

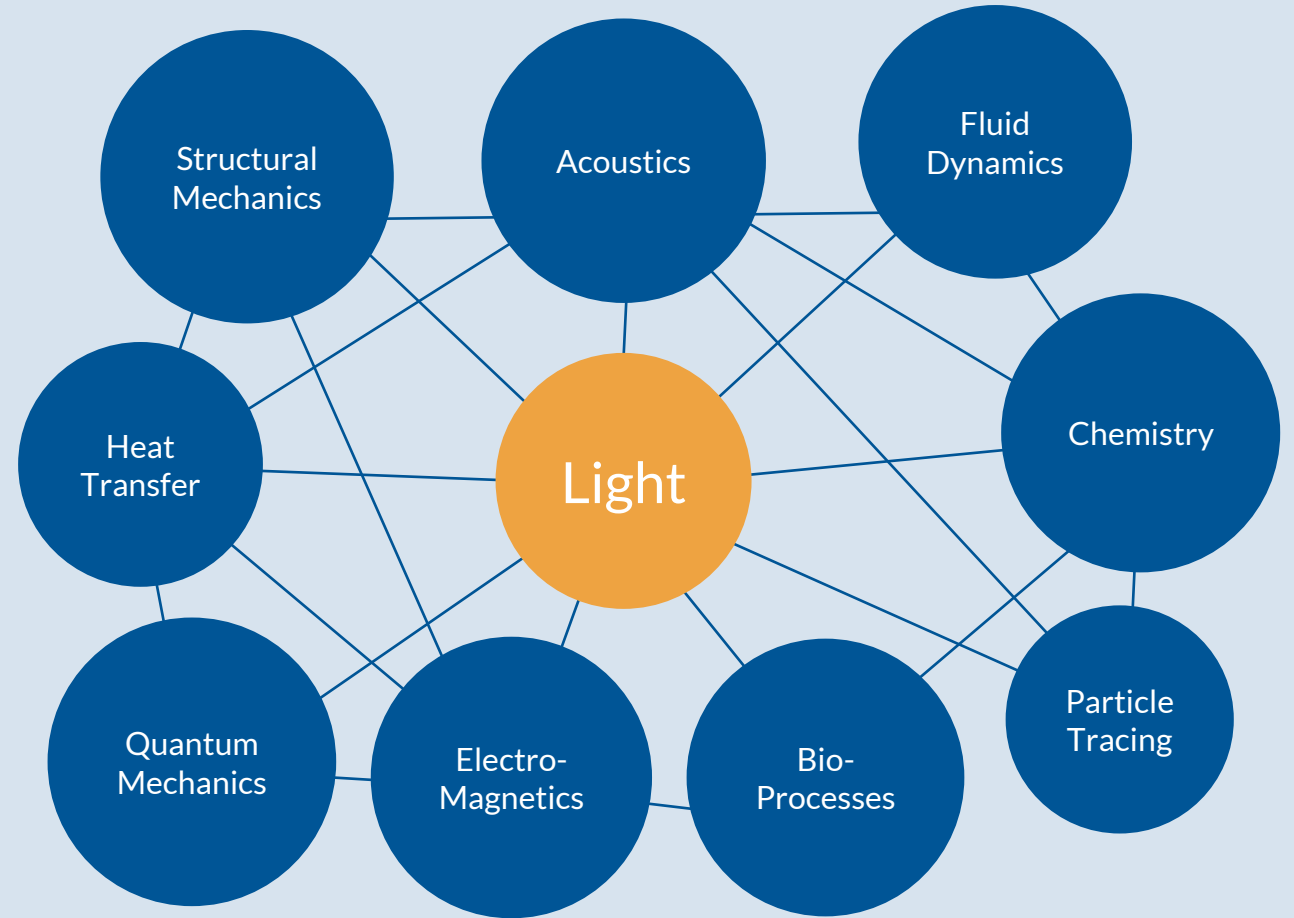
Simulation-driven development of PICs

Justus Bohn - COMSOL® Multiphysics

Photonic Integrated Circuits and Multiphysics

In photonic integrated circuits (PIC), optical fields interact in a desired or undesired way:

- Sensing
- Switching
- Heating
- Miniaturization



OPTOMECHANICS - ELECTROOPTICS - PHOTOCHEMISTRY -
OPTOFLUIDICS - OPTOACOUSTICS - STOP ANALYSIS - QUANTUMOPTICS-
OPTOELECTRONICS - OPTOMAGNETICS - THERMOOPTICS -- LASER-
MATERIAL-INTERACTION - BIOPHOTONICS - MAGNETOOPTICS -
BIOOPTOFLUIDICS - PHOTOPHORESIS - ETC.

COMSOL DESKTOP®

An Integrated Environment for Modeling and Simulation

Model Builder

- Build physics-based models

Application Builder

- Build apps to share

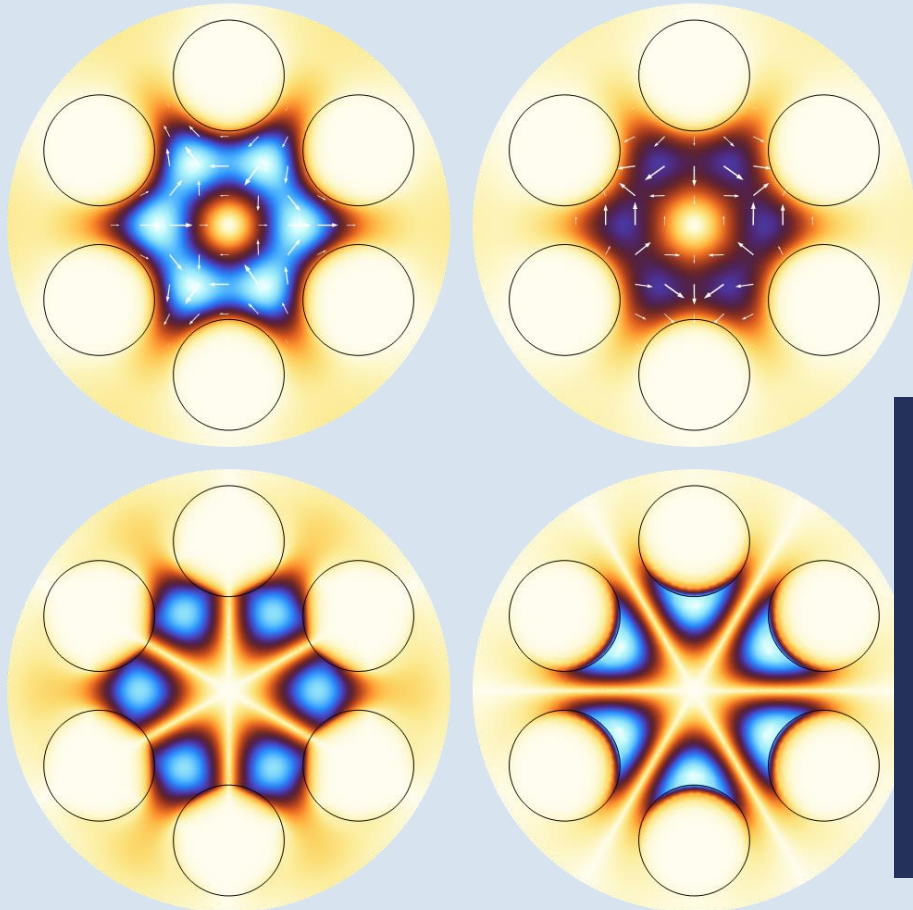
Model Manager

- Organize models and data efficiently

Switch to Application Builder or Model Manager mode

The screenshot displays the COMSOL Desktop interface in Model Builder mode. The top toolbar features buttons for switching between Application Builder and Model Manager, along with various modeling and simulation tools. The central workspace shows a hierarchical tree view of the model structure for a Petzval lens stop analysis. The tree includes sections for Global Definitions, Component 1 (comp 1), Definitions, Petzval Lens Stop Analysis Geometry Sequence, Materials, Geometrical Optics (gop), Solid Mechanics (solid), Heat Transfer in Solids (ht), Surface-to-Surface Radiation (rad), Multiphysics, and Mesh 1. The right-hand Settings panel is open, showing options for protection, unit system (SI), and presentation details such as title and description. A 3D visualization of the lens assembly is visible in the bottom right corner.

Mode Analysis



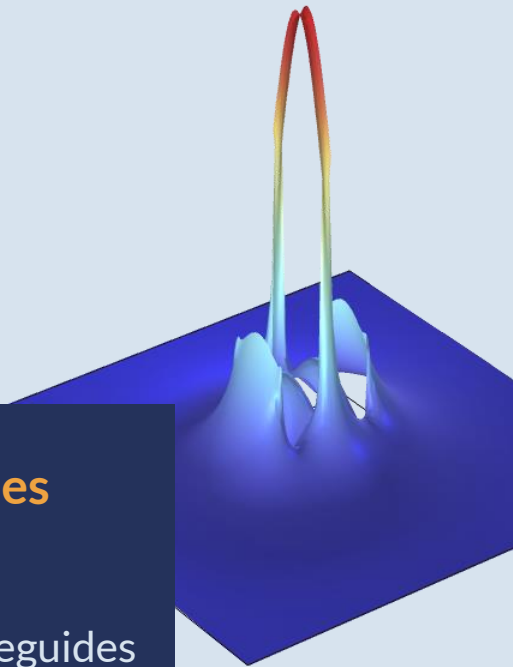
Problem

Analyze a waveguide cross section and deduce *mode fields* and *propagation constants*

$$E(x, y, z) = E_m(x, y) \exp(-j\beta_m z)$$

Typical Examples

- Optical fibers
- Dielectric waveguides
- Anisotropic waveguides



Stress-Optical Effect

- Birefringence in a silica-on-silicon waveguide
- Solid mechanics analysis of silica layer on silicon wafer
 - Deformation leads to stress
 - Stress leads to optical birefringence

stress_optical.mph - COMSOL Multiphysics

File Home Definitions Geometry Sketch Materials Physics Mesh Study Results Developer

Application Builder Model Manager Component 1 Add Component Parameters Pi Variables Functions Variable Utilities Build All Import LiveLink Add Material Solid Mechanics Add Physics Build Mesh Mesh 1 Compute Study 1 Add Study

Workspace Model Definitions Geometry Mesh Study

Model Builder

- stress_optical.mph (root)
 - Global Definitions
 - Parameters 1
 - Default Model Inputs
 - Materials
 - Component 1 (comp1)
 - Definitions
 - Geometry 1
 - Materials
 - Solid Mechanics (solid)
 - Linear Elastic Material 1
 - Free 1
 - Initial Values 1
 - Rigid Motion Suppression 1
 - Electromagnetic Waves, Frequency Domain
 - Wave Equation, Electric 1
 - Perfect Electric Conductor 1
 - Initial Values 1
 - Mesh 1
 - Study 1
 - Results
 - Datasets
 - Views
 - Derived Values
 - Tables
 - Stress (solid)
 - Surface 1
 - Electric Field (ewfd)
 - 2D Plot Group 3
 - 1D Plot Group 4
 - Export
 - Reports

Settings

Linear Elastic Material

Label: Linear Elastic Material 1

Domain Selection

Override and Contribution

Equation

Show equation assuming: Study 1, Stationary

$$0 = \nabla \cdot \mathbf{S} + \mathbf{F}_v$$

$$\mathbf{S} = \mathbf{S}_{inel} + \mathbf{S}_{el}, \quad \boldsymbol{\epsilon}_{el} = \boldsymbol{\epsilon} - \boldsymbol{\epsilon}_{inel}$$

$$\boldsymbol{\epsilon}_{inel} = \boldsymbol{\epsilon}_0 + \boldsymbol{\epsilon}_{ext} + \boldsymbol{\epsilon}_{th} + \boldsymbol{\epsilon}_{hs} + \boldsymbol{\epsilon}_{pl} + \boldsymbol{\epsilon}_{cr} + \boldsymbol{\epsilon}_{vp} + \boldsymbol{\epsilon}_{ve}$$

$$\mathbf{S}_{el} = \mathbf{C} : \boldsymbol{\epsilon}_{el}$$

$$\mathbf{S}_{inel} = \mathbf{S}_0 + \mathbf{S}_{ext} + \mathbf{S}_q$$

$$\boldsymbol{\epsilon} = \frac{1}{2} [(\nabla \mathbf{u})^T + \nabla \mathbf{u}]$$

$$\mathbf{C} = \mathbf{C}(E, \nu)$$

Model Input

Coordinate System Selection

Linear Elastic Material

Material symmetry: Isotropic

Specify: Young's modulus and Poisson's ratio

Young's modulus: E From material

Poisson's ratio: ν From material

Density: ρ From material

Use mixed formulation: None

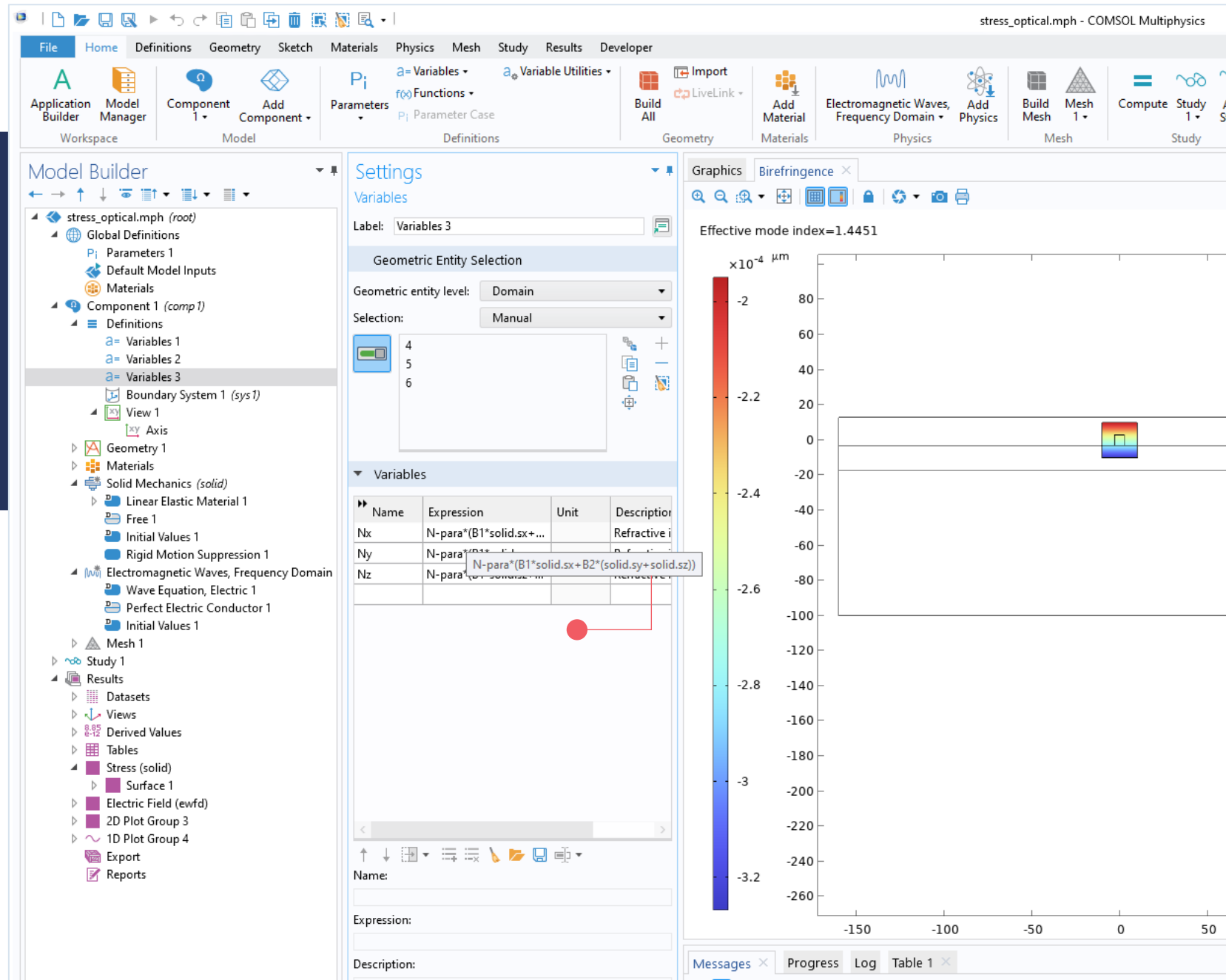
Graphics Von Mises Stresses

MPa μm

Messages Progress Log Table 1

Stress-Optical Effect

- Mode analysis of optical waveguide with anisotropic (birefringent) refractive index
 - More stress leads to more birefringence
 - increasing shift of the modes' effective indices



Beam Envelope Method

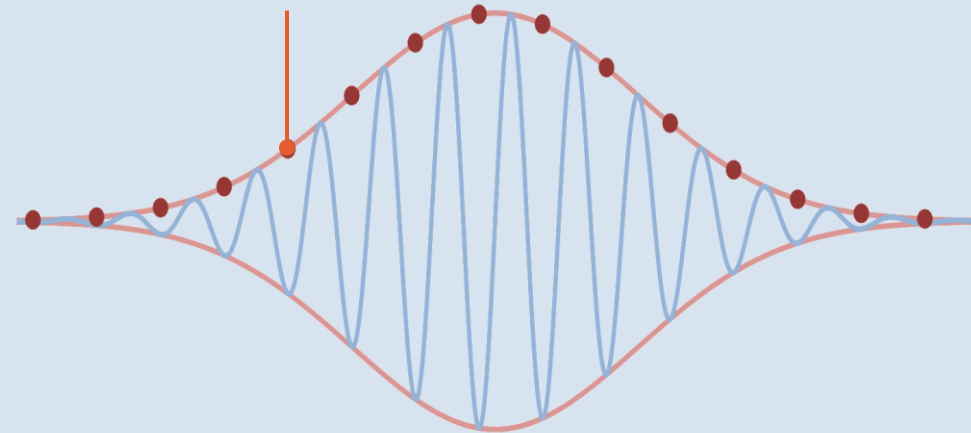
Rigorous simulations of optically large devices.



Electric field, $\mathbf{E}(\mathbf{r})$

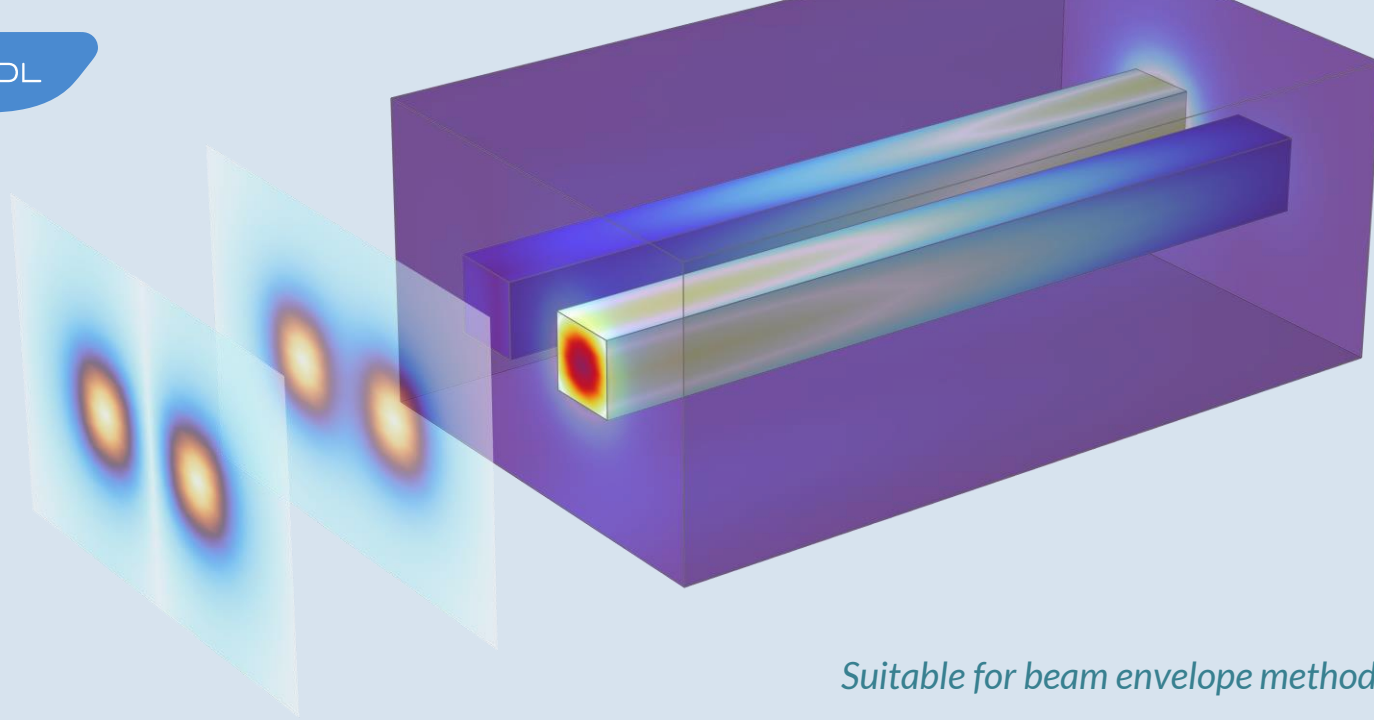
Five mesh elements per wavelength.

Electric field envelope, $\mathbf{E}_i(\mathbf{r})$

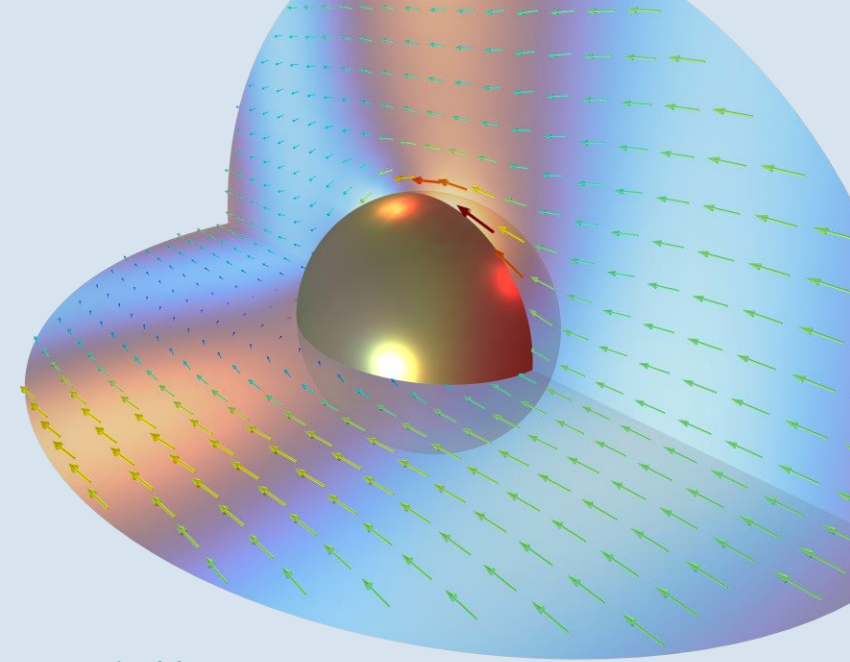


$$\mathbf{E}(\mathbf{r}) = \mathbf{E}_i(\mathbf{r})e^{-j\mathbf{k}_i \cdot \mathbf{r}}$$

Mesh only needs to resolve electric field envelope.



Suitable for beam envelope method.



Not suitable.

When to Use the Beam Envelope Method

- You need to be able to guess good wave vectors (or phase functions).
 - If your problem is not characterized by one or two main wave vectors, use the *Electromagnetic Waves, Frequency Domain* interface instead.
- The beam envelope method is not suitable for scattering problems.
 - The incoming wave has a well-known wave vector, but the scattered wave propagates in many directions.

Optical Ring Resonator

Interferes of electric fields from the ring and the straight waveguide

Phase propagation well known and even analytical.

optical_ring_resonator_3d.mph - COMSOL Multiphysics

File Home Definitions Geometry Materials Physics Mesh Study Results Developer

Application Builder Model Manager Component 1 Add Component Parameters Variables Functions Import Build All LiveLink Add Material Electromagnetic Waves, Beam Envelopes Add Physics Build Mesh Mesh 1 Compute Study 1 Add Study Electric Field (ewbe) Add Plot Group Predefined

Workspace Model Definitions Geometry Materials Physics Mesh Study Results

Model Builder

- optical_ring_resonator_3d.mph (root)
 - Global Definitions
 - Component 1 (comp1) (comp1)
 - Definitions
 - a= Variables 1 {var1}
 - a= Variables 2 {var2}
 - a= Variables 3 {var3}
 - Selections
 - Boundary System 1 (sys1) (sys1)
 - View 1 (view1)
 - Geometry 1 (geom1)
 - Rectangular Waveguide Straight-to-Ring Coupler 1 (pi1)
 - Form Union (fin) (fin)
 - Materials
 - Electromagnetic Waves, Beam Envelopes (ewbe) (ewbe)
 - Wave Equation, Beam Envelopes 1 (webe1)
 - Perfect Electric Conductor 1 (pec1)
 - Initial Values 1 (init1)
 - Port 1 (port1)
 - Port 2 (port2)
 - Scattering Boundary Condition 1 (sctr1)
 - Field Continuity 1 (fcont1)
 - Mesh 1 (mesh1)
 - Study 1 (std1)
 - Parametric Sweep (param)
 - Step 1: Boundary Mode Analysis (bma)
 - Step 2: Boundary Mode Analysis 1 (bma1)
 - Step 3: Wavelength Domain (wave)
 - Solver Configurations
 - Job Configurations
 - Results
 - Datasets
 - Derived Values
 - Tables
 - Electric Field (ewbe) (pg1)
 - Electric Field (mstc1)
 - Deformation 1 (def1)
 - Transparency 1 (tran1)
 - Waveguide (vol1)
 - Transparency 1 (tran1)
 - Core (vol2)
 - Selection 1 (sel1)
 - Transmittance and Loss (ewbe) (pg2)
 - Electric Mode Field, Port 1 (ewbe) (pg3)
 - Electric Mode Field, Port 2 (ewbe) (pg4)
 - Export
 - Reports

Settings

Electromagnetic Waves, Beam Envelopes

Label: Electromagnetic Waves, Beam Envelopes

Name: ewbe

Domain Selection

Equation

Equation form: Study controlled

Show equation assuming: Study 1 {std1}, Wavelength Domain {wave}

$$(\nabla - i\nabla\phi_1) \times \mu_r^{-1}((\nabla - i\nabla\phi_1) \times \mathbf{E1}) - k_0^2(\epsilon_r - \frac{i\sigma}{\omega\epsilon_0})\mathbf{E1} = 0$$

Wave Vectors

Number of directions: Unidirectional

Type of phase specification: User defined

Phase, first wave: ϕ_1 phi rad

User Defined Wave Vector Specification

Port Sweep Settings

Use manual port sweep

Discretization

Dependent Variables

Graphics Wave Propagation X

Ida0(6)=1.56 um lambda0(1)=1.56 um Multislice: Electric field, z-component

Messages Progress Log Table X

8.85 e-12 8.5 e-1 850 e-3 0.85

Electro-Optic Modulation

- Mach-Zehnder modulator:
 - Two-directional coupler
 - Electro-optic modulation of one interferometer path
 - Applied voltage controls power flow to output ports
- Physics interfaces:
 - *Electromagnetic Waves, Beam Envelopes* (Wave Optics Module)
 - *Electrostatics* (AC/DC Module)
- Multiphysics coupling:
 - Refractive index (Wave Optics Module) controlled by applied voltage (AC/DC Module) through electro-optic effect

The screenshot displays the COMSOL Multiphysics interface for a Mach-Zehnder modulator simulation. The Model Builder tree on the left shows the hierarchy: mach_zehnder_modulator.mph (root) > Global Definitions > Component 1 (comp1) > Definitions > Refractive index (rfi). The Settings panel for the Refractive Index property shows the Name as 'rfi' and the Expression as $n_{\text{core}} - 0.5 \cdot n_{\text{core}} \cdot \text{es.Ey}$. The 3D visualization on the right shows the electric field distribution (V/m) in the modulator structure, with a color scale ranging from 0.2 to 1.2 $\times 10^4$ V/m. The structure is a Mach-Zehnder modulator with a central waveguide and two output waveguides, with dimensions in meters indicated as 10^{-3} m and 10^{-5} m.

USER STORY: EPFL

Silicon Photonic MEMS Phase Shifter to Boost Optical Network Speed

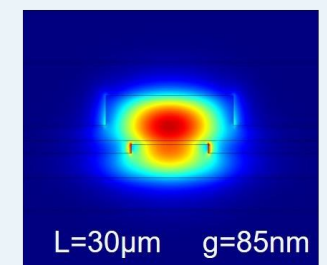
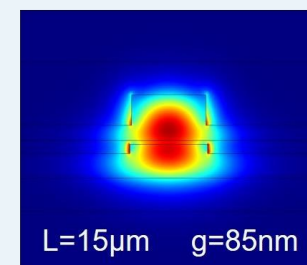
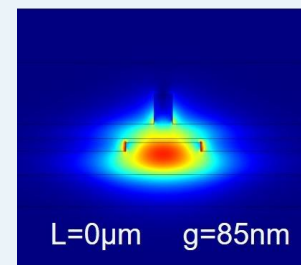
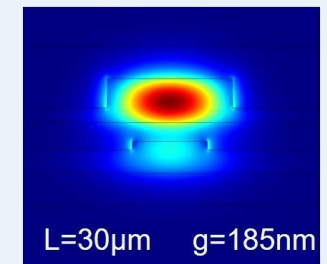
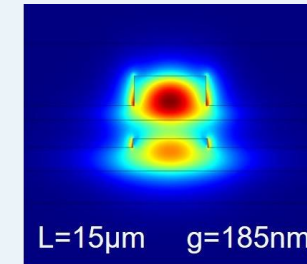
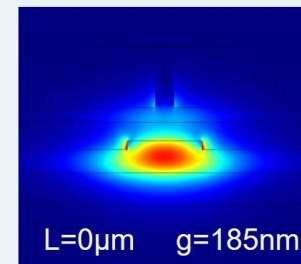
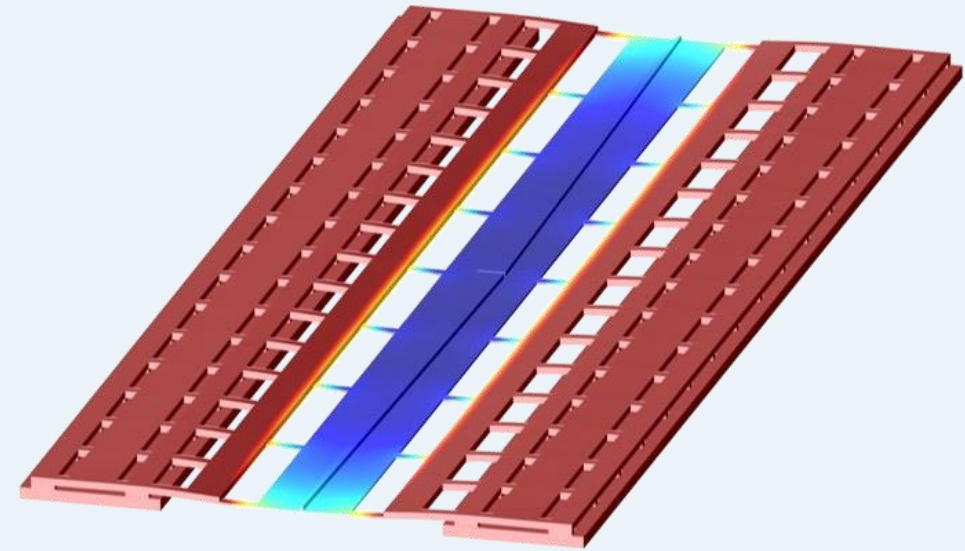
CHALLENGES

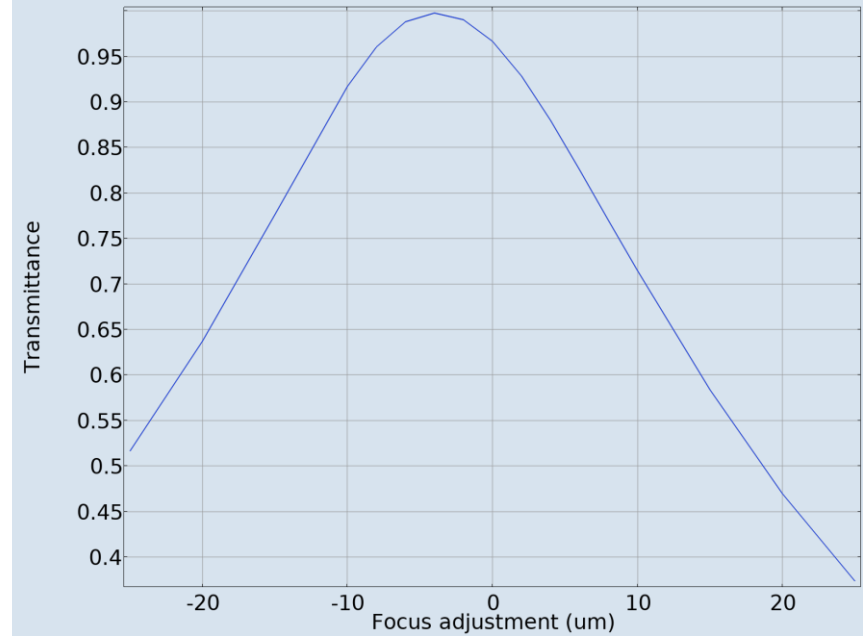
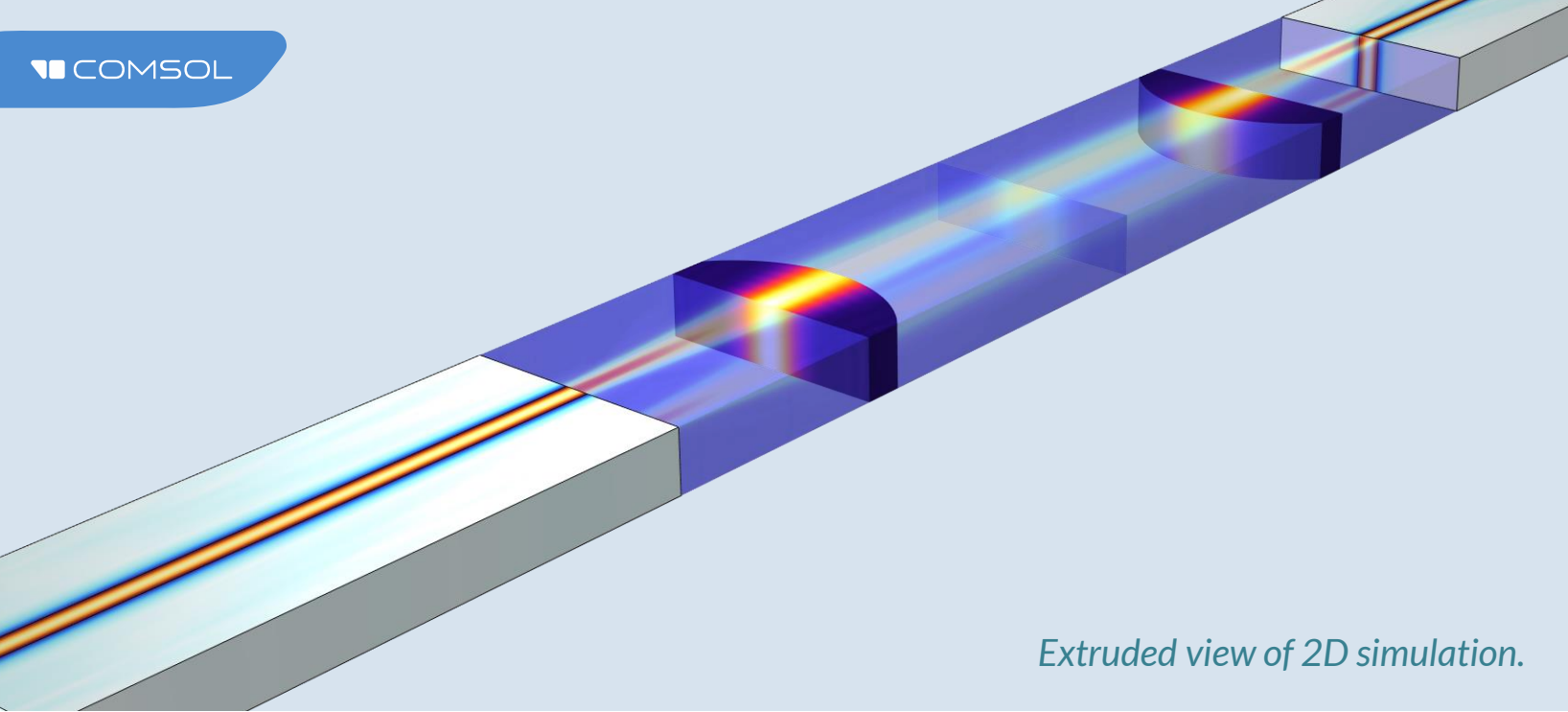
Optical fiber networks, the backbone of the internet, still rely on many electrical signal processing devices.

Nanoscale silicon photonic network components, such as MEMS phase shifters, can boost optical network speed, capacity, and reliability.

MODELING

The team at EPFL analyzed how much voltage had to be applied to a MEMS supporting a waveguide to induce a wanted shift in a photonic signal.





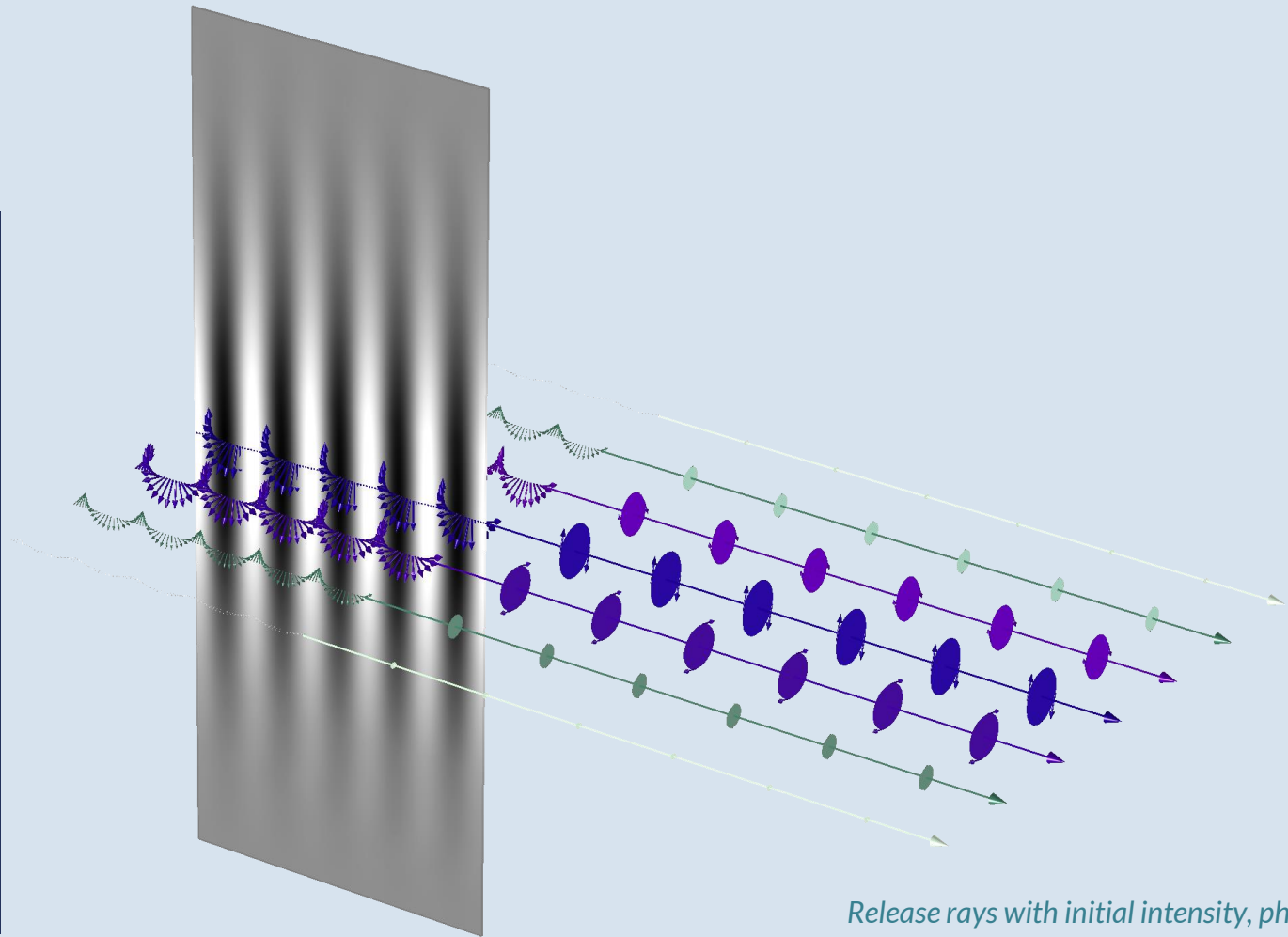
Fiber-to-Fiber Coupling

- Free-space coupling between two single-mode fiber ends
- Coupling efficiency depends on the lens positions
- *Transition Boundary Conditions* are used as antireflection coatings:
 - Fiber facets
 - Lens surfaces

RAY OPTICS AND EM FIELDS

Multiscale Electromagnetics Modeling

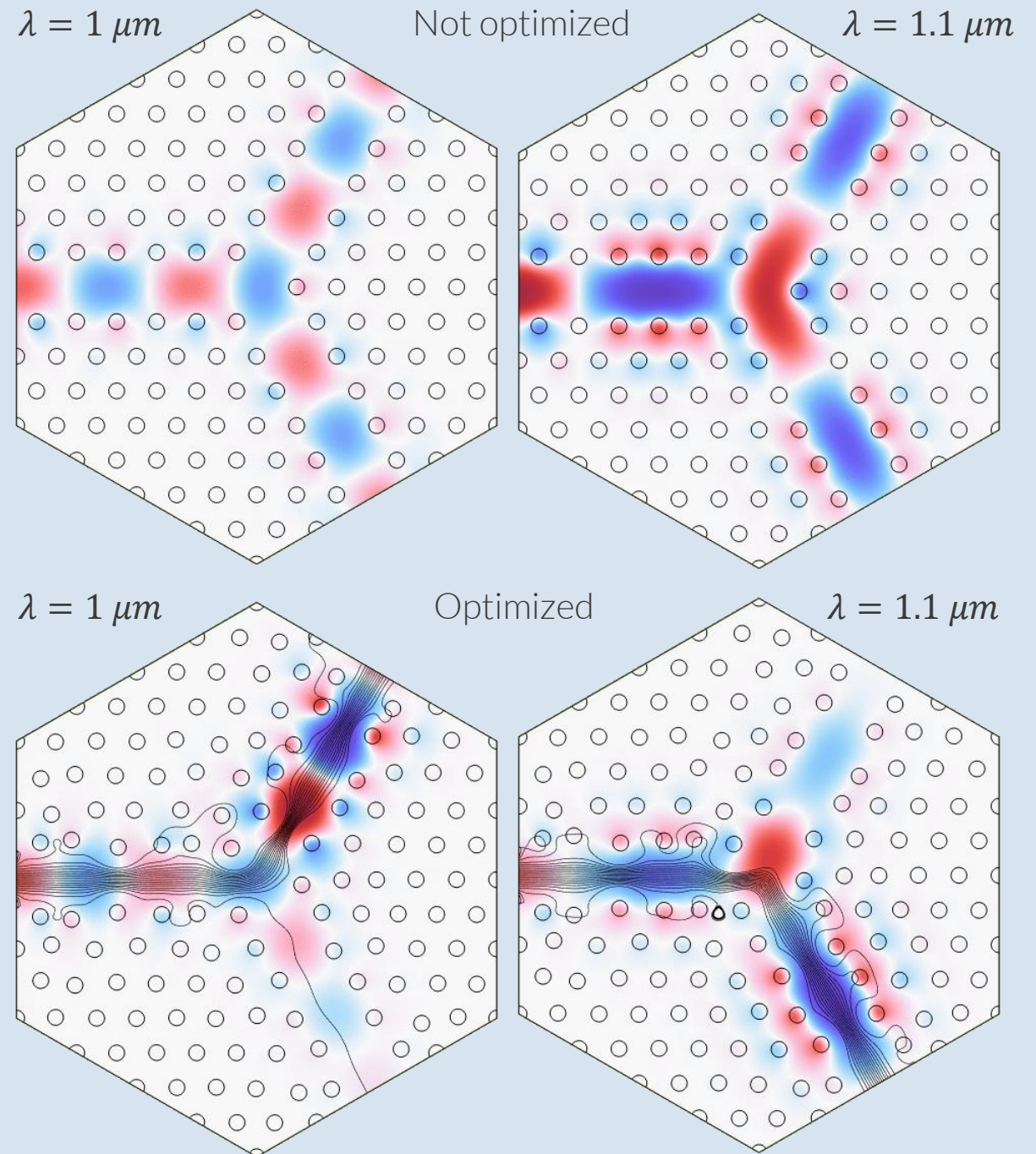
Solve for the electric field over several wavelengths using FEM: Electromagnetic Waves, Frequency Domain or Electromagnetic Waves, Beam Envelopes



Release rays with initial intensity, phase, and polarization based on the frequency domain solution.

Optimization

- Gradient-free optimization
 - Geometric parameters optimization
 - Remeshing of the geometry
 - Optimize geometry for a CAD model created in COMSOL® or via the LiveLink™ products
- Gradient-based optimization
 - Differentiable objective function via moving mesh
 - Can handle many more design variables and solve much faster
 - Adjoint method is used to compute exact sensitivities





12:00

KEYNOTE TALK

▼ [Quantum-Enhanced Sensing with Photonic Integrated Circuits](#)

Phoebe Tengdin, Miraex SA

See what is possible with modeling in the development of sensors

Join us for this COMSOL Day to see how multiphysics modeling facilitates the design and optimization of sensing devices across many research areas and industries.

» comsol.com/comsol-days/sensor-technology

Topics Include

- Electromechanical sensors
- Chemical sensors
- Modeling of hall sensing and inductive sensing
- Parameter estimation
- Uncertainty quantification
- Speeding up sensor calculations

