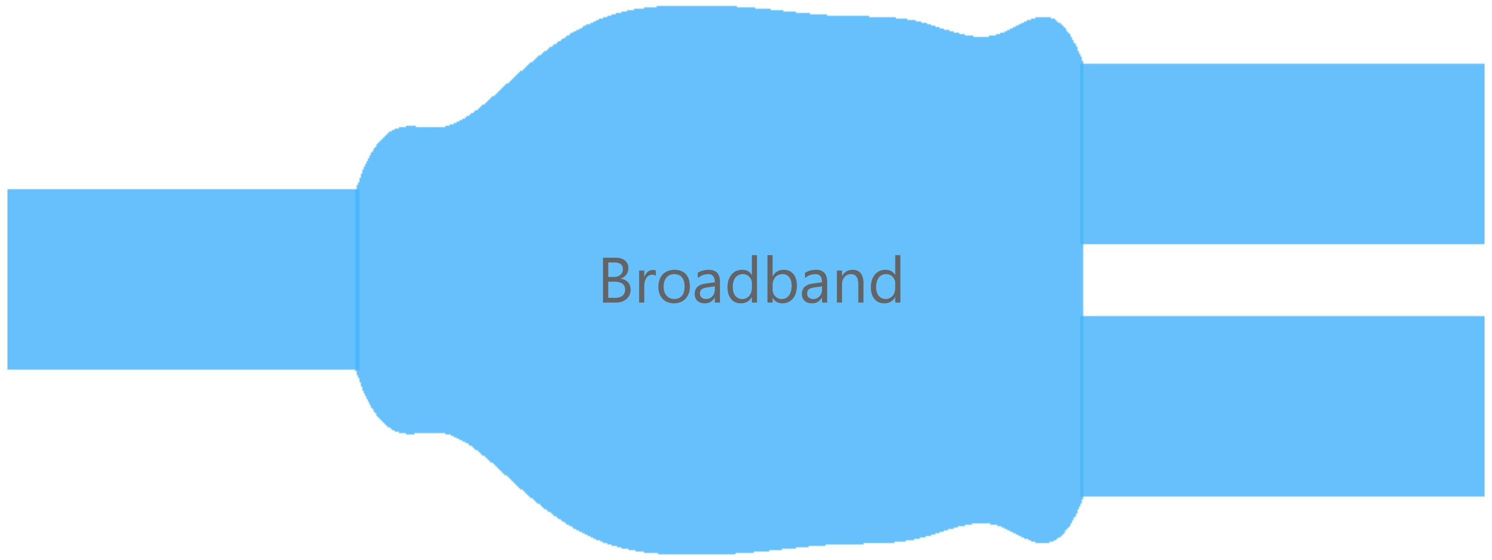
Broadband Inverse Design

- Optimize FOM over a spectrum
- No additional FDTD simulations required!

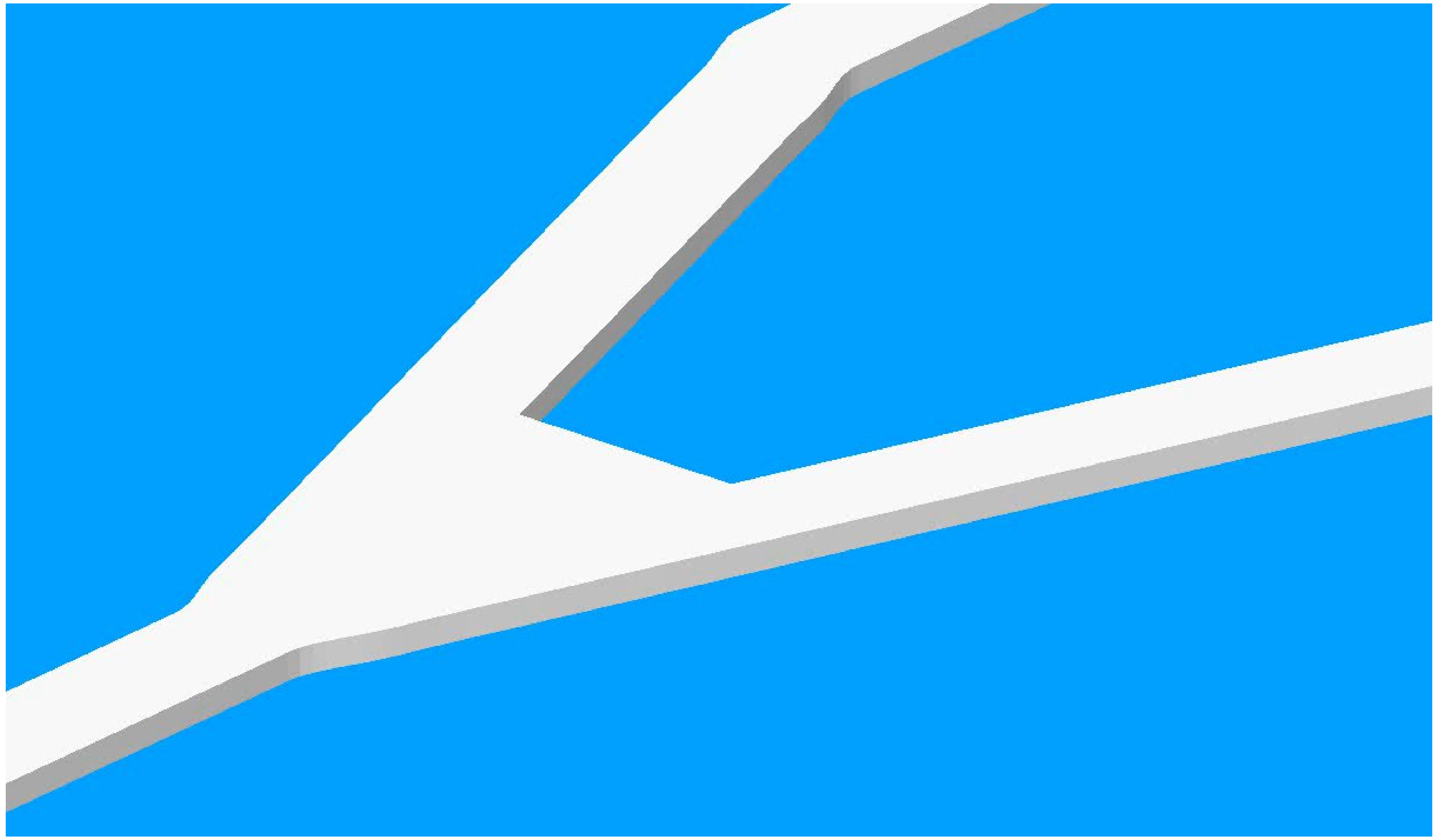




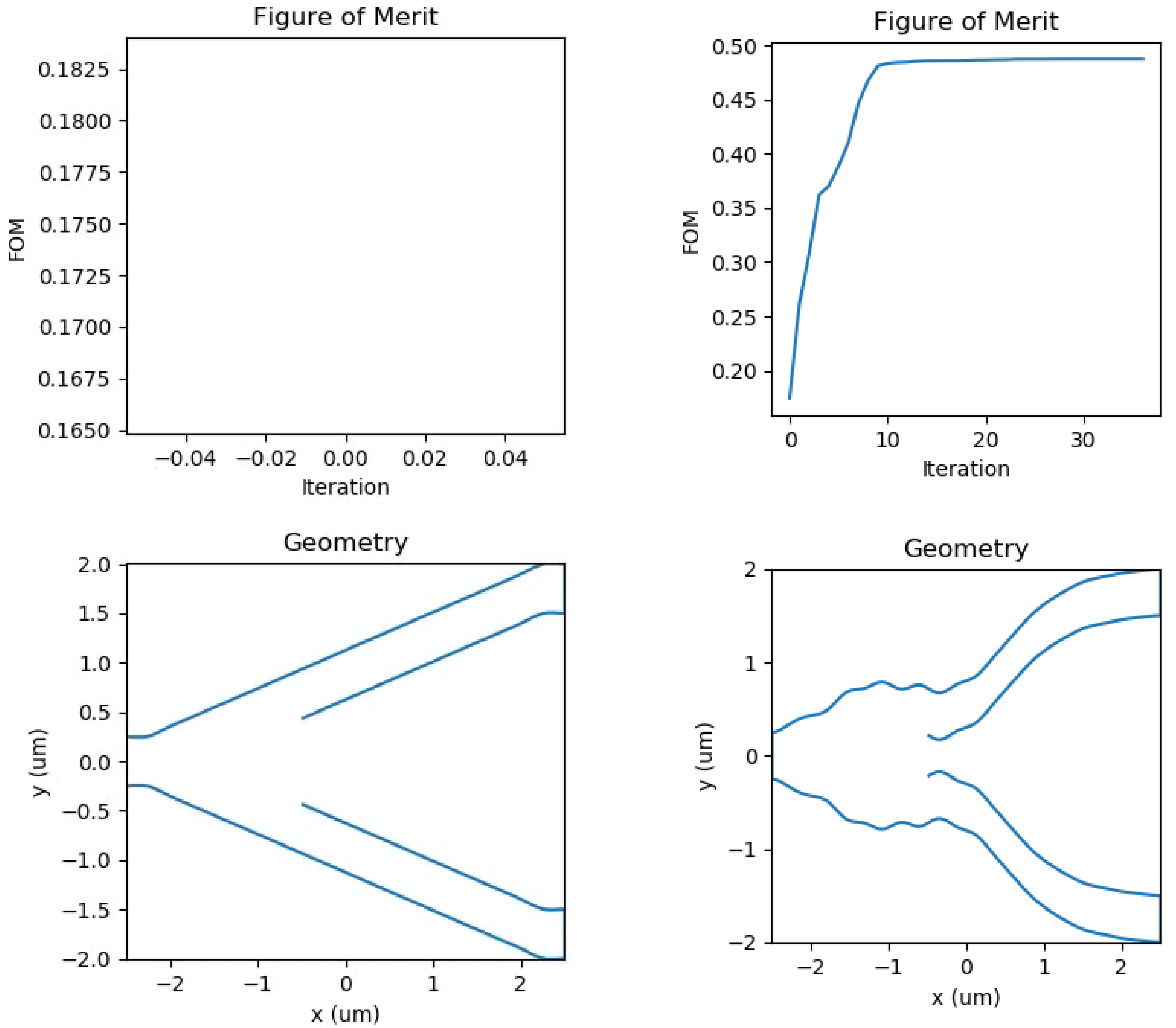


Step 3: Run fast 2D optimization

This example takes ~60 minutes to run:



FOM = 0.5 = ideal



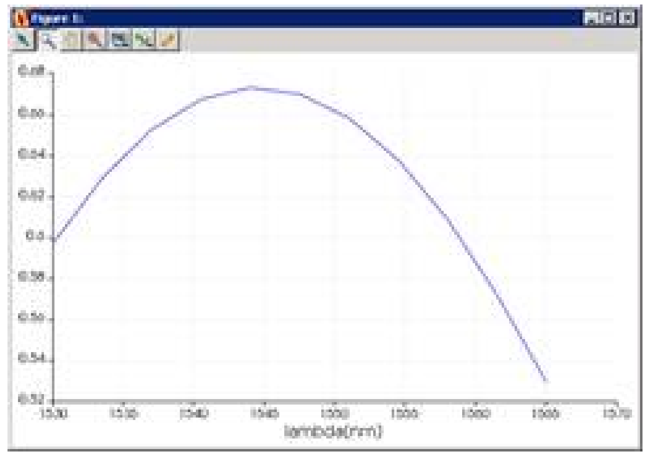
Example: Grating coupler

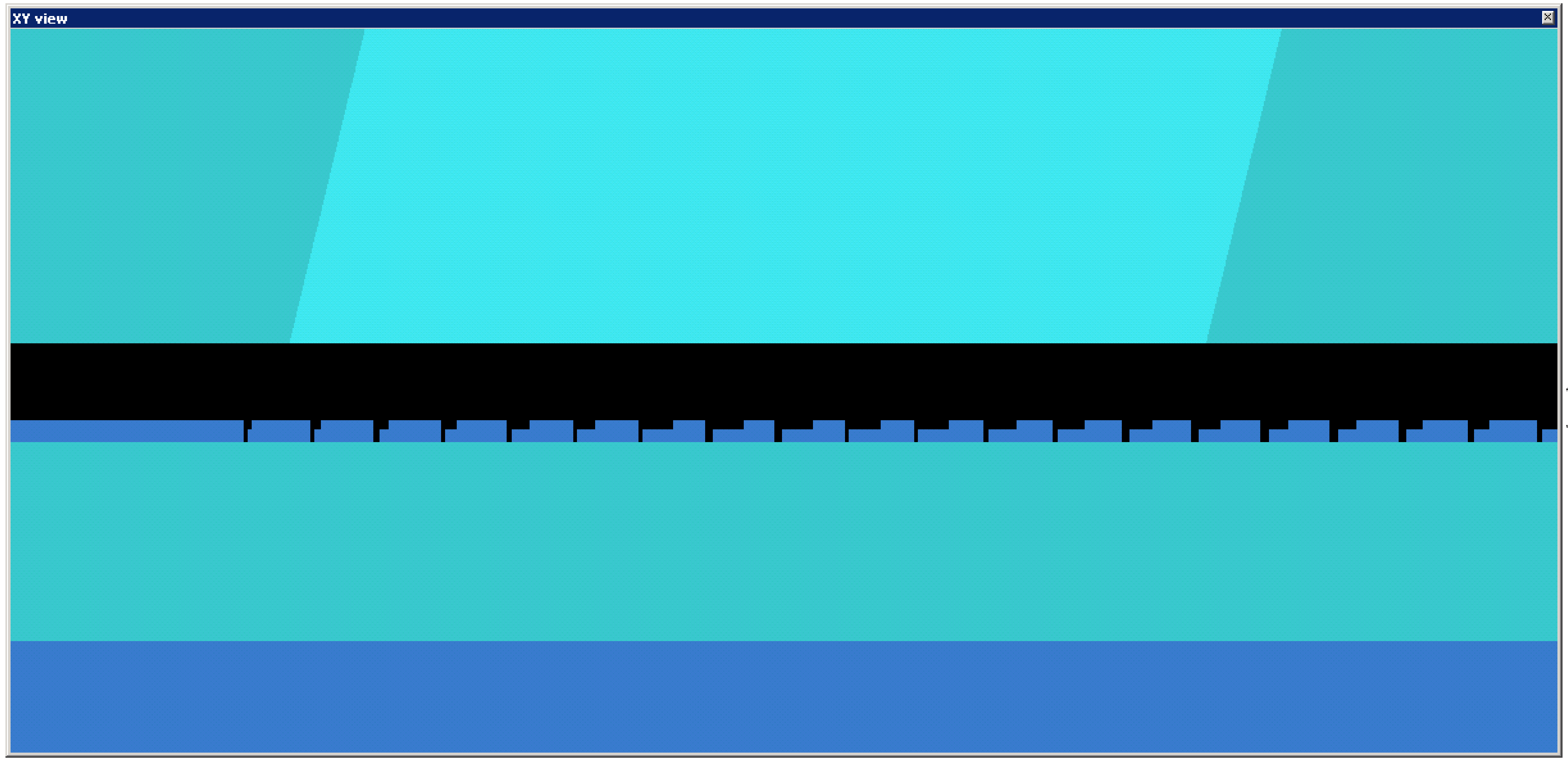
Available soon!!

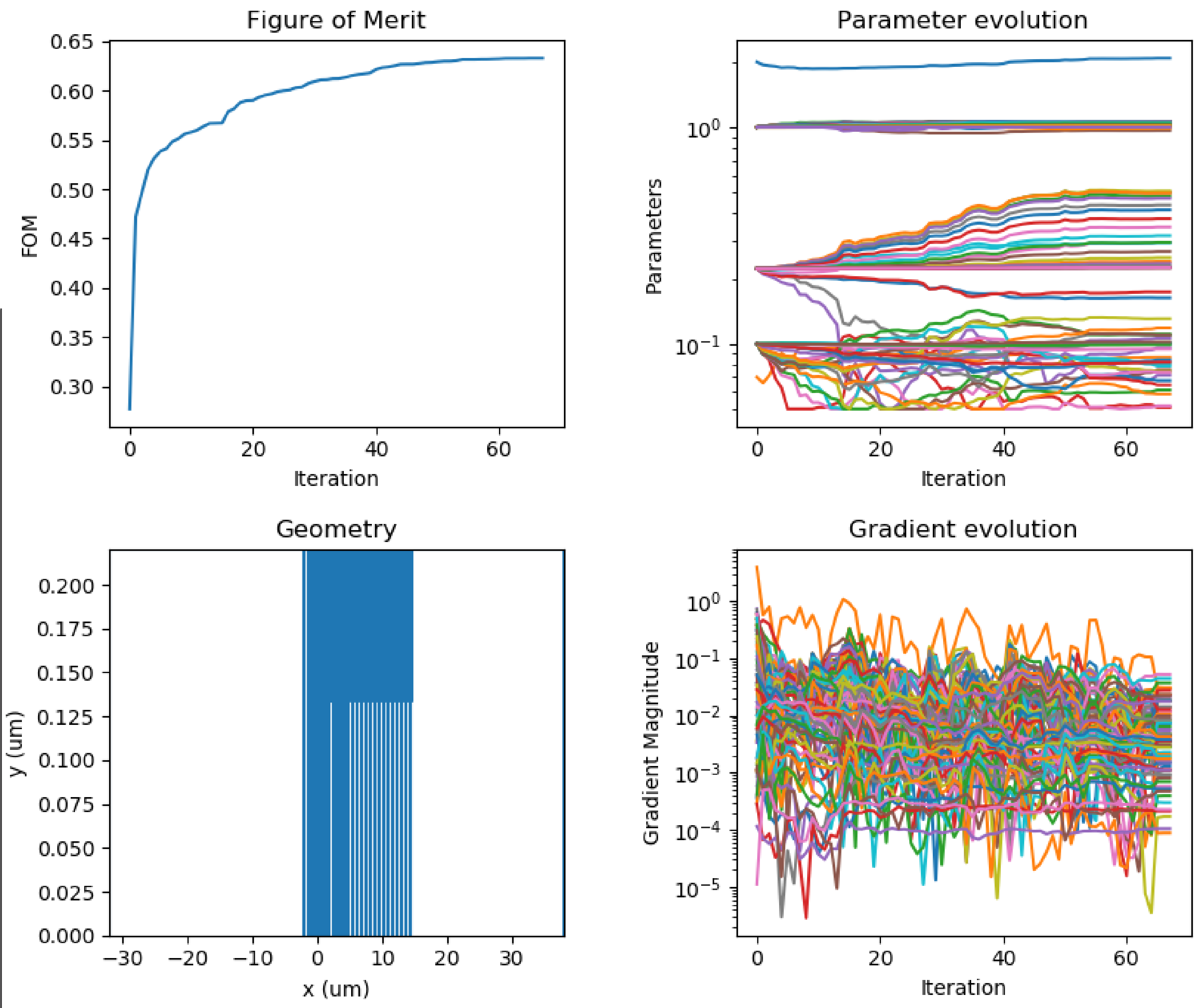
Double etch grating coupler

Example available soon

>80 optimization parameters







Example: Robust Y-Branch

Lumopt in Action

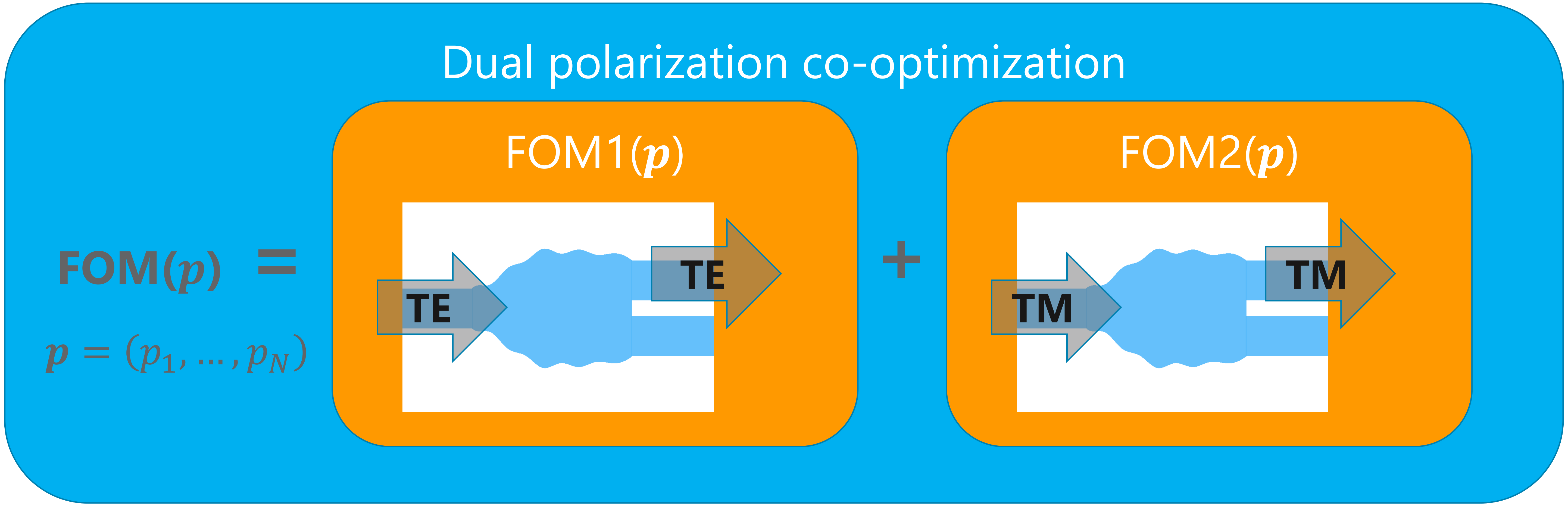
Co-Optimization

Co-optimization:

- Run multiple optimizations concurrently
- Optimizations share same parameters
- Figure of merit or structure can be different

Example uses:

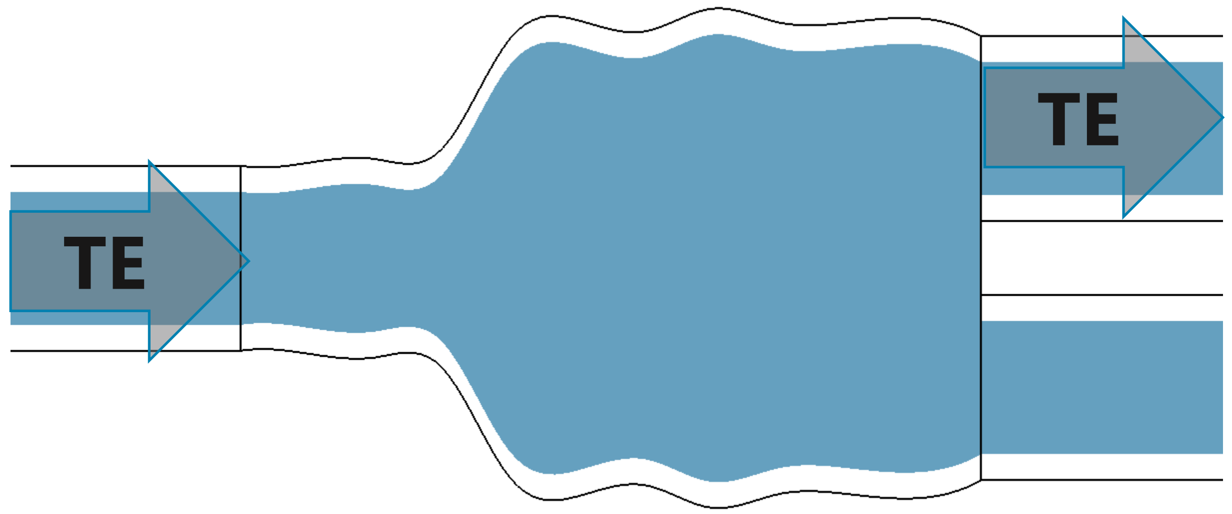
- Dual polarization devices (different FOM)
- Multiple wavelengths (different FOM)
- Optimize process corners (different geometry)



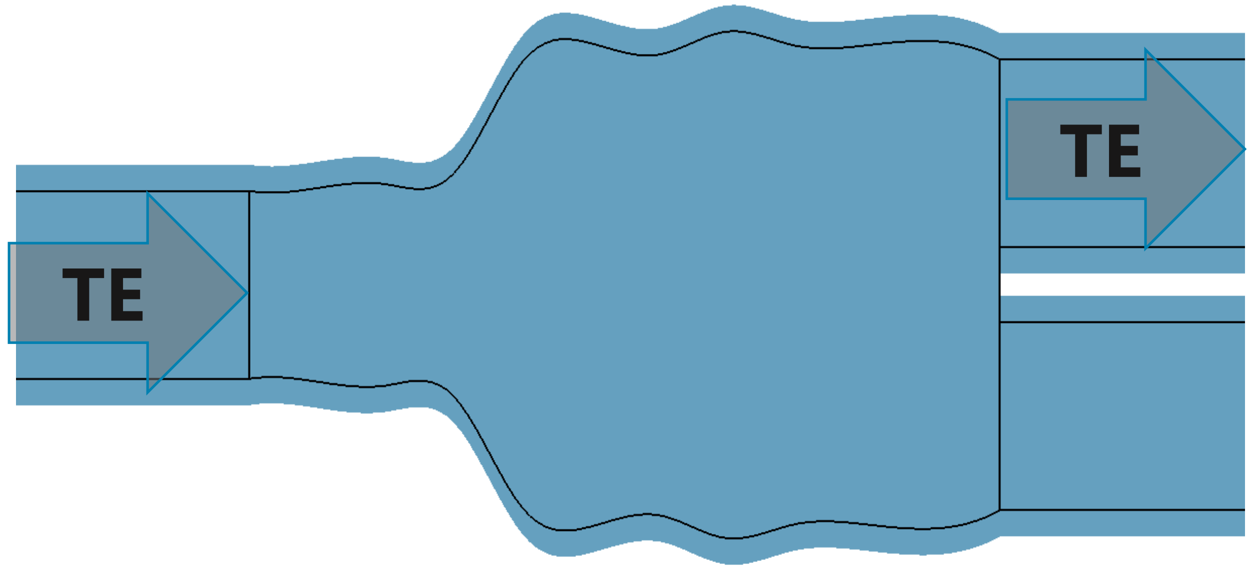
Co-optimization: Robust splitter

- Build a splitter tolerant to manufacturing error
- Co-optimize 2 different shapes (same parameters)
- “Over etch” slightly smaller than nominal
- “Under etch” slightly larger than nominal
- Same FOM function

Over etch

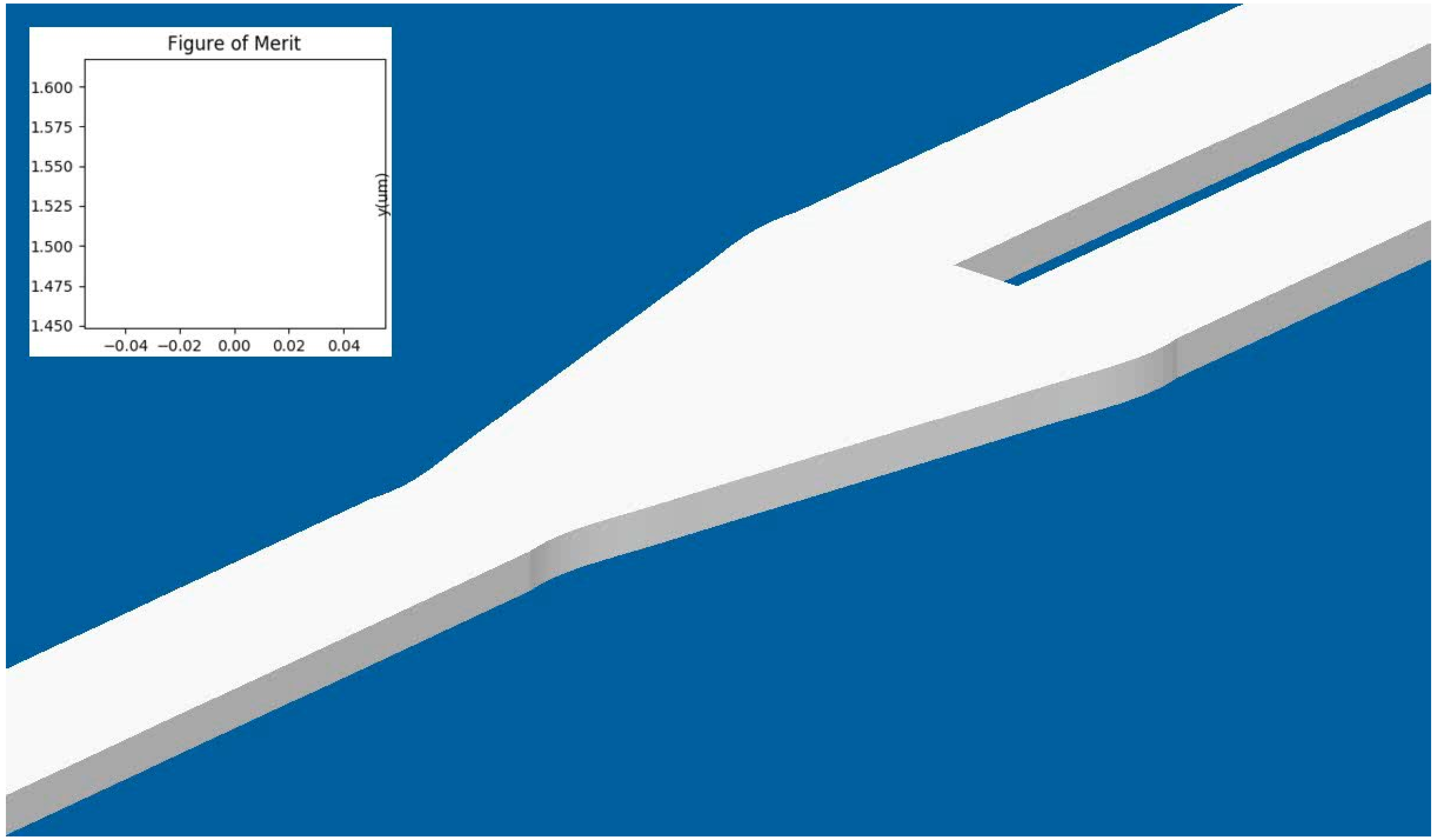


Under etch

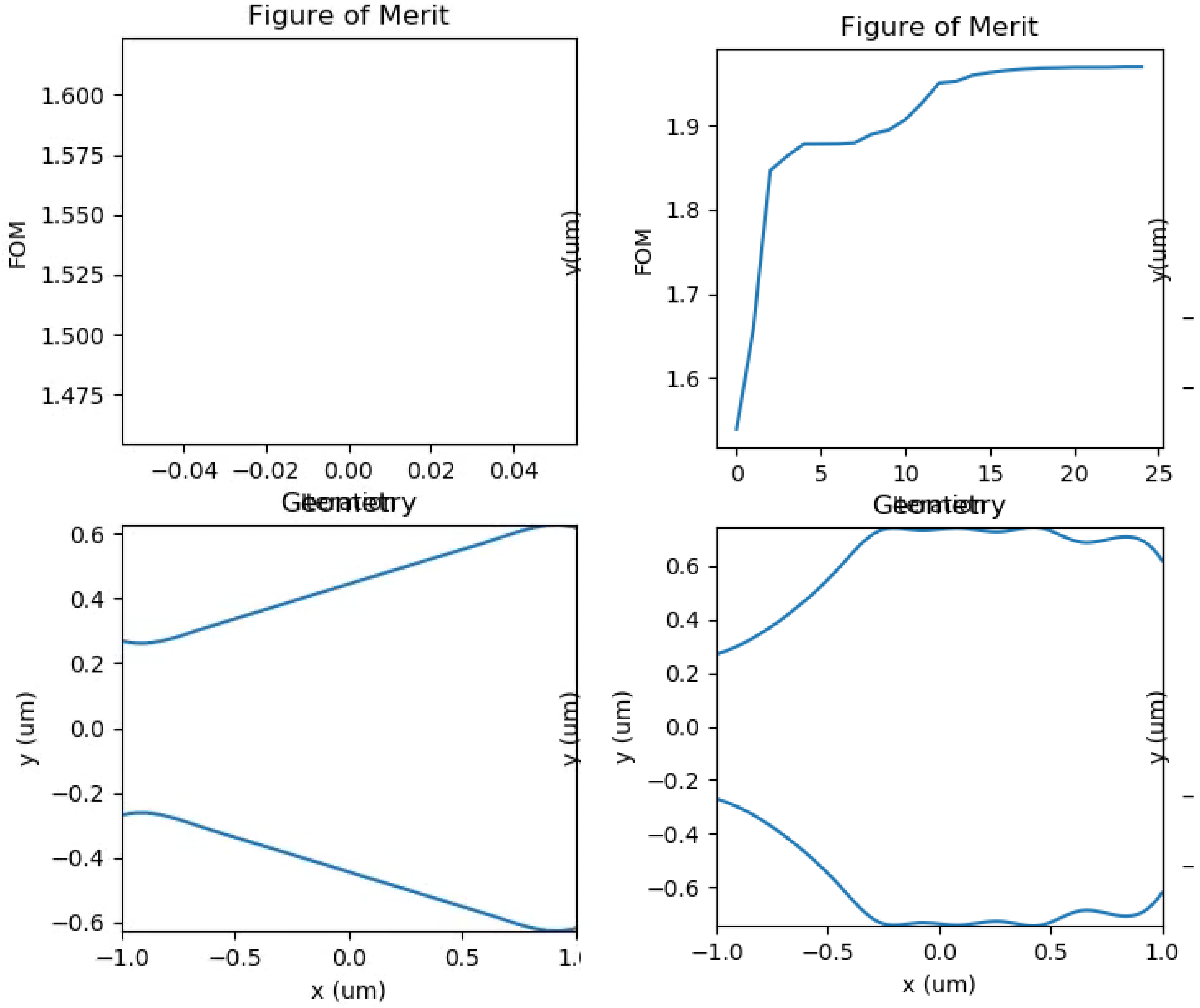


Co-optimization: Robust splitter

- Setup 2 optimizations
- Sum the figures of merit
- 2 FDTD simulations/FOM/iteration



Co-optimization of +/- 20nm on edge position



Nice smooth shape!

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Upcoming features

Layout using Cadence's Virtuoso CurvyCore Technology

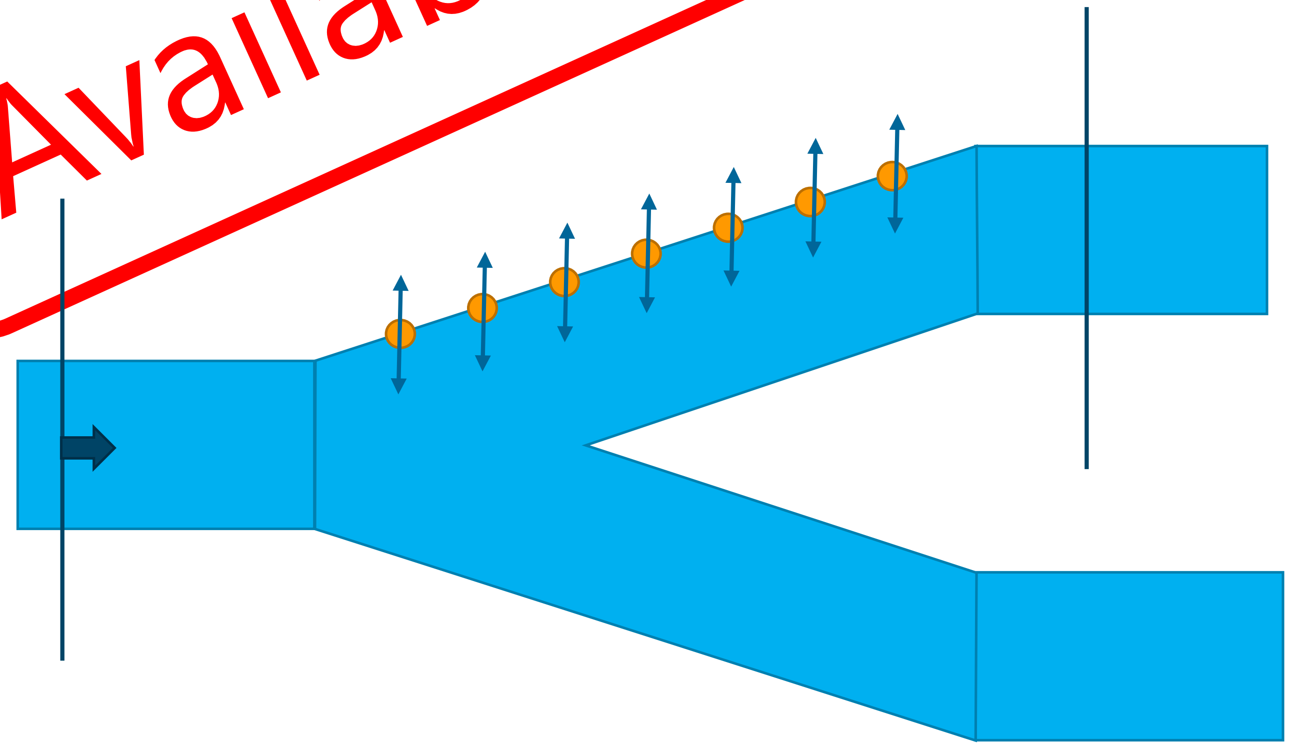
- Non-Manhattan shapes
- Symbolic equations provide accurate mathematical model
- Generates high-quality polygon representations for fabrication
- Ideal for inverse design shapes

Two Approaches to Inverse Design

Parametric Geometry Optimization

- Finds optimal parameters for shape(s)
- Parametric shape defines/limits design space

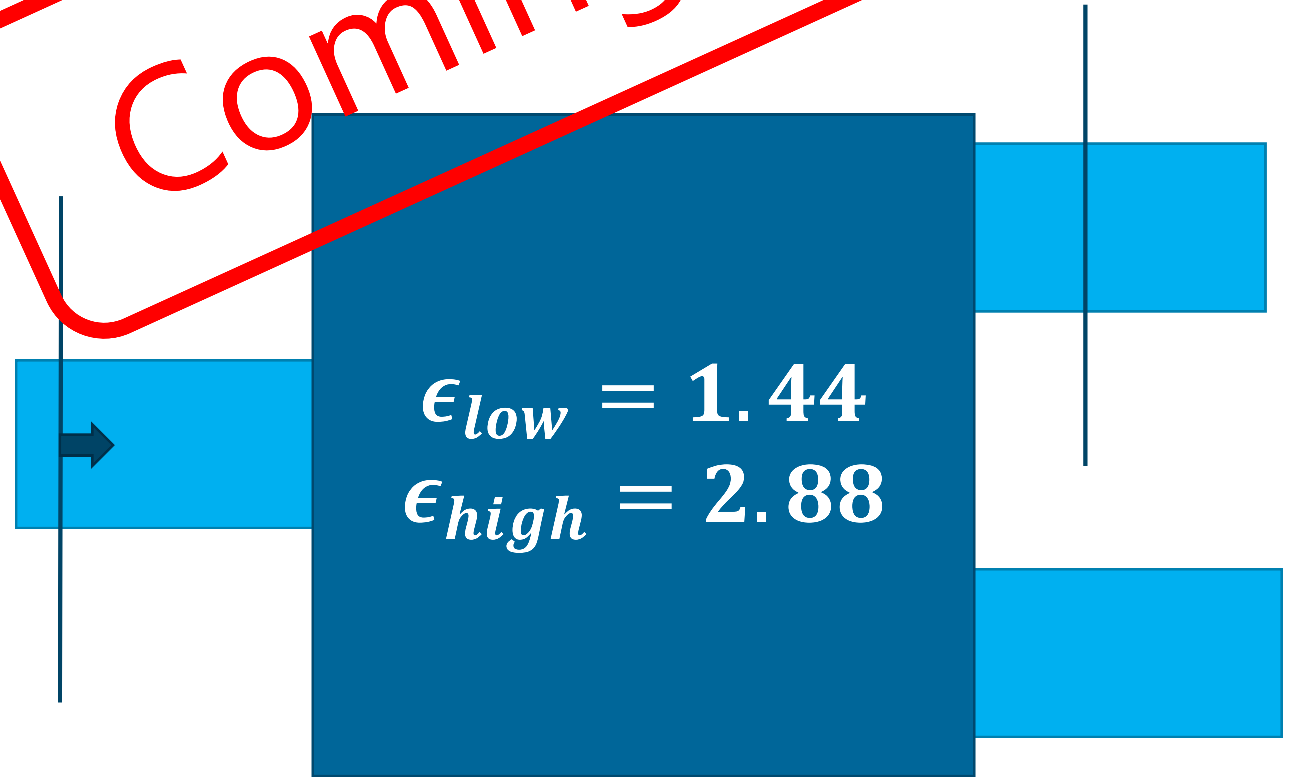
Available Now!



Topology Optimization

- User provides footprint and 2 materials
- No intuition about shape required!
- Solver finds best solution

Coming Soon!



Topology Optimization

Supports:

- Broadband
- Quasi-2D
- Constrained feature size
- Co-optimization

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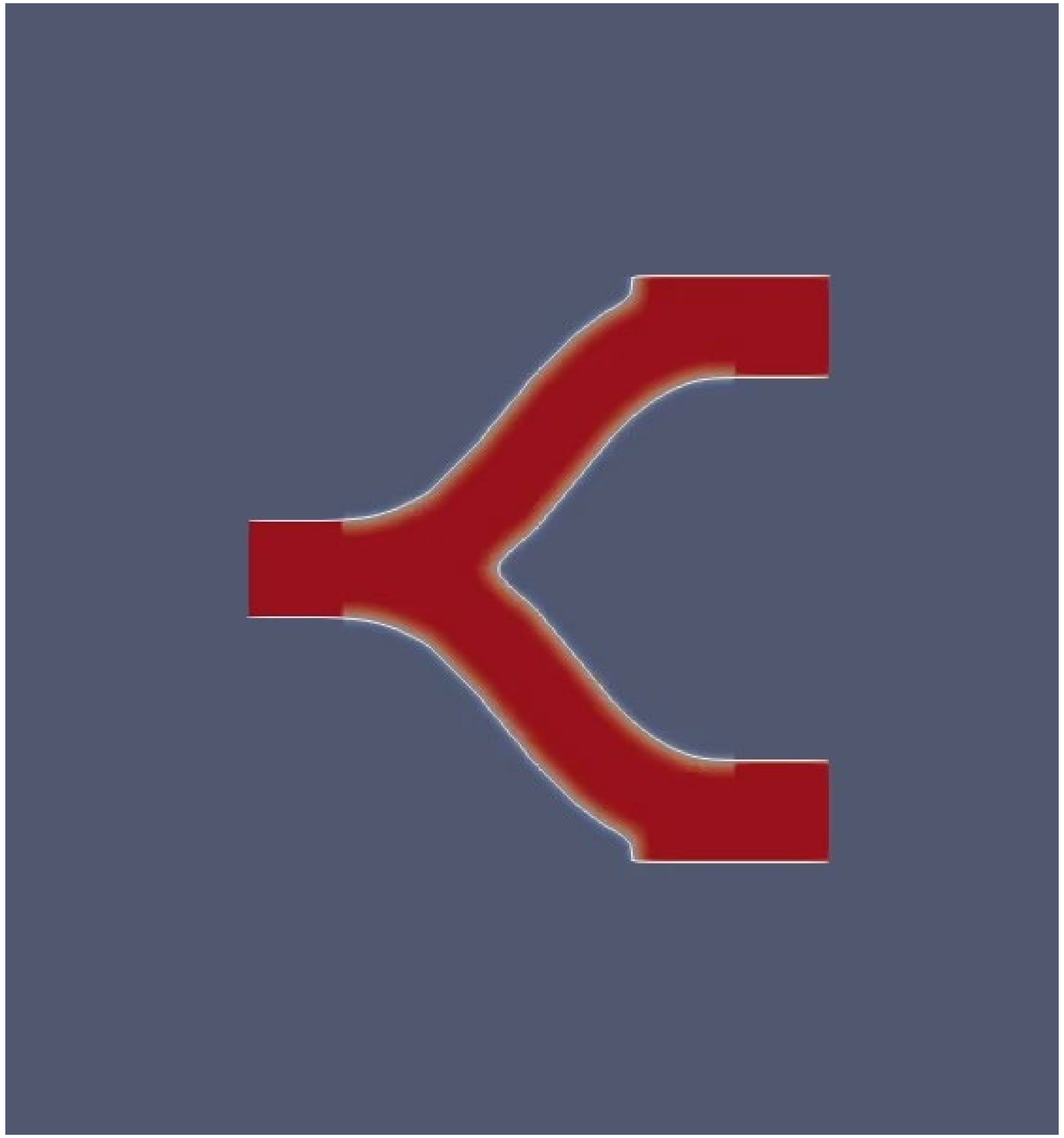
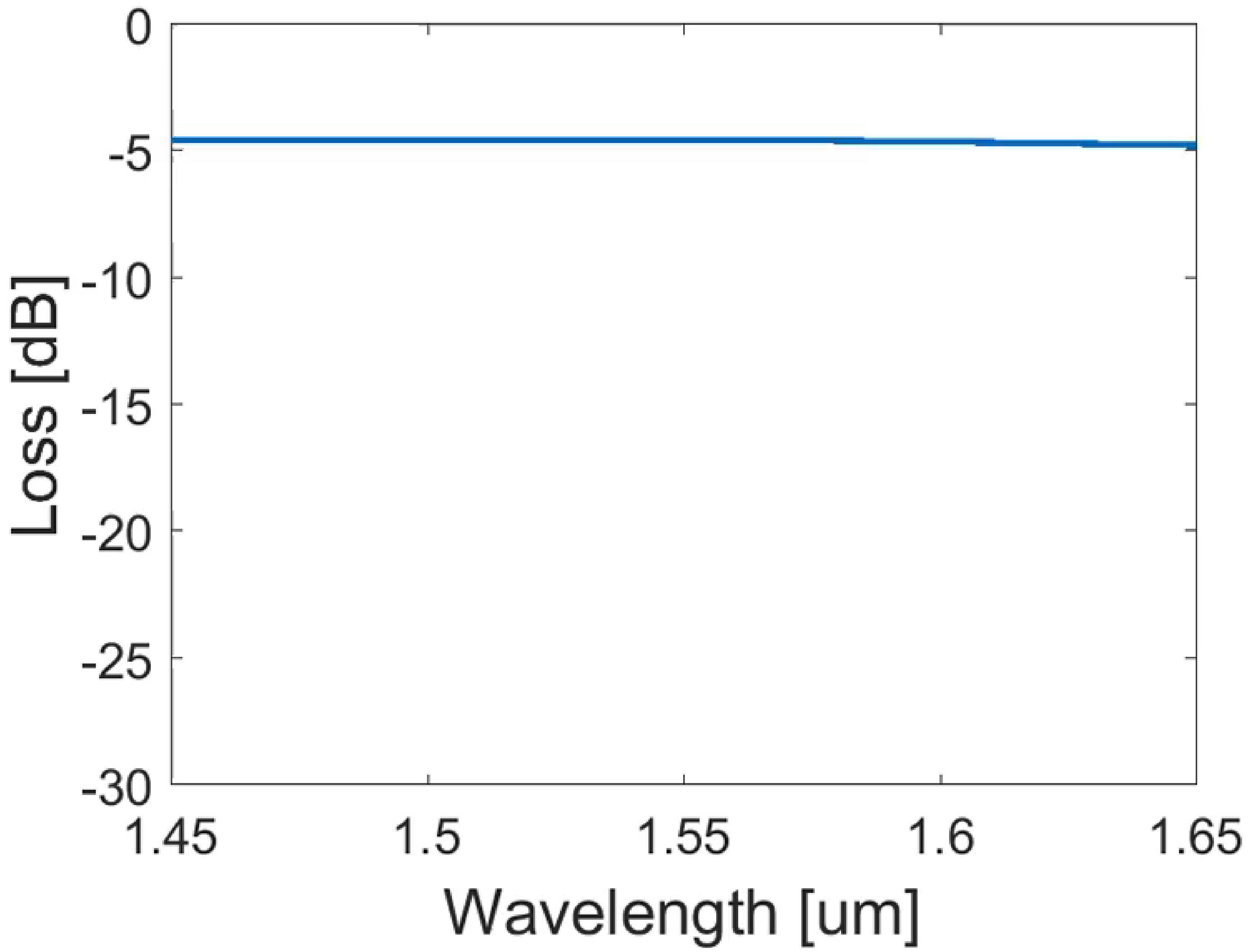
Topology Optimization: Broadband (1450-1650nm) TE Splitter





Next Steps

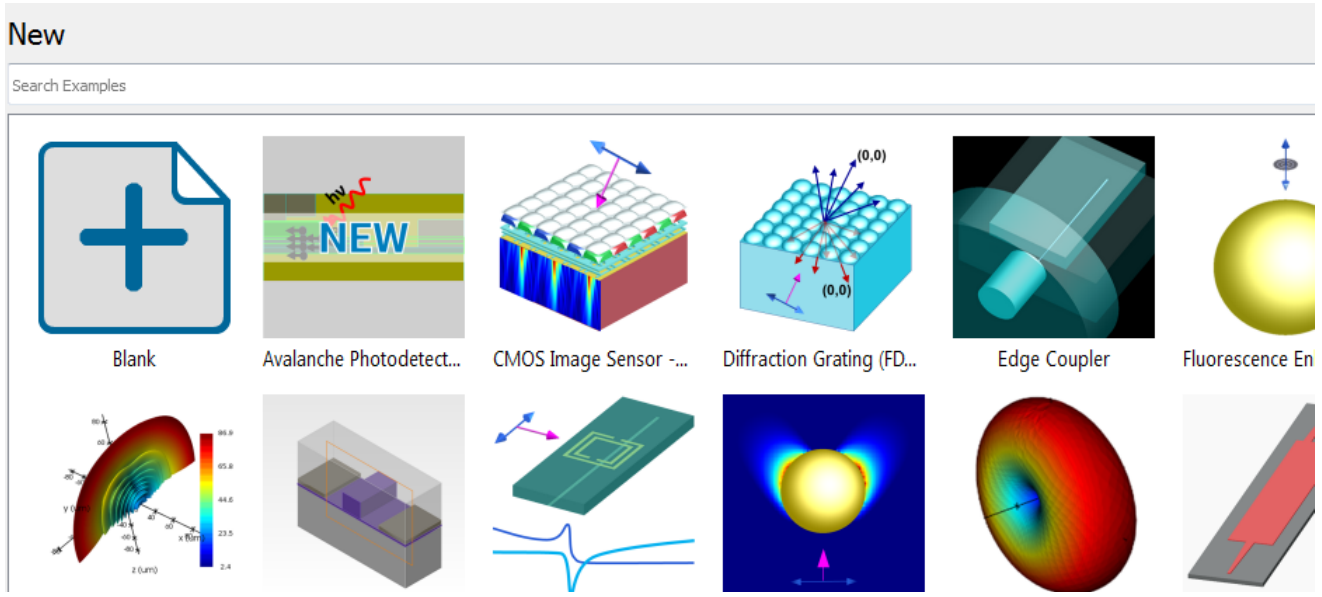
Try running examples

- Stick to 2D, get results in minutes
- Set max_iter=3 to get suboptimal device fast

Try some modifications

- Change device footprint
- Change bandwidth
- Change number of optimization parameters
- Try pCell suggestions in tutorial

More examples available in applications gallery



See more
Exhibit Hall Booth 5438