Wave Optics Simulations with COMSOL Multiphysics®

Linus Andersson
Global Technical Support
COMSOL

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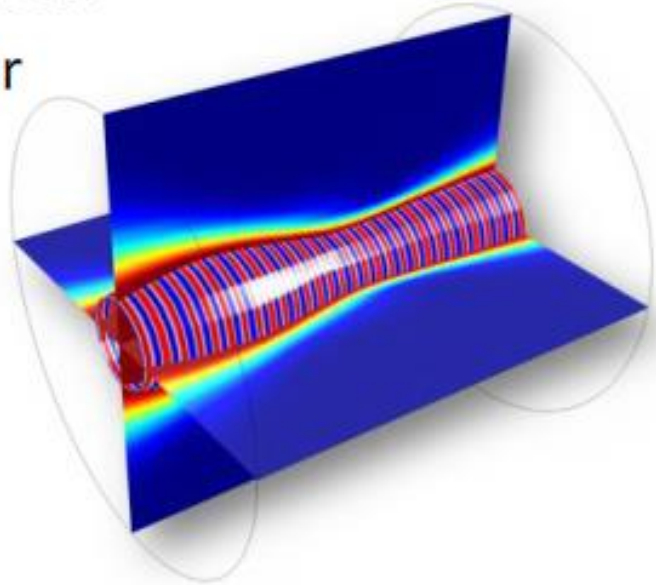
Agenda

- Why Simulate Wave Optics?
- Modeling with COMSOL Multiphysics®
- Wave Optics Modeling and Applications
- Demo of a Mach-Zehnder Modulator
- Q&A
- How To
  - Try COMSOL Multiphysics
  - Contact Us



Self-focusing Gaussian beam

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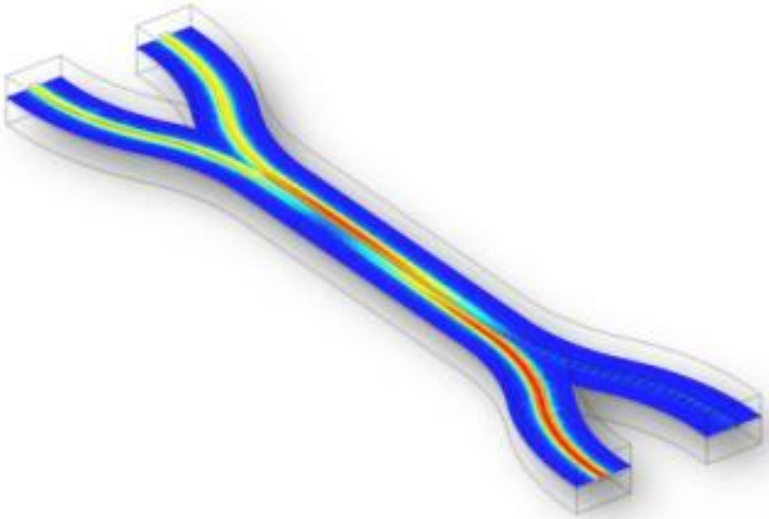
Why Simulate Wave Optics?

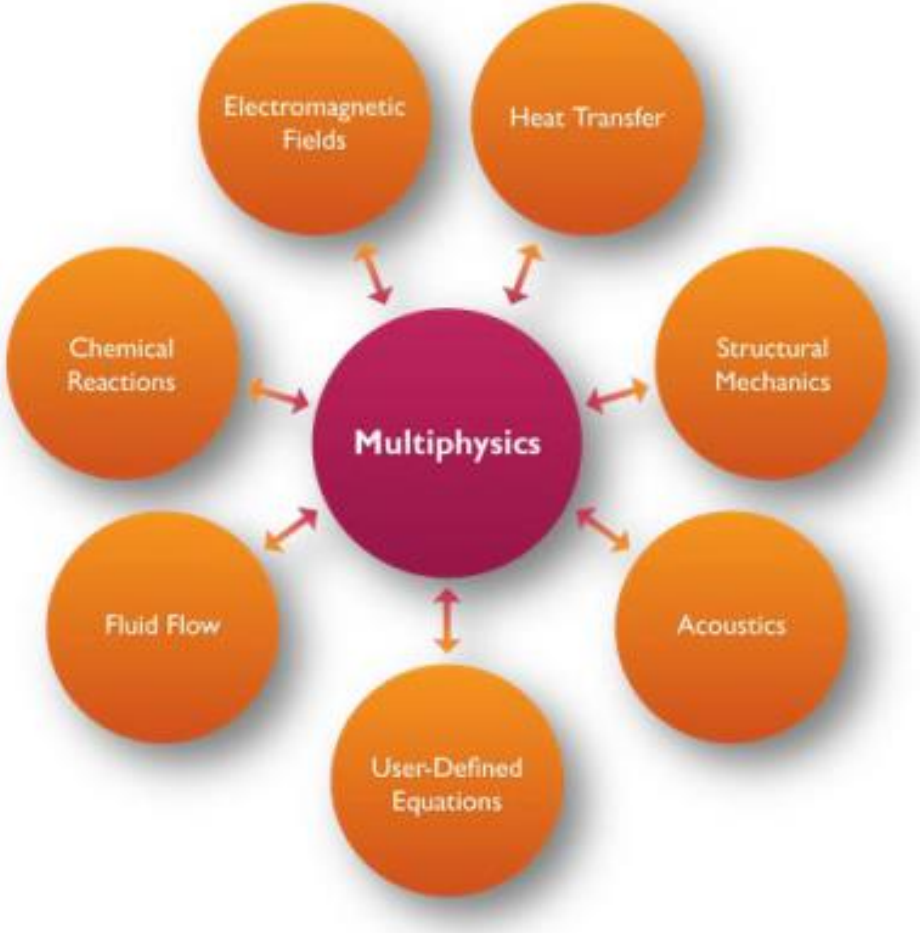
- Understand
- Verify
- Optimize



Directional coupler

COMSOL

The Multiphysics Approach



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Simulating with COMSOL Multiphysics

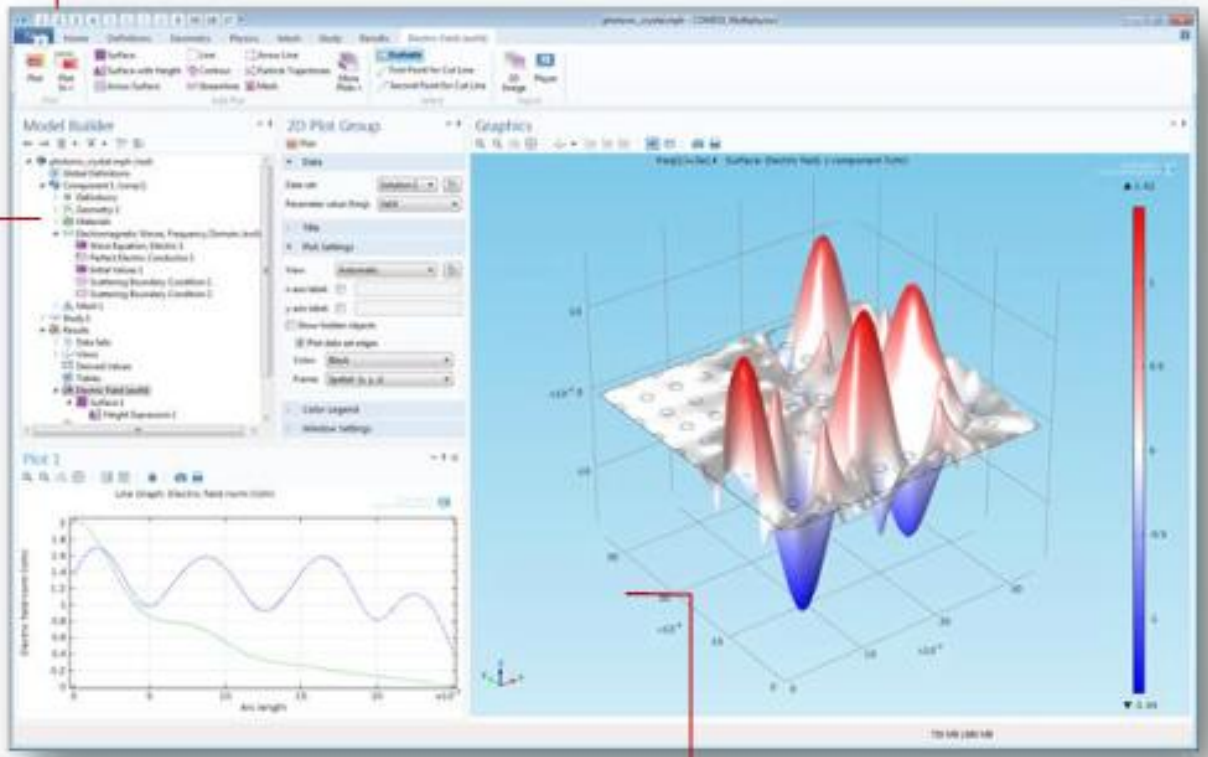
- Electrical, Mechanical, Acoustical, Fluid, and Chemical
- Multiphysics – Coupled phenomena
- Single physics in one integrated environment
- Cross-disciplinary product development

Intensity radiation from a vented loudspeaker cabinet.

COMSOL

All Inclusive Interactive Modeling Environment

COMSOL Desktop®
Straightforward to use, it gives full insight and control over the modeling process



Model Builder
Provides instant access to any part of the model settings

- CAD/Geometry
- Materials
- Physics
- Mesh
- Solve
- Results

Graphics
Ultrafast graphic presentation, stunning visualization, and multiple plots

COMSOL

Product Suite – COMSOL 4.4

COMSOL Multiphysics®

ELECTRICAL
- AC/DC Module
- RF Module
- Wave Optics Module
- MEMS Module
- Plasma Module
- Semiconductor Module

MECHANICAL
- Heat Transfer Module
- Structural Mechanics Module
- Nonlinear Structural Materials Module
- Geomechanics Module
- Fatigue Module
- Multibody Dynamics Module
- Acoustics Module

FLUID
- CFD Module
- Mixer Module
- Microfluidics Module
- Subsurface Flow Module
- Pipe Flow Module
- Molecular Flow Module

CHEMICAL
- Chemical Reaction Engineering Module
- Batteries & Fuel Cells Module
- Electrodeposition Module
- Corrosion Module
- Electrochemistry Module

MULTIPURPOSE
- Optimization Module
- Material Library
- Particle Tracing Module

INTERFACING
- LiveLink™ for MATLAB®
- LiveLink™ for Excel®
- CAD Import Module
- ECAD Import Module
- LiveLink™ for SolidWorks®
- LiveLink™ for SpaceClaim®
- LiveLink™ for Inventor®
- LiveLink™ for AutoCAD®
- LiveLink™ for Creo™ Parametric
- LiveLink™ for Pro/ENGINEER®
- LiveLink™ for Solid Edge®
- File Import for CATIA® V5

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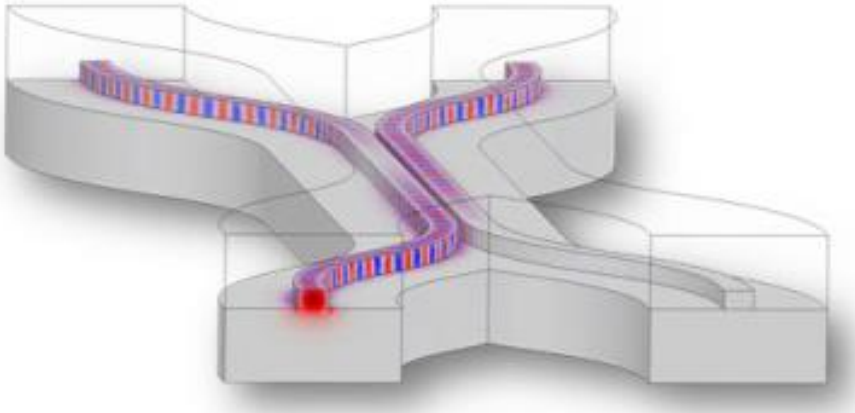
Wave Optics

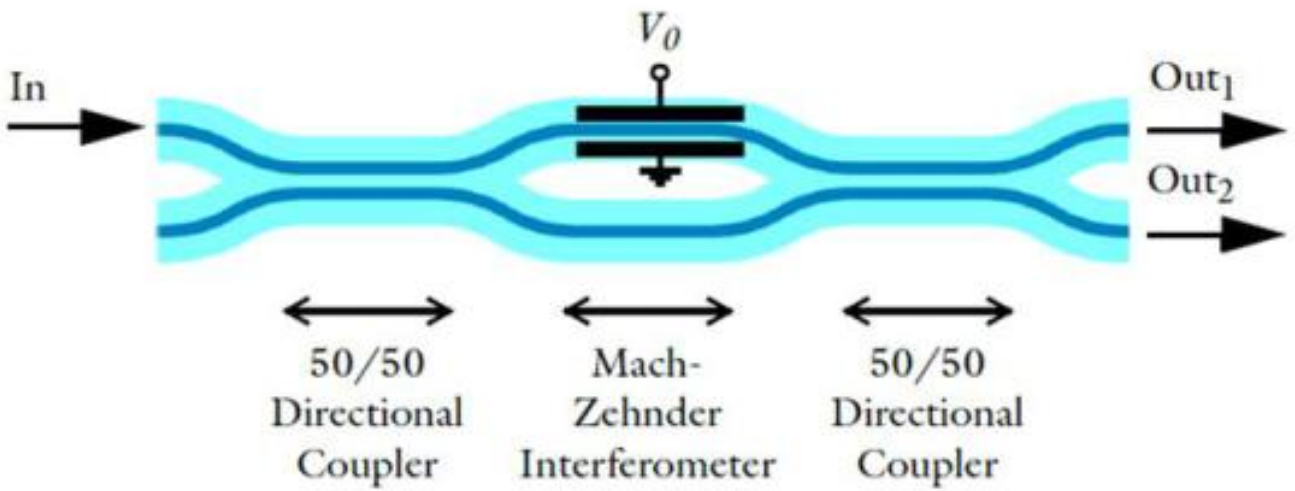
- Electromagnetic wave simulations at optical frequencies (wavelengths from nm to µm)
- Optical components are often much larger than the wavelength

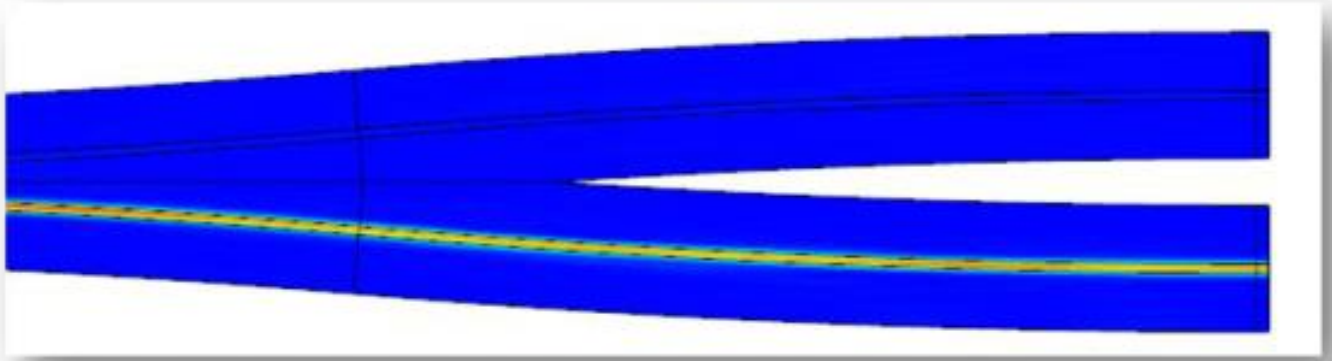


Directional coupler

COMSOL

Coming up: Mach-Zehnder Modulator Demo





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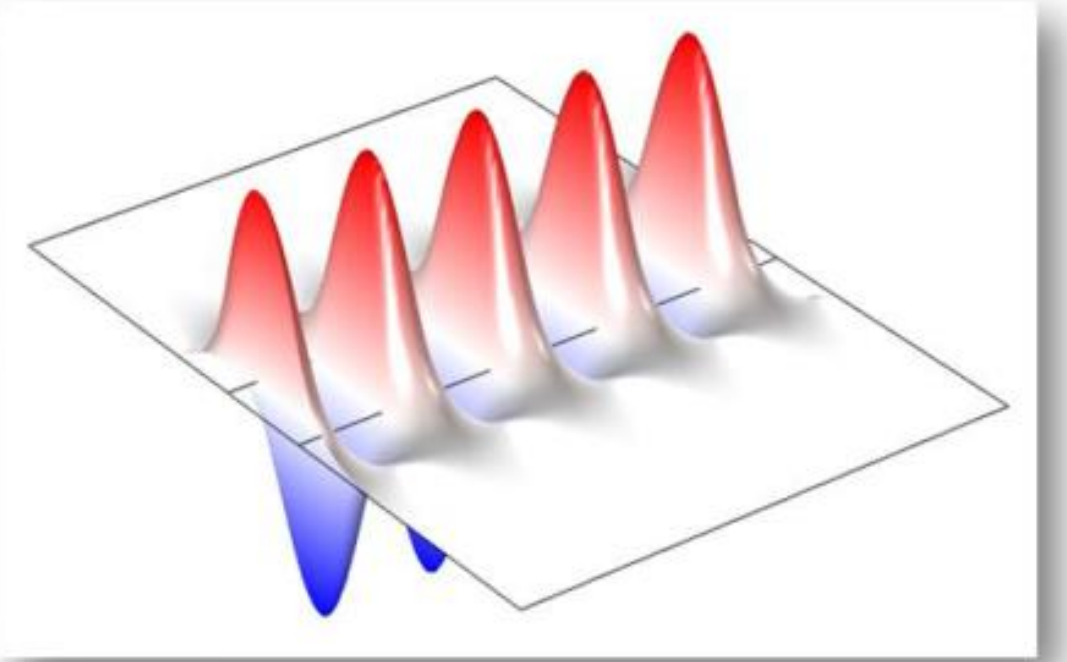
Applications

- Integrated optics
  - Waveguides and couplers
- Fiber optics
  - Photonic crystal fibers
  - Fiber Bragg gratings
- Nonlinear optics
  - Frequency mixing
- Scattering
  - Surface scattering
  - Scattering from nanoparticles
- Multiphysics
  - Sensors
  - Optoelectronics
  - Laser heating
  - ....

Applications: Integrated Optics

- Waveguides
- Filters
- Modulators



E-field in dielectric slab waveguide

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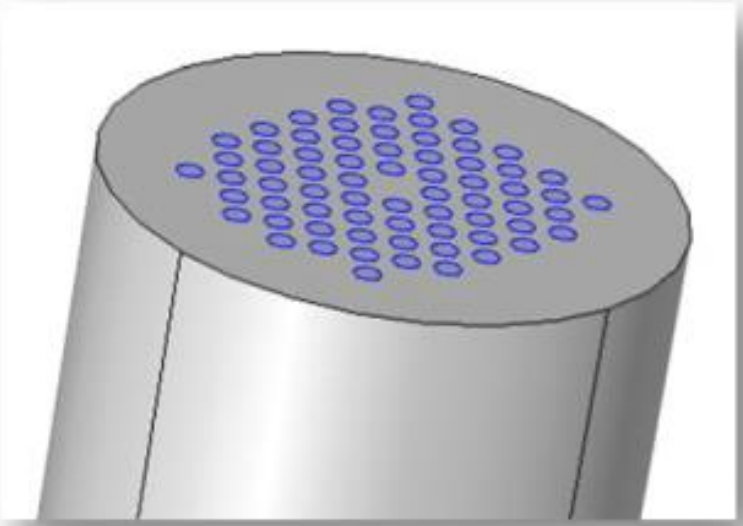
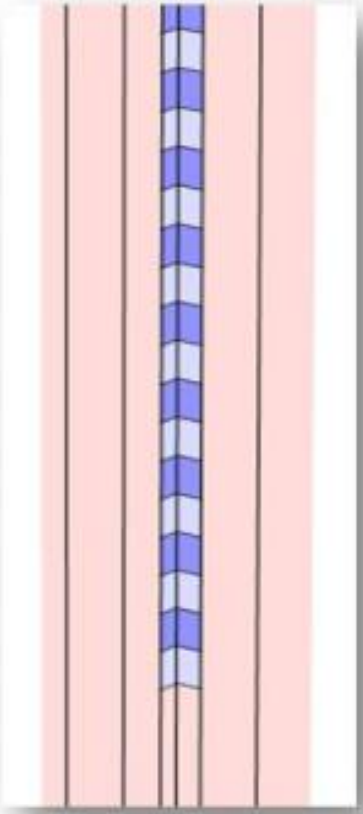
Applications: Fiber Optics

- Photonic crystal fibers
- Fiber Bragg gratings





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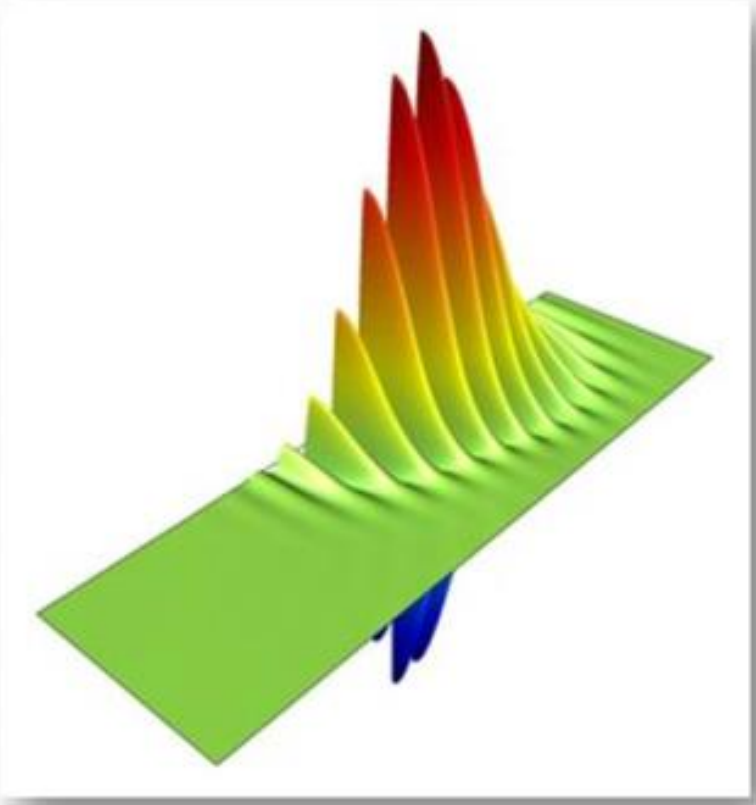
Applications: Nonlinear Optics

- Frequency mixing
- Second harmonic generation



Nd:YAG laser in nonlinear crystal

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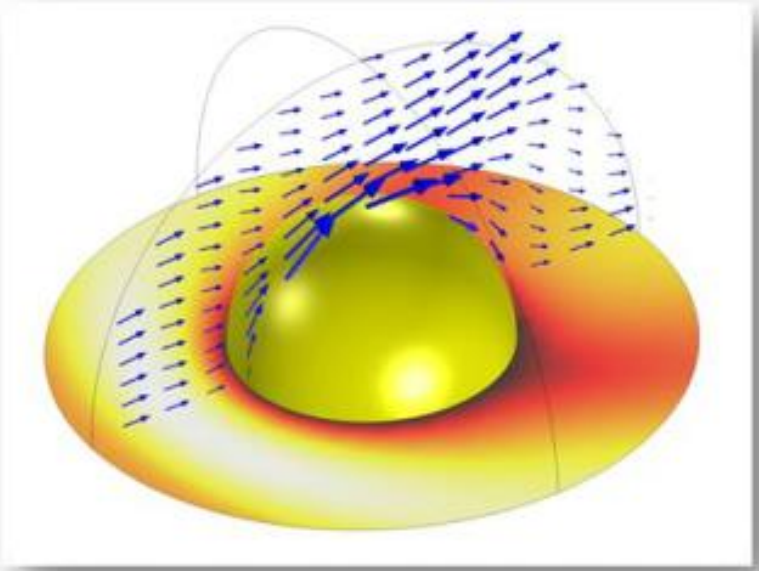
Applications: Scattering

- Scattering from nanoparticles



Scattering off gold nanosphere

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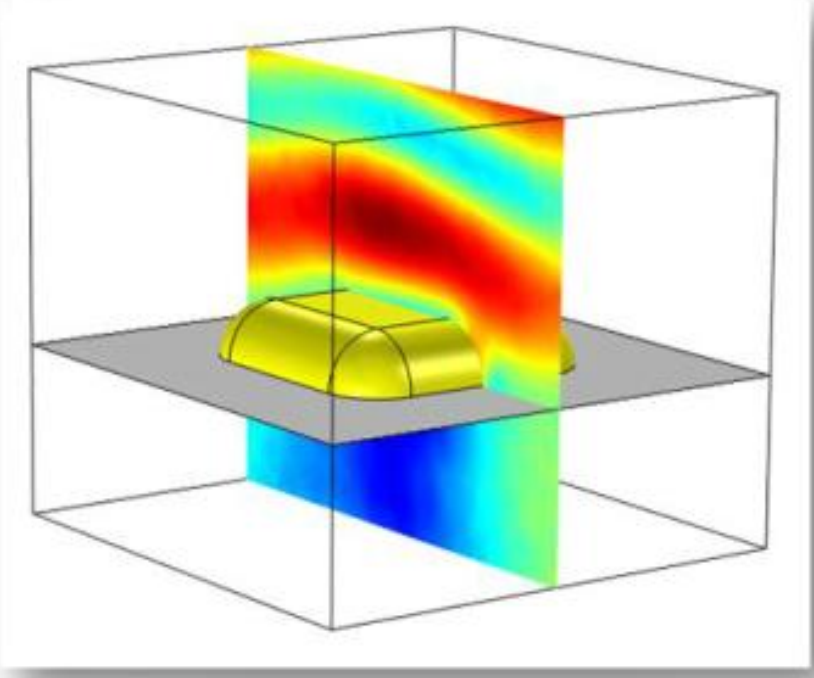
Applications: Scattering

- Scattering from nanoparticles
- Surface scattering



Gold nanoparticle on substrate

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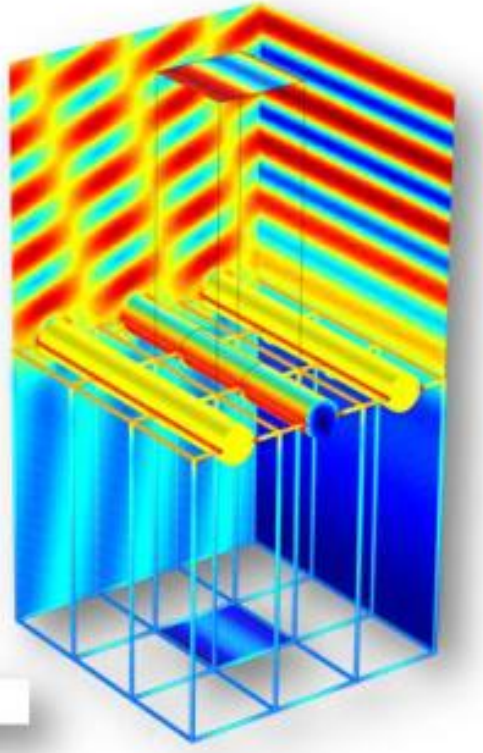
Applications: Scattering

- Scattering from nanoparticles
- Surface scattering
- Periodic structures

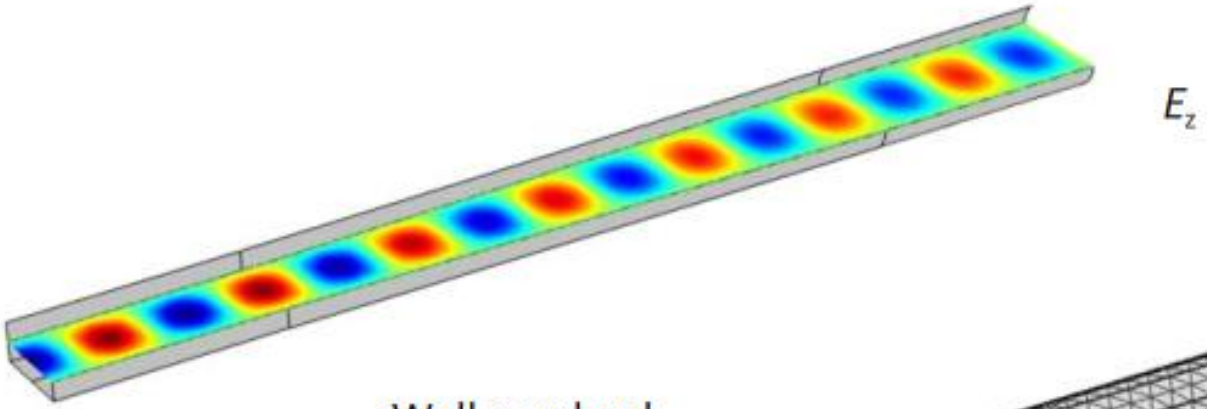


Wire grating on substrate

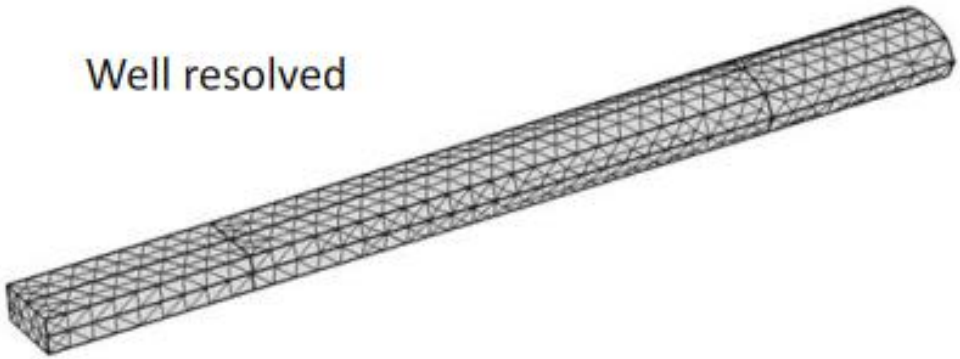
COMSOL

Resolving the Wave

- Example: Microwave waveguide
  - ~ 6 second order elements per wavelength



Well resolved



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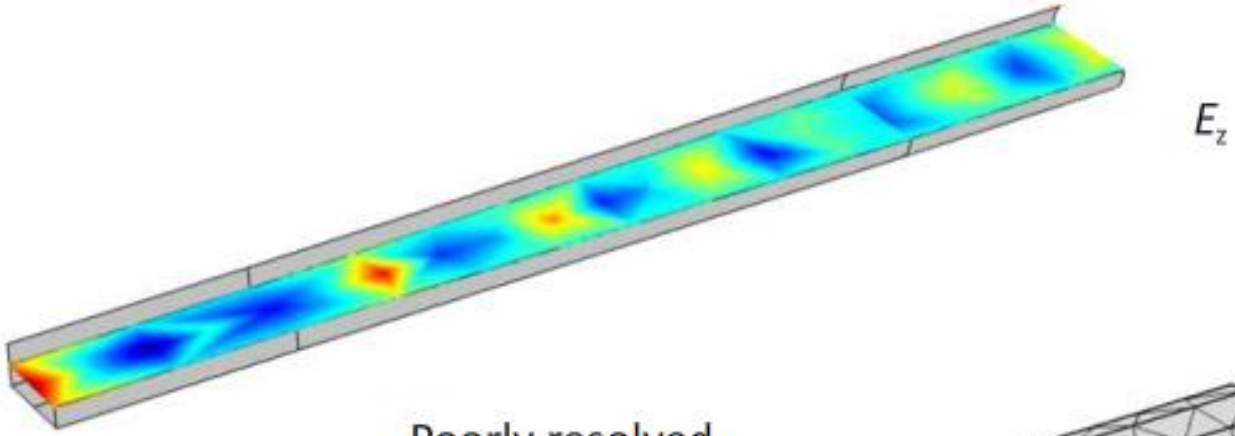
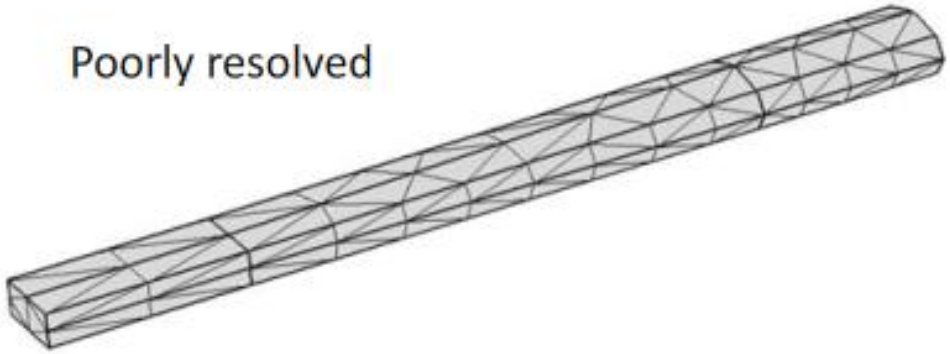
Resolving the Wave

- Example: Microwave waveguide
  - ~ 2 second order elements per wavelength



Poorly resolved



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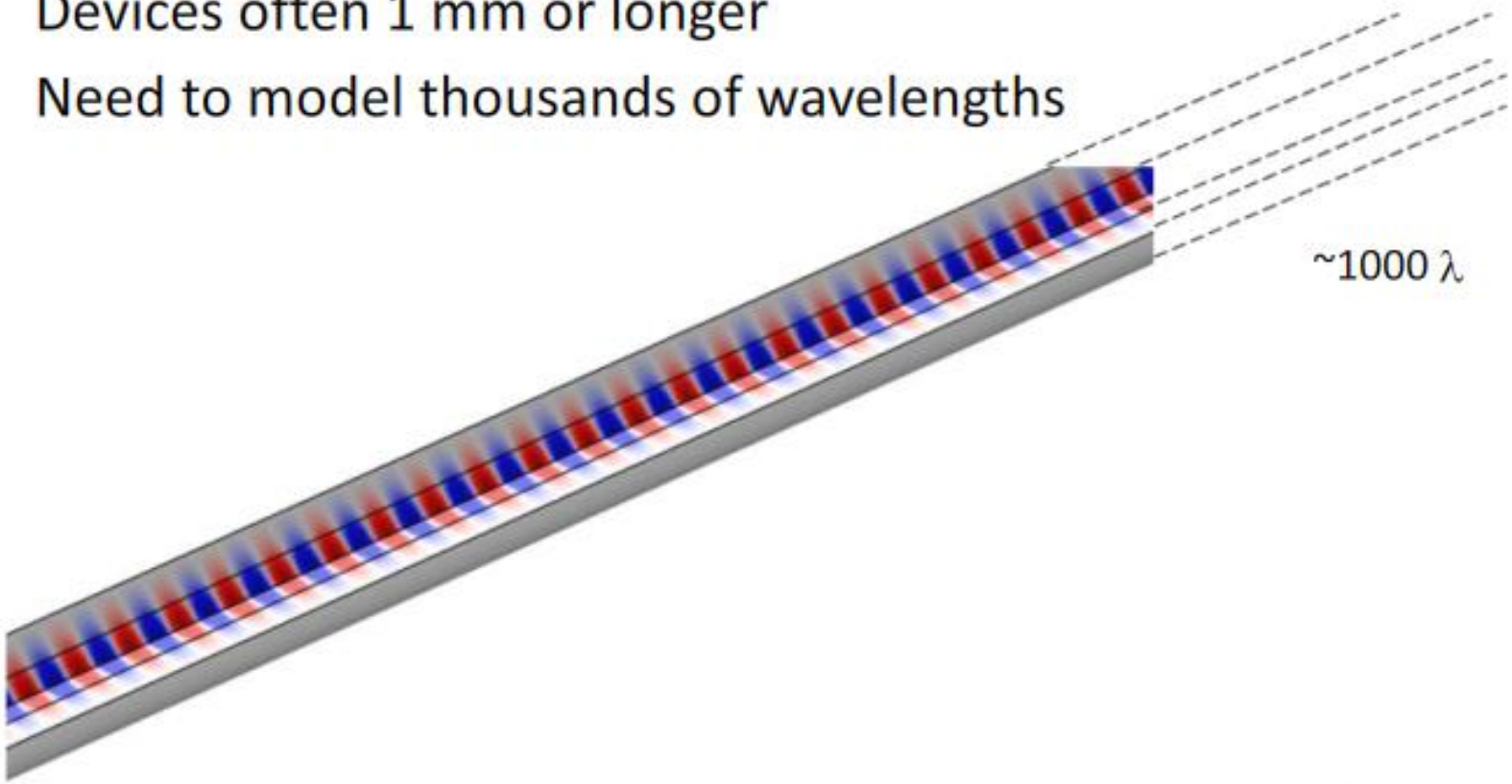
Optical Waveguides

- Optical wavelengths typically < 1 μm
- Devices often 1 mm or longer
- Need to model thousands of wavelengths



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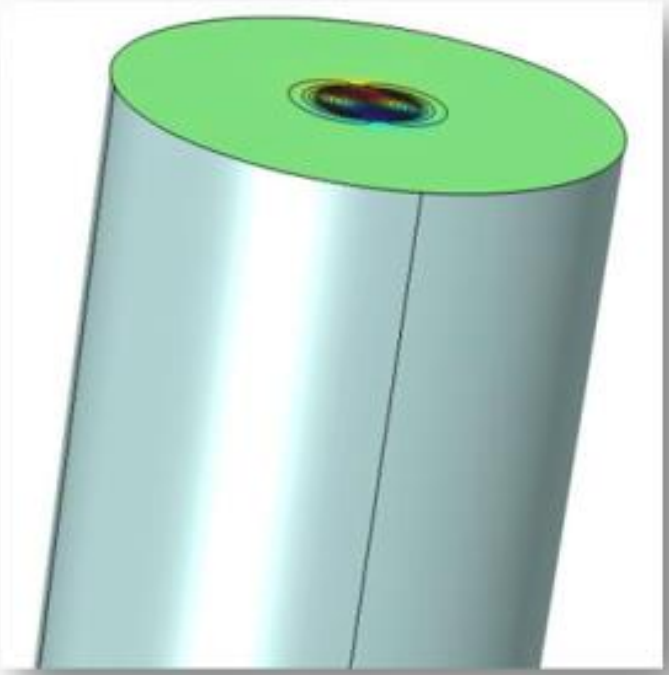
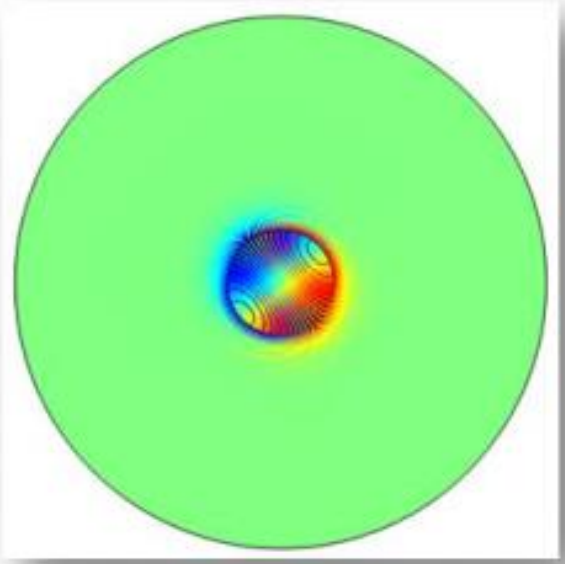
Model the Cross Section

- Step-Index Fiber
- Find modes, propagation constants
- Requires invariance in out-of-plane direction





E, H fields

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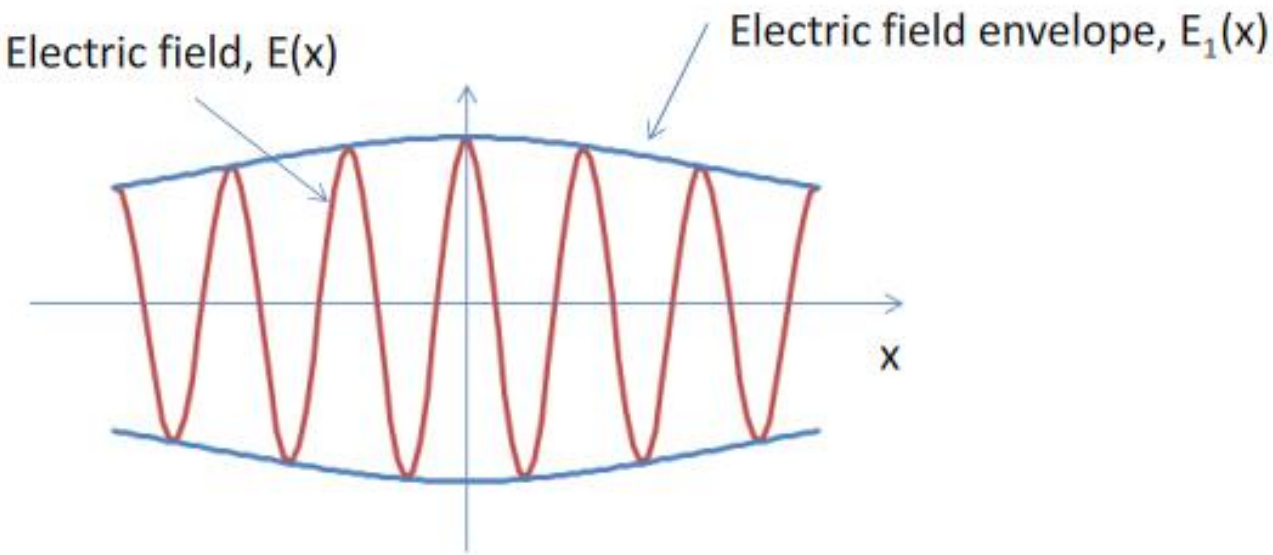
Beam Envelope Method



$$E(x) = E_1(x)\exp(-jk_1x)$$

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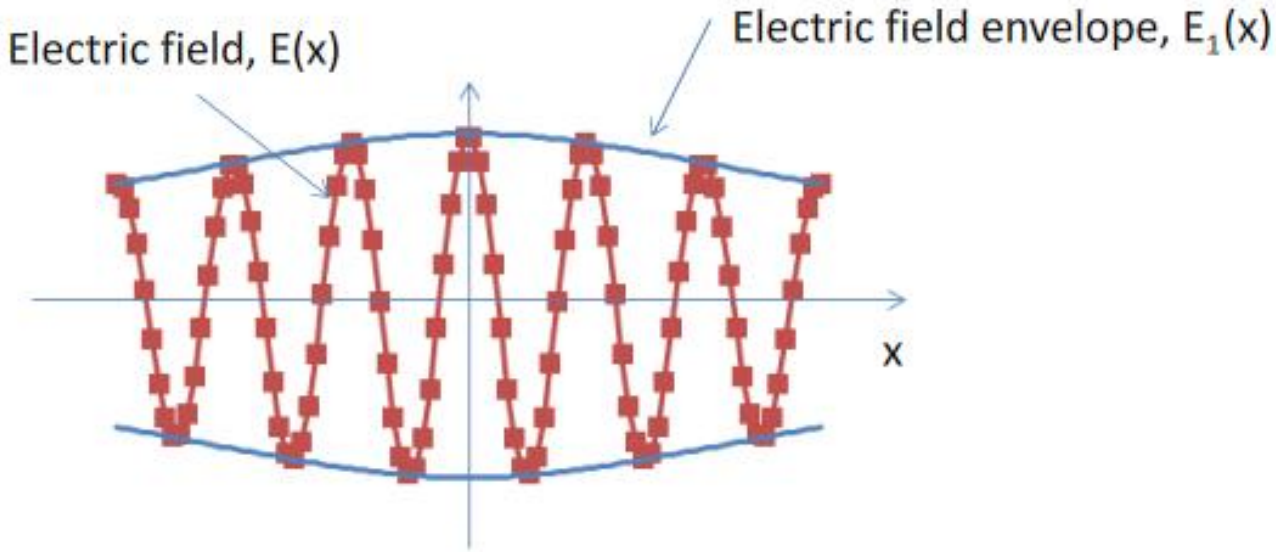
Beam Envelope Method



$$E(x) = E_1(x)\exp(-jk_1x)$$

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Beam Envelope Method

- Helmholtz equation

$$\nabla \times [\mu_{\mathrm{r}}^{-1} \nabla \times \mathbf{E}] - k_0^2 \varepsilon_{rc} \mathbf{E} = \mathbf{0} \qquad (1)$$

- Substitute $\mathbf{E}(\mathbf{r}) = \mathbf{E}_1(\mathbf{r}) \exp(-j\mathbf{k}_1 \cdot \mathbf{r})$

$$(\nabla - \mathbf{k}_1) \times [\mu_{\mathrm{r}}^{-1} (\nabla - \mathbf{k}_1) \times \mathbf{E}_1] - k_0^2 \varepsilon_{rc} \mathbf{E}_1 = \mathbf{0} \qquad (2)$$

- (2) is <u>not</u> an approximation of (1)!

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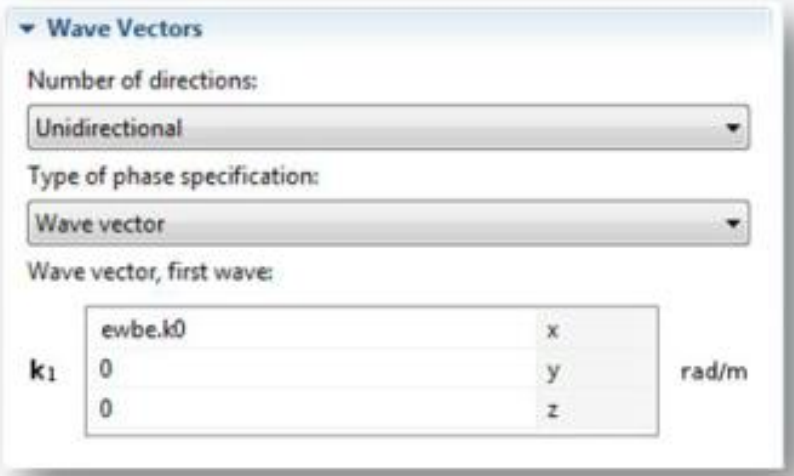
Beam Envelope Method

- Unidirectional
  - $\mathbf{E}(\mathbf{r}) = \mathbf{E}_1(\mathbf{r}) \cdot \exp(-j\mathbf{k}_1 \cdot \mathbf{r})$
  - One main propagation direction



- Bidirectional
  - $\mathbf{E}(\mathbf{r}) = \mathbf{E}_1(\mathbf{r}) \cdot \exp(-j\mathbf{k}_1 \cdot \mathbf{r}) + \mathbf{E}_2(\mathbf{r}) \cdot \exp(-j\mathbf{k}_2 \cdot \mathbf{r})$
  - Use in models with reflective surfaces
    - Fabry-Perot Cavities
    - Beam Splitters

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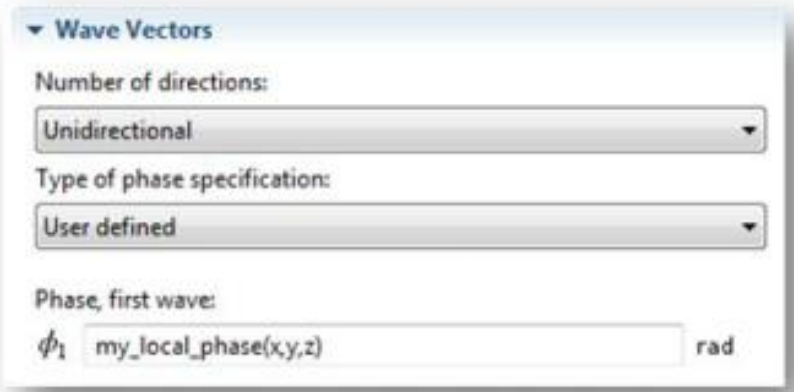
Beam Envelope Method

- User defined
  - Specify your own local phase



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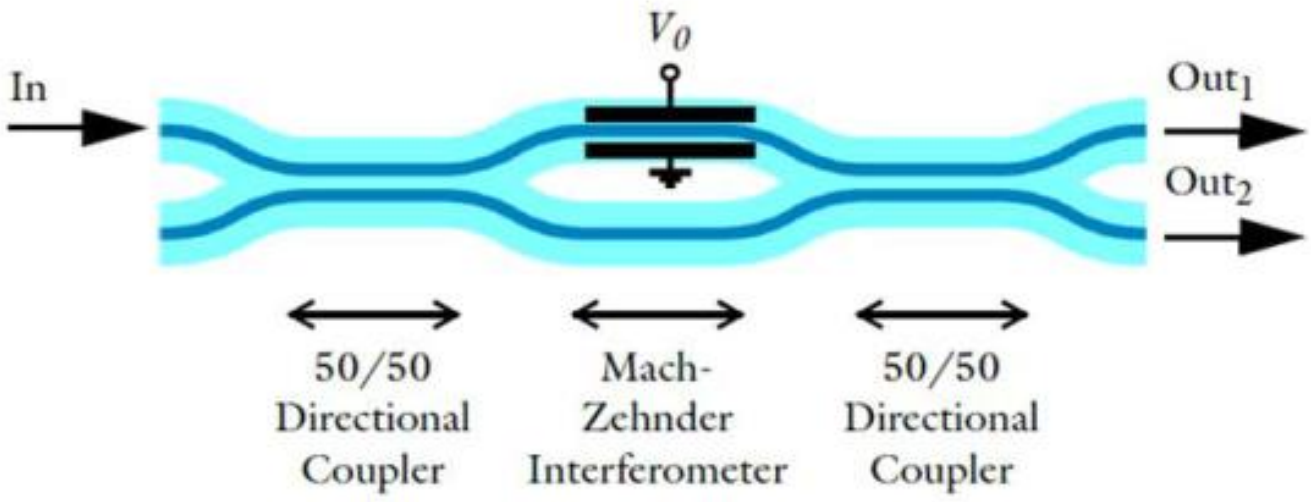
Demo: Mach-Zehnder Modulator

- Static electric field in upper interferometer arm modifies refractive index
- Interference in second coupler



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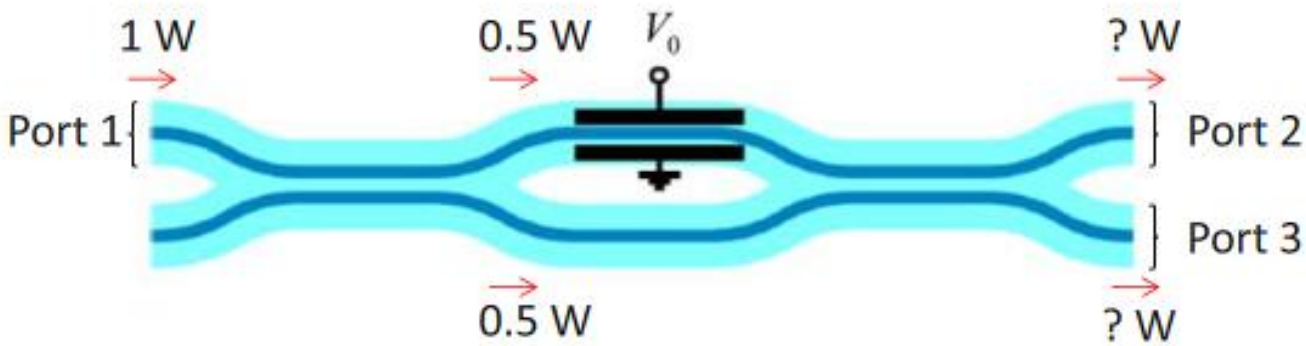
Demo: Mach-Zehnder Modulator

- Ports find and transmit propagating modes
- Calculate S21 and S31 as functions of V_0



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Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Component 1 | Add Component | Parameters | Variables | Functions | Build All | Import | Materials | Electrostatics | Add Physics | Build Mesh | Mesh 1 | Compute | Study 1 | Add Study | Add Plot Group | Model Libraries | More Windows | Layout

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
  - Study 1
  - Results

Root

Model version:

Model description: Mach-Zehnder Modulator

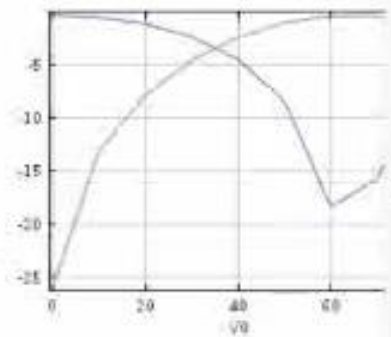
A Mach-Zehnder modulator is used for controlling the

Used Products

COMSOL Multiphysics

Wave Optics Module

Model Thumbnail

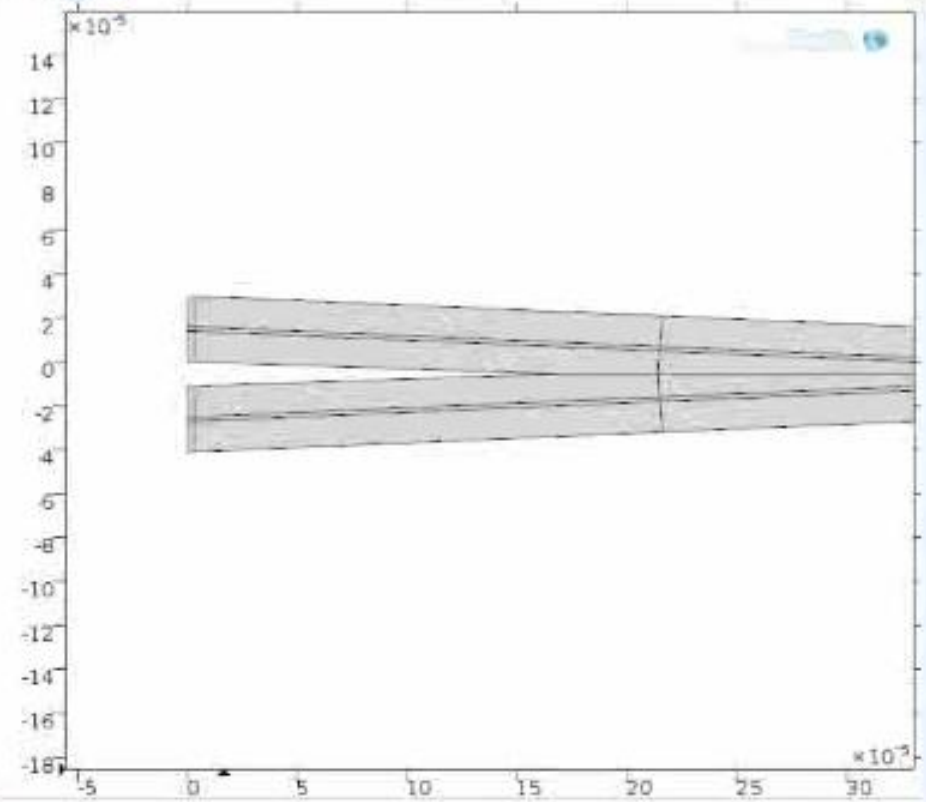


Set Model Thumbnail

Unit System

SI

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

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  - Results

Parameters

Parameters

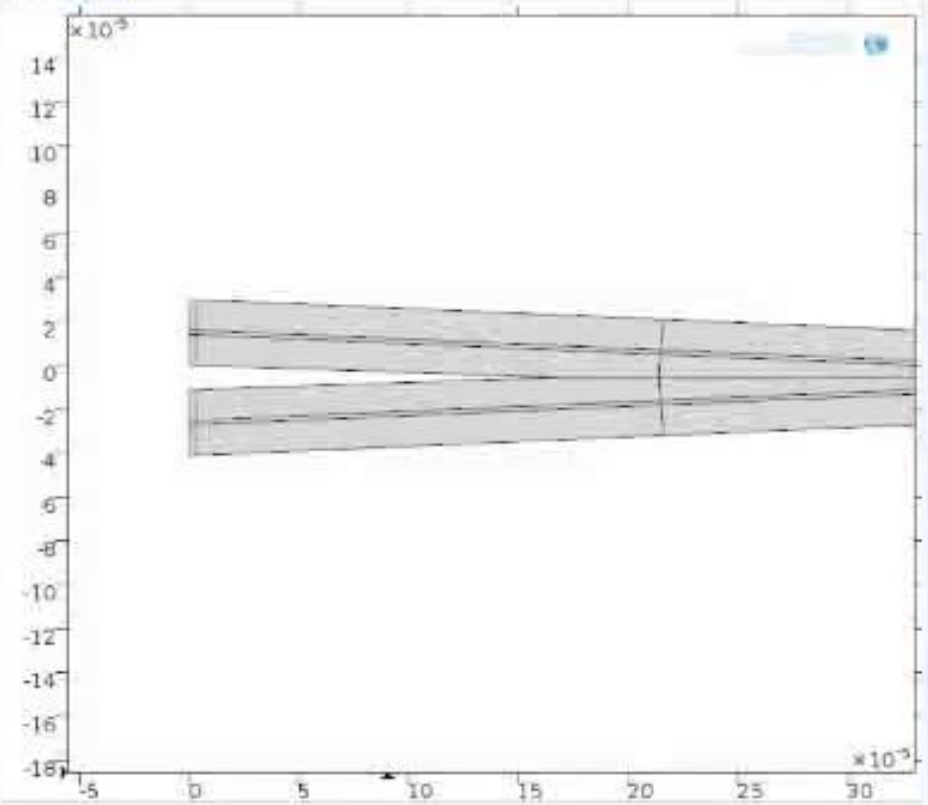
Name	Expression	Value
wl	1.55[um]	1.5500E-6 m
f0	c_const/wl	1.9341E14 1/s
w	2[um]	2.0000E-6 m
w_tot	30[um]	3.0000E-5 m
n_clad	2.2	2.2000
n_core	2.22	2.2200
d0	2*wl	3.1000E-6 m
dy_bend	0.6*w_tot	1.8000E-5 m
r0	2.5[mm]	0.0025000 m
alpha	acos((r0-dy_ben...	0.084878 rad
dx_bend	2*r0*sin(alpha)	4.2388E-4 m
d_dc	380[um]	3.8000E-4 m
d_mz	2[cm]	0.020000 m
hx	wl/(6*n_core)/(1...	3.2324E-5 m
hy	wl/(6*n_core)/si...	1.3726E-6 m
dy_wg	3[um]	3.0000E-6 m

Name:

Expression:

Description:

Graphics



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Mach_Zehnder.mph - COMSOL Multiphysics

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    - Parameters
  - Component 1 (comp1)
    - Definitions
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dy_bend	0.6*w_tot	1.8000E-5 m
r0	2.5[mm]	0.0025000 m
alpha	acos((r0-dy_ben...	0.084878 rad
dx_bend	2*r0*sin(alpha)	4.2388E-4 m
d_dc	380[um]	3.8000E-4 m
d_mz	2[cm]	0.020000 m
hx	wl/(6*n_core)/(1...	3.2324E-5 m
hy	wl/(6*n_core)/si...	1.3726E-6 m
dy_wg	3[um]	3.0000E-6 m

Name:

f0

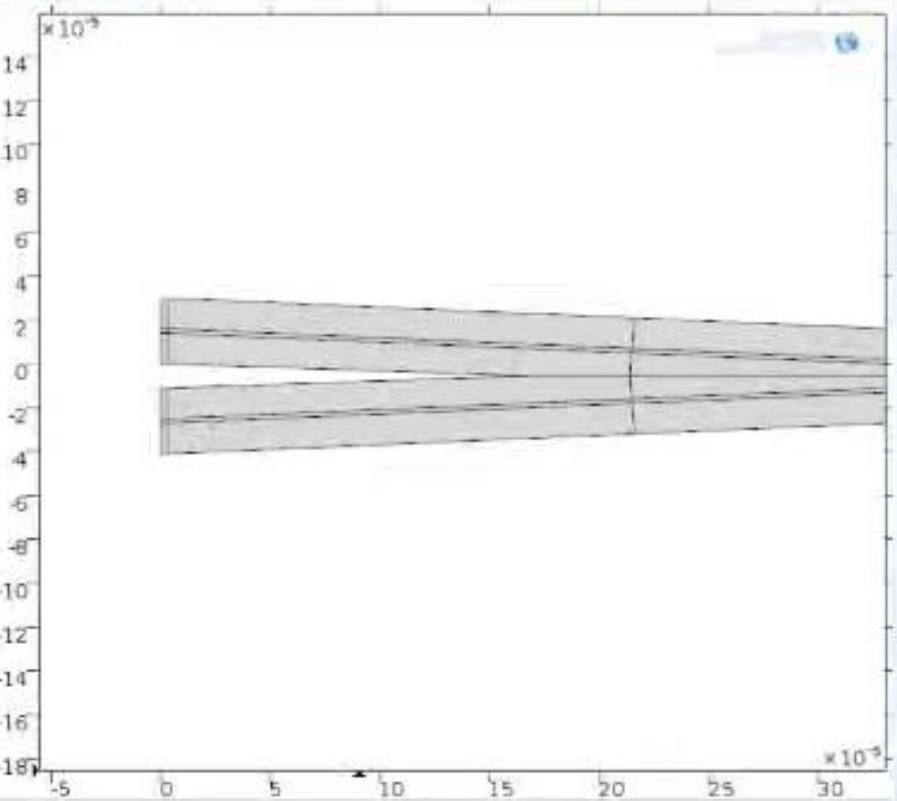
Expression:

c_const/wl

Description:

Frequency

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

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Component 1 | Add Component | Parameters | Variables | Functions | Build All | Import | Materials | Electrostatics | Add Physics | Build Mesh | Mesh 1 | Compute | Study 1 | Add Study | Add Plot Group | Model Libraries | More Windows | Layout

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
      - Rectangle 1 (r1)
      - Circle 1 (c1)
      - Circle 2 (c2)
      - Circle 3 (c3)
      - Circle 4 (c4)
      - Difference 1 (dif1)
      - Rotate 1 (rot1)
      - Rectangle 2 (r2)
      - Mirror 1 (mir1)
      - Rectangle 3 (r3)
      - Mirror 2 (mir2)
      - Rectangle 4 (r4)
      - Difference 2 (dif2)
      - Mirror 3 (mir3)
      - Polygon 1 (pol1)
      - Polygon 2 (pol2)
      - Form Union (fin)
    - Materials
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
  - Study 1
  - Results

Geometry

Build All

Units

Scale values when changing units

Length unit:

m

Angular unit:

Degrees

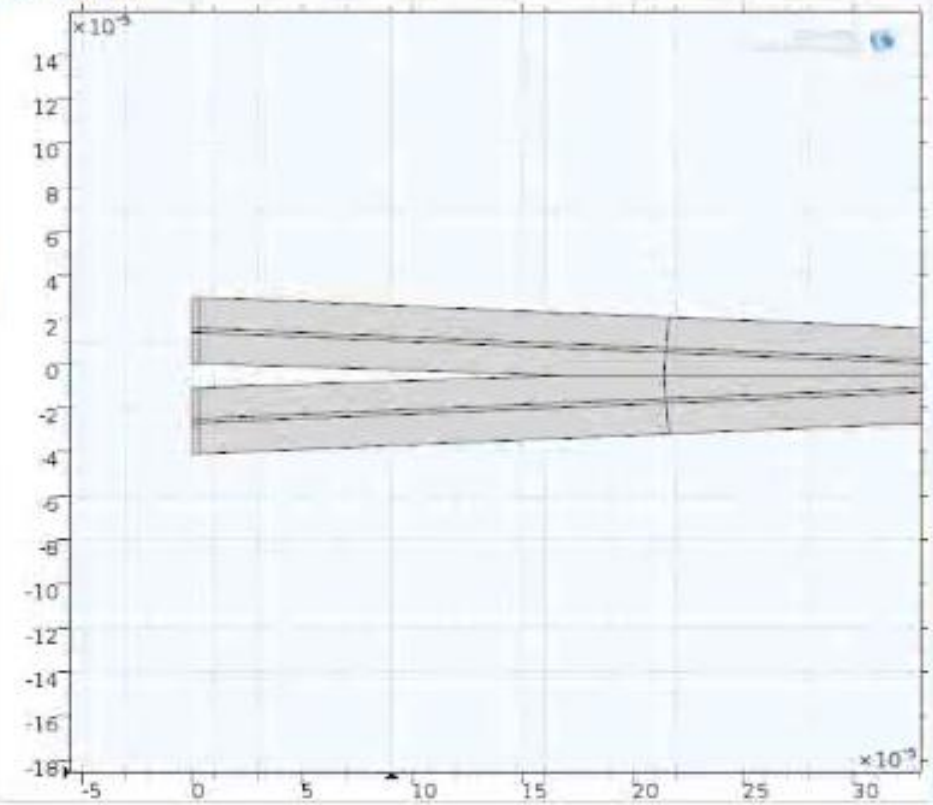
Advanced

Default relative repair tolerance:

1E-6

Automatic rebuild

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Component 1 | Add Component | Parameters | Variables | Functions | Build All | Import | Materials | Electrostatics | Add Physics | Build Mesh | Mesh 1 | Compute | Study 1 | Add Study | Add Plot Group | Model Libraries | More Windows | Layout

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
  - Study 1
  - Results

Geometry

Build All

Units

Scale values when changing units

Length unit:

m

Angular unit:

Degrees

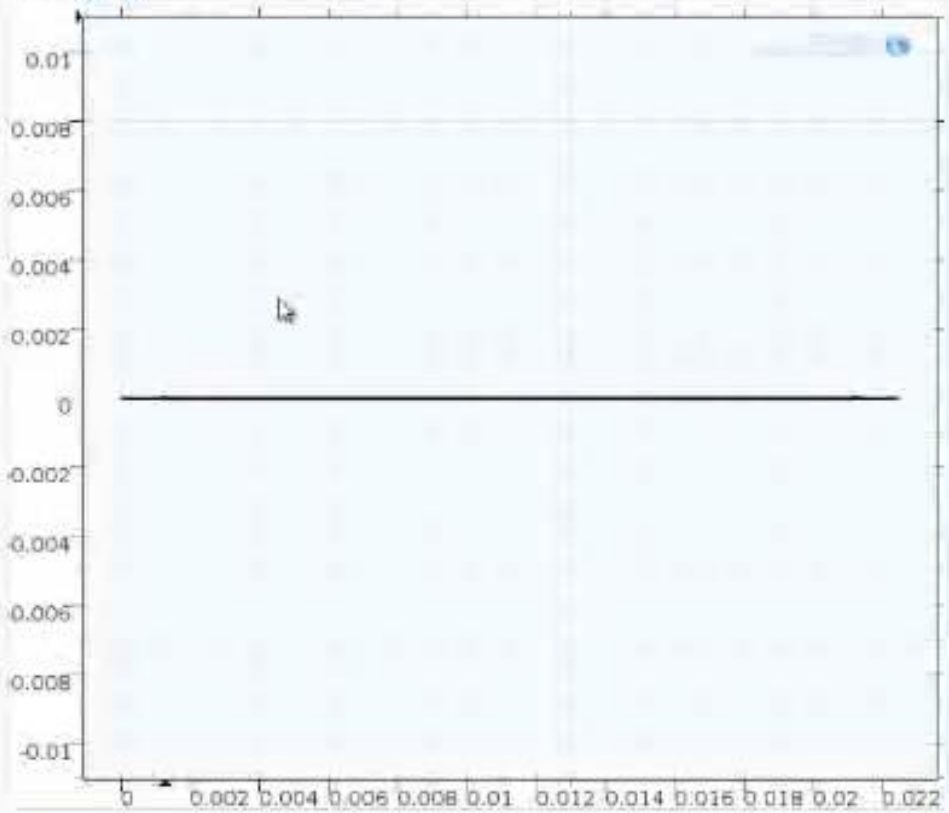
Advanced

Default relative repair tolerance:

1E-6

Automatic rebuild

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Component 1 | Add Component | Parameters | Variables | Functions | Build All | Import | Materials | Electrostatics | Add Physics | Build Mesh | Mesh 1 | Compute | Study 1 | Add Study | Add Plot Group | Model Libraries | More Windows | Layout

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
      - Core (mat2)
      - Cladding (mat1)
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
  - Study 1
  - Results

Material

Geometric Entity Selection

Geometric entity level: Domain

Selection: Core

Active

2, 5, 8, 11, 15, 16, 20

Override

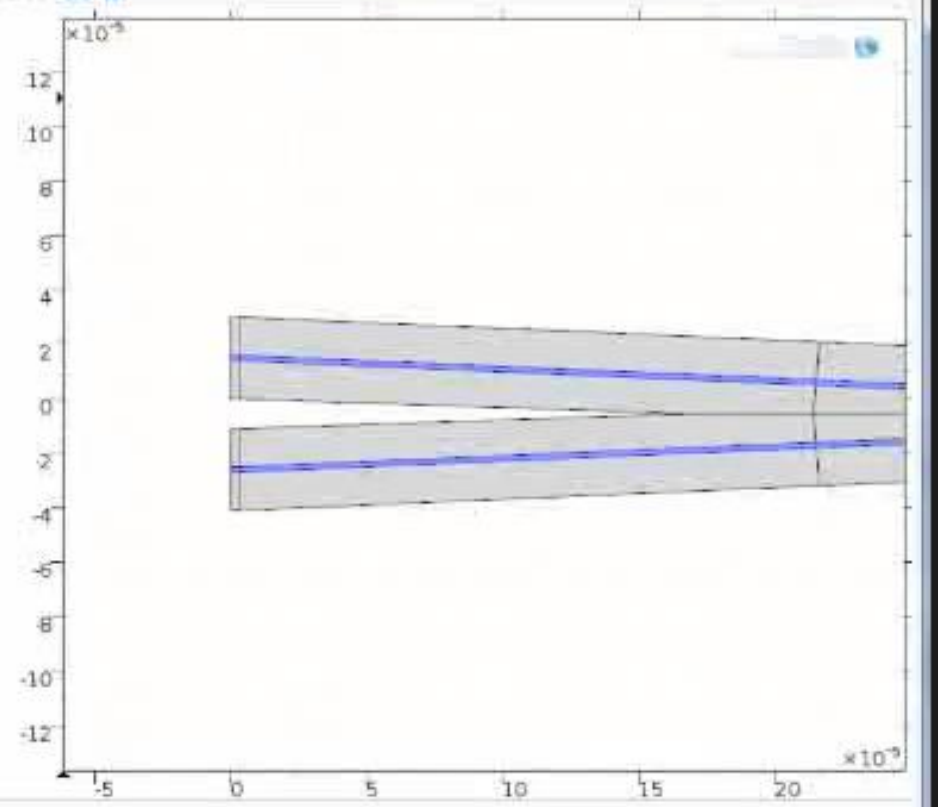
Material Properties

Material Contents

Property	Name	Valu
Relative permittivity	epsilonr	epsr
Refractive index	n	n_co
Refractive index, imaginary part	ki	0

Appearance

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Component 1 | Add Component | Model
Parameters | Variables | Functions | Definitions
Build All | Import | Geometry
Materials
Electrostatics | Add Physics | Physics
Build Mesh | Mesh 1 | Mesh
Compute | Study 1 | Add Study | Study
Add Plot Group | Results
Model Libraries | More Windows | Windows
Layout

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
      - Core (mat2)
      - Cladding (mat1)
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
  - Study 1
  - Results

Material

Geometric Entity Selection

Geometric entity level: Domain

Selection: Core

Active

2
5
8
11
15
16
20

Override

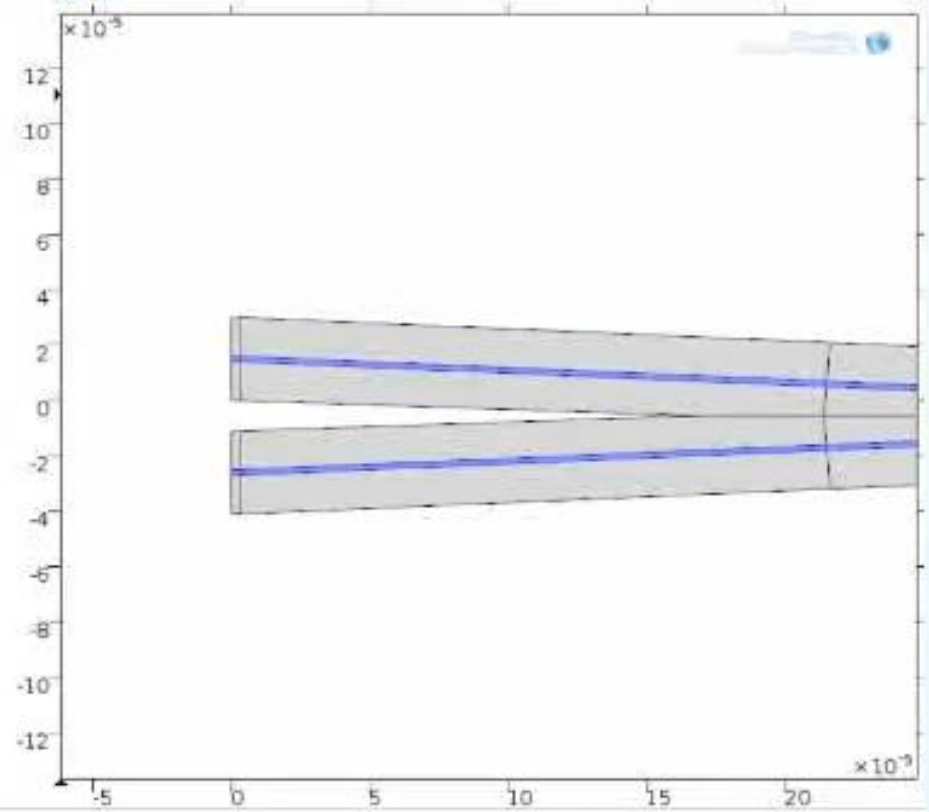
Material Properties

Material Contents

Property	Name	Value
Relative permittivity	epsilonr	epsr
Refractive index	n	n_core
Refractive index, imaginary part	ki	0

Appearance

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Component 1 | Add Component | Parameters | Variables | Functions | Geometry | Materials | Electromagnetic Waves, Beam Envelopes | Add Physics | Build Mesh | Mesh 1 | Compute | Study 1 | Add Study | Add Plot Group | Model Libraries | More Windows | Layout

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
    - Electrostatics (es)
    - Mesh 1
  - Study 1
  - Results

Electromagnetic Waves,...

Interface Identifier

Identifier: ewbe

Domain Selection

Selection: All domains

Active: 1, 2, 3, 4, 5, 6, 7

Equation

Components

Electric field components solved for:

Out-of-plane vector

Wave Vectors

Number of directions:

Unidirectional

Type of phase specification:

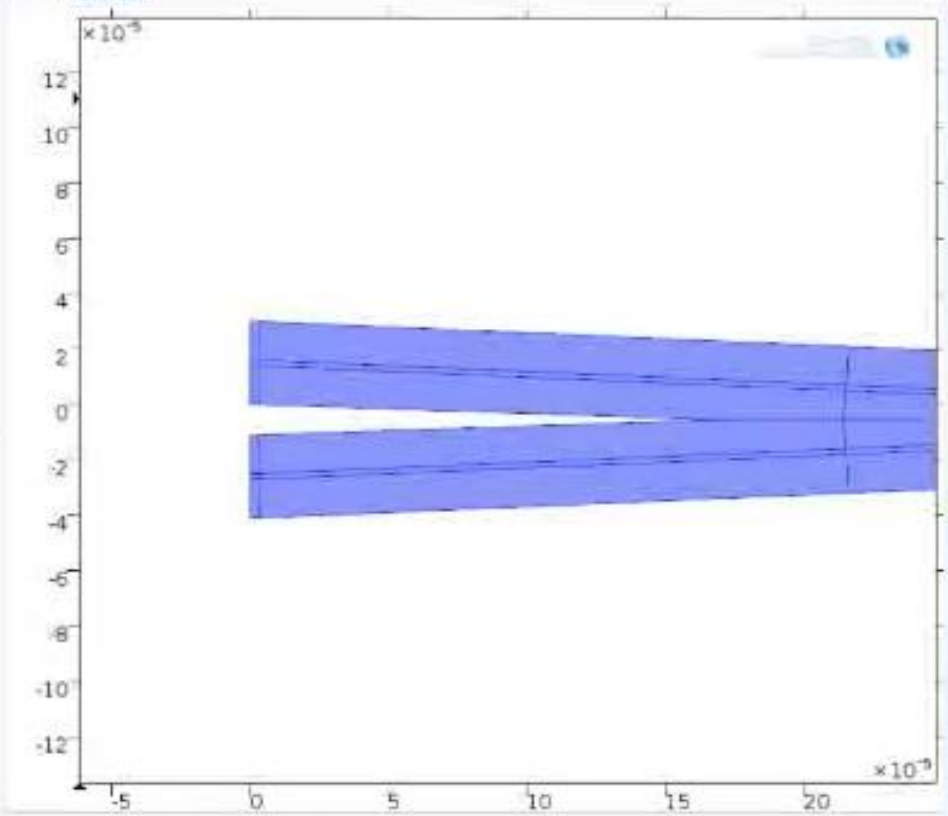
Wave vector

Wave vector, first wave:

k_1 0 x, 0 y rad/m

Port Sweep Settings

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Component 1 | Add Component | Parameters | Variables | Functions | Build All | Import | Materials | Electrostatics | Add Physics | Build Mesh | Mesh 1 | Compute | Study 1 | Add Study | Add Plot Group | Model Libraries | More Windows | Layout

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
    - Mesh 1
  - Study 1
  - Results

Electrostatics

Interface Identifier

Identifier: es

Domain Selection

Selection: All domains

Active

1
2
3
4
5
6
7

Equation

Thickness

Out-of-plane thickness

d 1 m

Terminal Sweep Settings

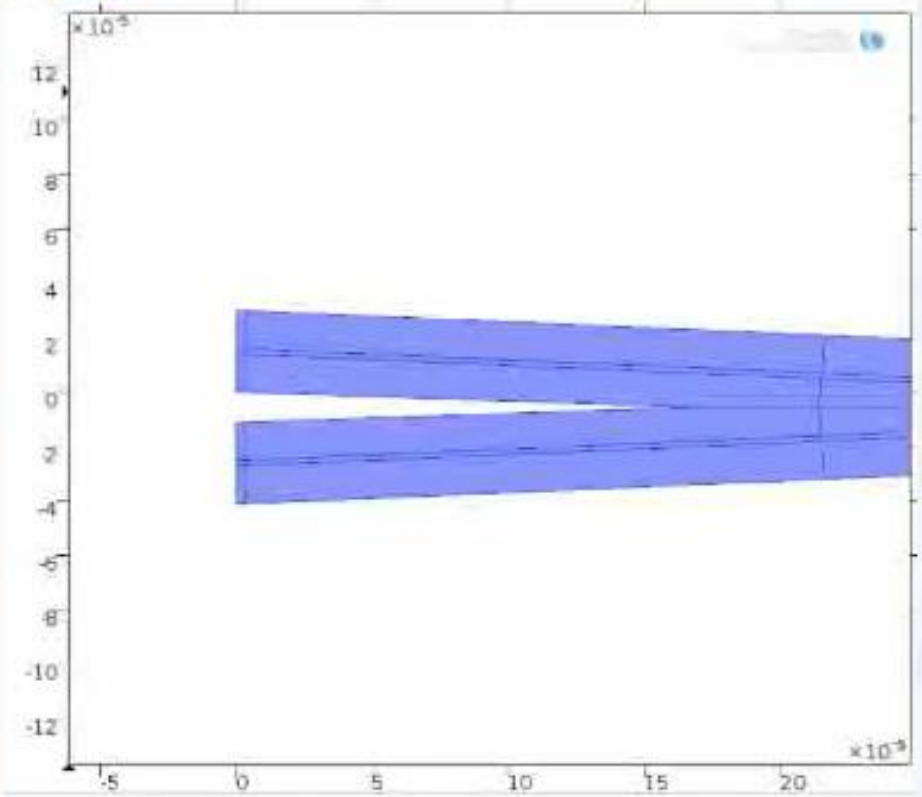
Reference impedance:

Z_{ref} 50[ohm] Ω

Activate terminal sweep

Dependent Variables

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electromagnetic Waves, Beam Envelopes | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Global

Recently Used
- Port

Electromagnetic Waves, Beam Envelopes
- Perfect Electric Conductor
- Scattering Boundary Condition
- Perfect Magnetic Conductor
- Magnetic Field
- Electric Field
- Surface Current
- Periodic Condition
- Port
- Matched Boundary Condition

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
    - Mesh 1
  - Study 1
  - Results

Domain Selection

Selection: All domains

Active: 1, 2, 3, 4, 5, 6, 7

Equation

Components

Electric field components solved for:

Out-of-plane vector

Wave Vectors

Number of directions:

Unidirectional

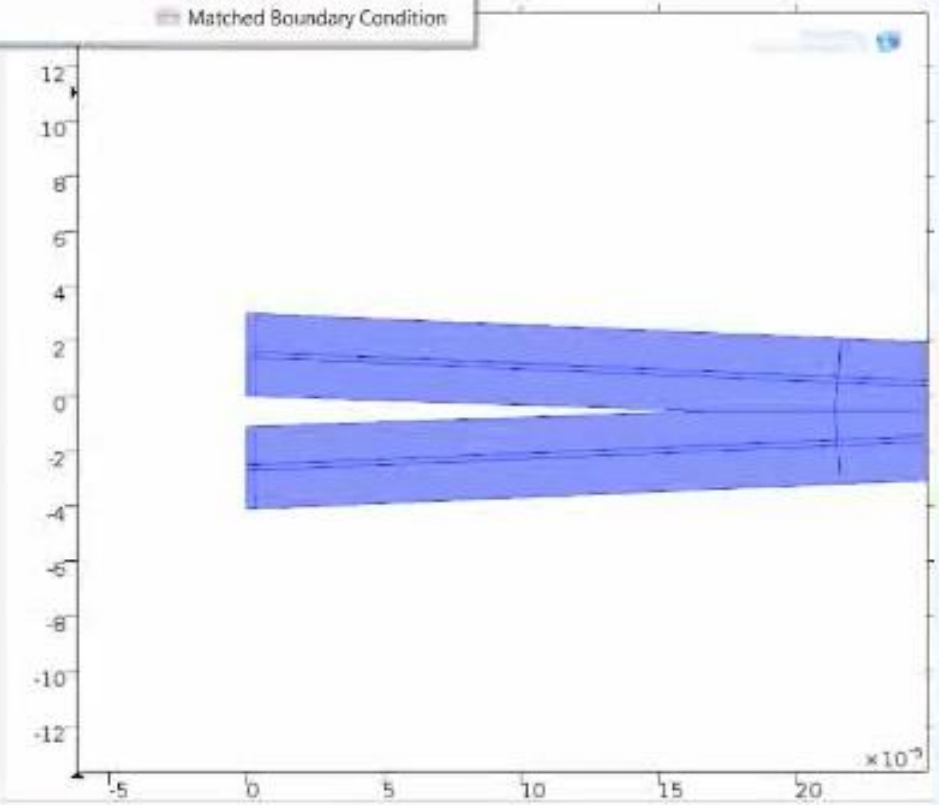
Type of phase specification:

Wave vector

Wave vector, first wave:

k_1 0 x, 0 y rad/m

Port Sweep Settings



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electromagnetic Waves, Beam Envelopes | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
    - Mesh 1
  - Study 1
  - Results

Port

Boundary Selection

Selection: Manual

Active

5

Override and Contribution

Equation

Port Properties

Port name:

1

Type of port:

User defined

Wave excitation at this port:

Off

Port phase:

θ_{in} 0 rad

Port Mode Settings

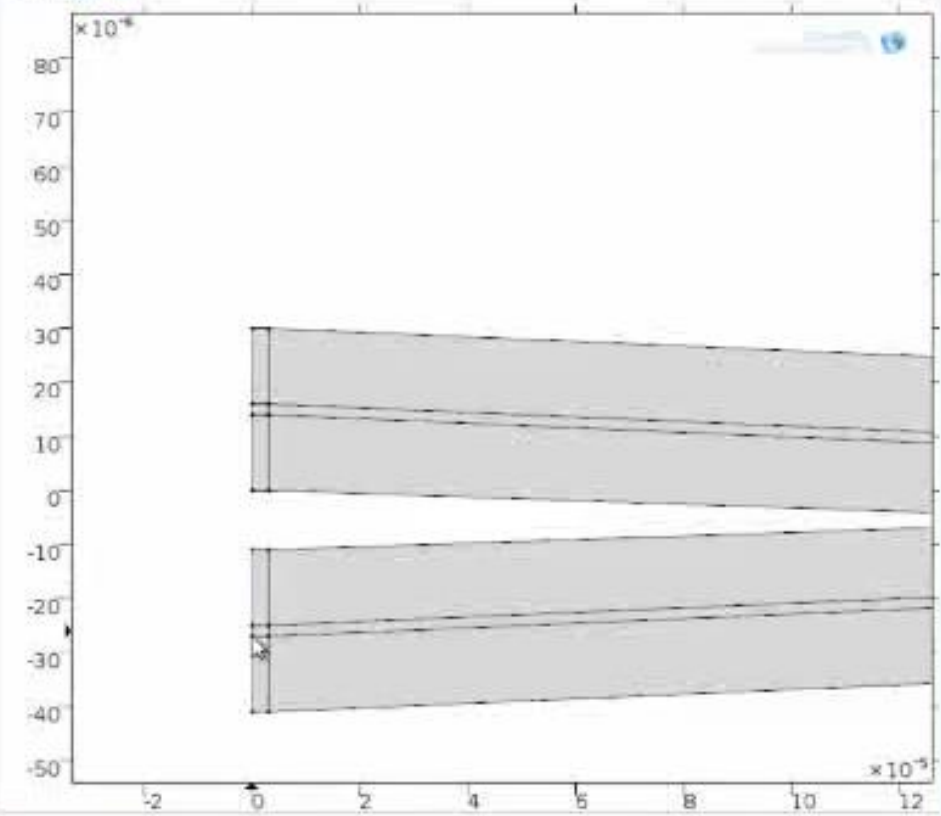
Input quantity:

Electric field

Electric field:

0 x

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electromagnetic Waves, Beam Envelopes | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
    - Mesh 1
  - Study 1
  - Results

Port

Boundary Selection

Selection: Manual

Active

1
3
5

Override and Contribution

Equation

Port Properties

Port name:

1

Type of port:

Numeric

Wave excitation at this port:

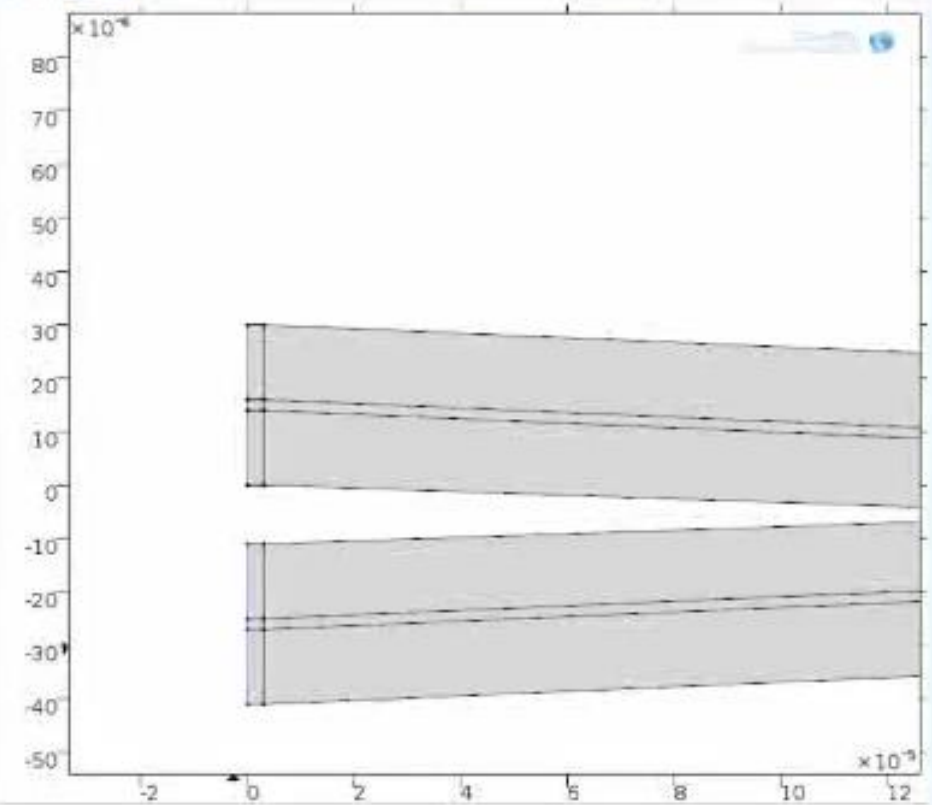
Off

Port phase:

θ_p 0 rad

Port Mode Settings

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electromagnetic Waves, Beam Envelopes | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Globals

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
    - Mesh 1
  - Study 1
  - Results

Port

Boundary Selection

Selection: Manual

Active

1
3
5

Override and Contribution

Equation

Port Properties

Port name:

1

Type of port:

Numeric

Wave excitation at this port:

On

Specify deposited power

Port input power:

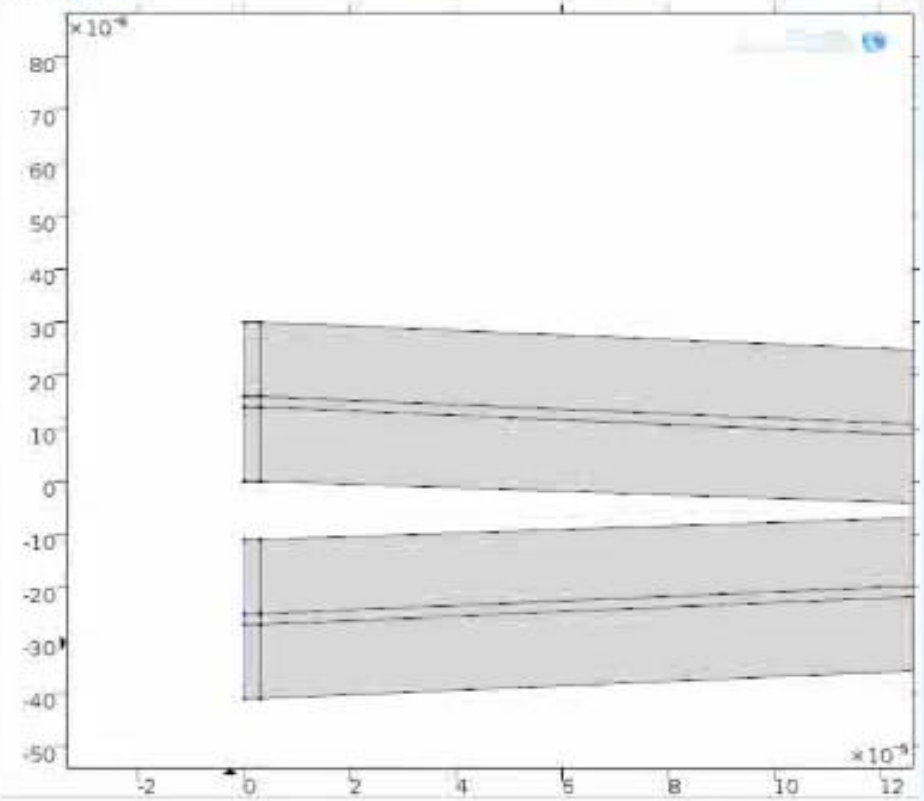
P_{in} 1 W

Port phase:

θ_{in} 0 rad

Port Mode Settings

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electromagnetic Waves, Beam Envelopes | Add Physics | Domains | Boundaries | Pairs | Points | Edges | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
    - Mesh 1
  - Study 1
  - Results

Electromagnetic Waves,...

Domain Selection

Selection: All domains

Active

1
2
3
4
5
6
7

Equation

Components

Electric field components solved for:

Out-of-plane vector

Wave Vectors

Number of directions:

Unidirectional

Type of phase specification:

Wave vector

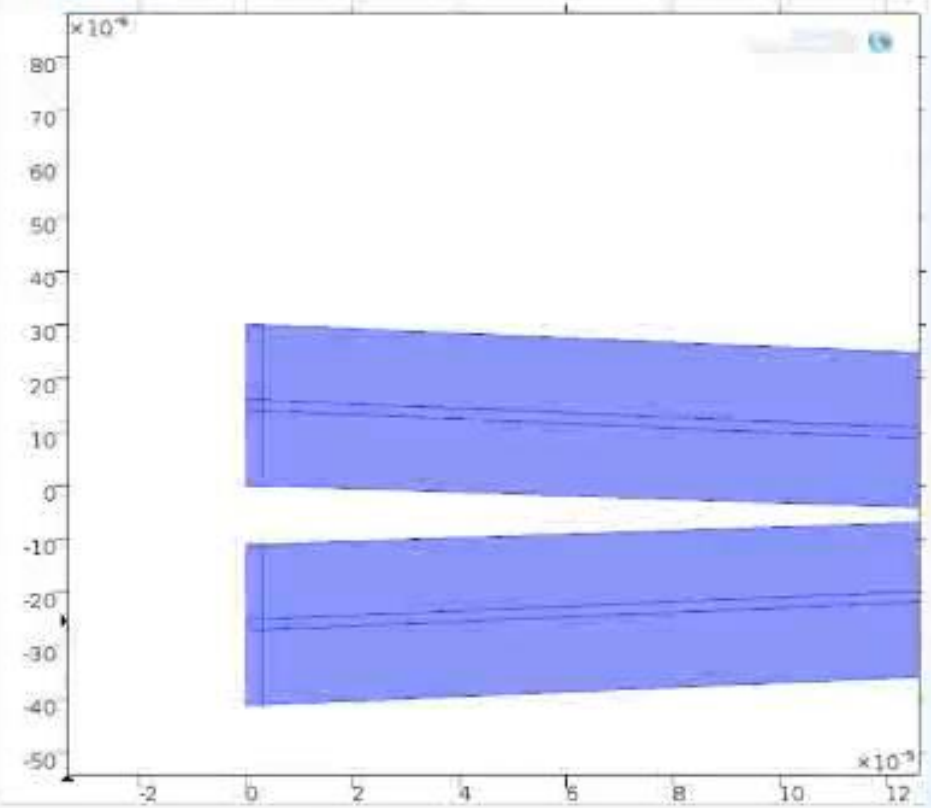
Wave vector, first wave:

k_1 x 0 y 0 rad/m

Port Sweep Settings

Activate port sweep

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electromagnetic Waves, Beam Envelopes | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
    - Mesh 1
  - Study 1
  - Results

Electromagnetic Waves,...

Domain Selection

Selection: All domains

Active

1
2
3
4
5
6
7

Equation

Components

Electric field components solved for:

Out-of-plane vector

Wave Vectors

Number of directions:

Unidirectional

Type of phase specification:

Wave vector

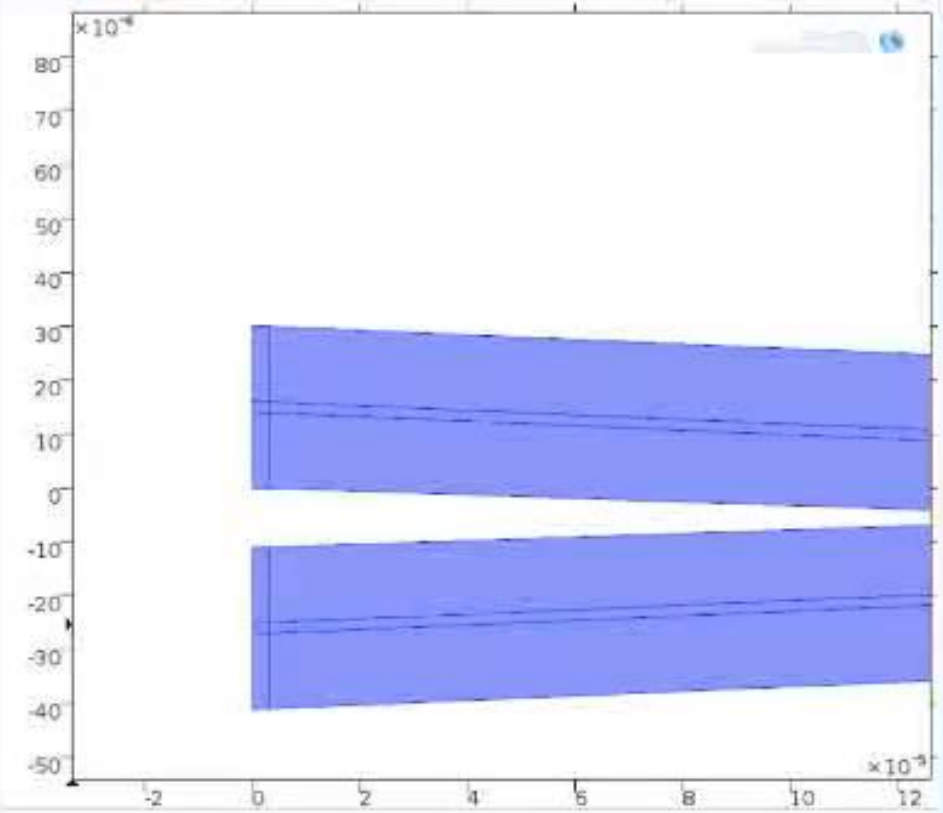
Wave vector, first wave:

k_1 ewbe.beta_1 x, 0 y rad/m

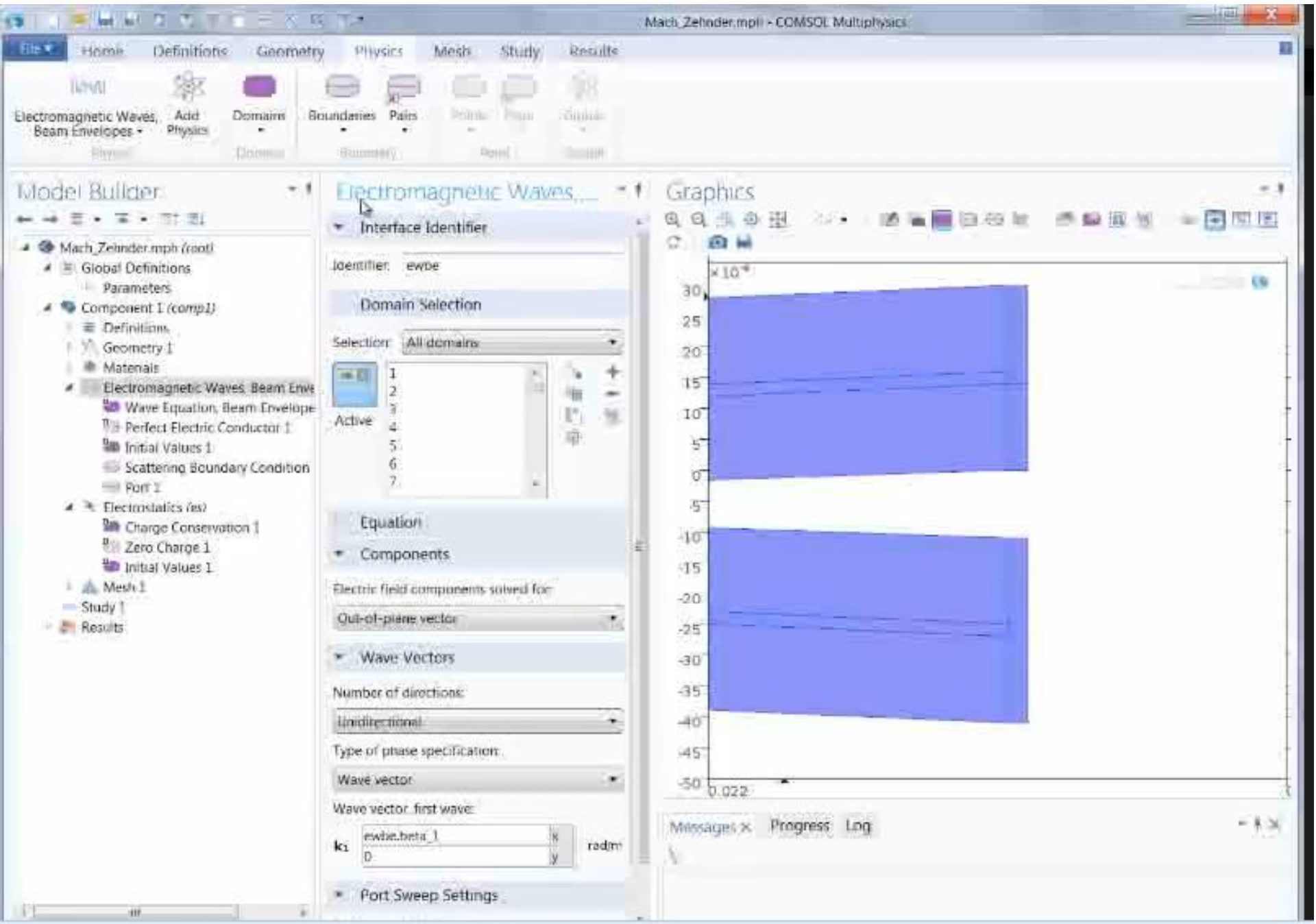
Port Sweep Settings

Activate port sweep

Graphics



Messages | Progress | Log


Mach_Zehnder.mph - COMSOL Multiphysics
File
Home
Definitions
Geometry
Physics
Mesh
Study
Results
Electromagnetic Waves, Beam Envelopes
Add Physics
Domains
Boundaries
Pairs
Model Builder
Mach_Zehnder.mph (root)
Global Definitions
Parameters
Component 1 (comp1)
Definitions
Geometry 1
Materials
Electromagnetic Waves, Beam Enve
Wave Equation, Beam Envelope
Perfect Electric Conductor 1
Initial Values 1
Scattering Boundary Condition
Port 1
Electrostatics (es)
Charge Conservation 1
Zero Charge 1
Initial Values 1
Mesh 1
Study 1
Results
Electromagnetic Waves...
Interface Identifier
Identifier: ewbe
Domain Selection
Selection: All domains
Active
1
2
3
4
5
6
7
Equation
Components
Electric field components solved for:
Out-of-plane vector
Wave Vectors
Number of directions:
Unidirectional
Type of phase specification:
Wave vector
Wave vector, first wave:
k1
ewbe.beta_1
0
x
y
rad/m
Port Sweep Settings
Graphics
×10⁻⁶
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
0.022
Messages
Progress
Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electromagnetic Waves, Beam Envelopes | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
      - Port 2
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
    - Mesh 1
  - Study 1
  - Results

Port

Boundary Selection

Selection: Manual

Active

134
135
136

Override and Contribution

Equation

Port Properties

Port name:

2

Type of port:

User defined

- User defined
- Numeric
- Rectangular
- Periodic

θ_v 0 rad

Port Mode Settings

Input quantity:

Electric field

Electric field:

0 x

Graphics

×10⁻⁴

30 25 20 15 10 5 0 -5 -10 -15 -20 -25 -30 -35 -40 -45 -50

0.022

Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electromagnetic Waves, Beam Envelopes | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
      - Port 2
      - Port 3
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
    - Mesh 1
  - Study 1
  - Results

Port

Boundary Selection

Selection: Manual

Active

132

Override and Contribution

Equation

Port Properties

Port name:

3

Type of port:

User defined

Wave excitation at this port:

Off

Port phase:

θ_p 0 rad

Port Mode Settings

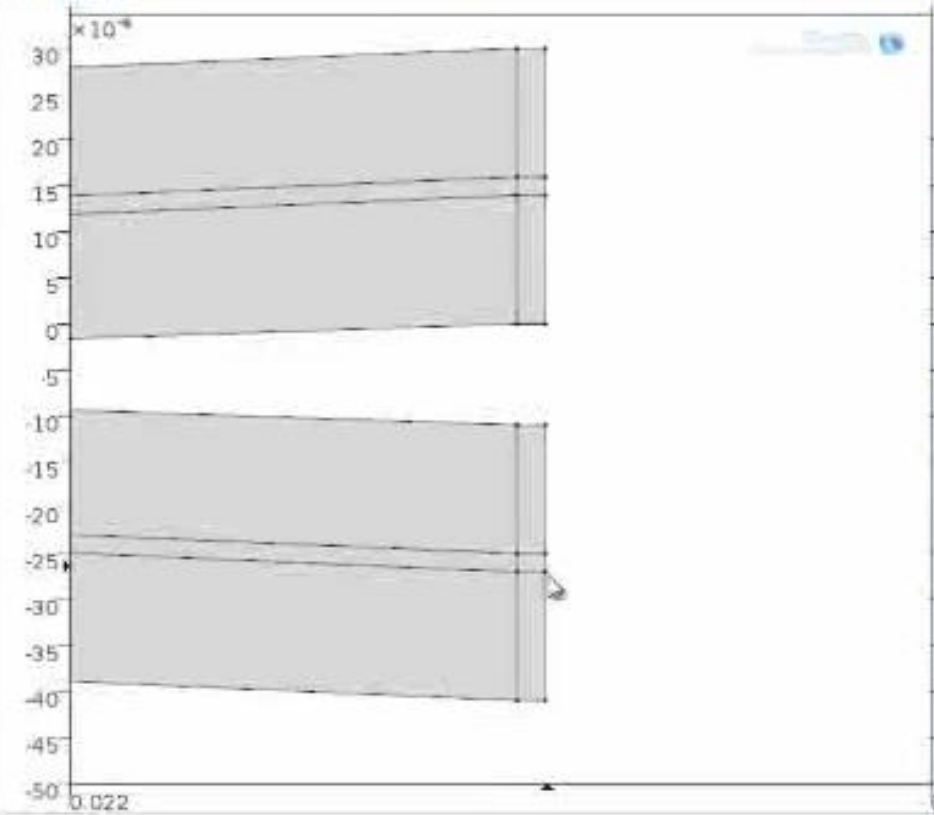
Input quantity:

Electric field

Electric field:

0 x

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electromagnetic Waves, Beam Envelopes | Add Physics | Domains | Boundaries | Pairs

Electromagnetic Waves, Beam Envelopes

Electrostatics

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
      - Port 2
      - Port 3
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
    - Mesh 1
  - Study 1
  - Results

Boundary Selection

Selection: Manual

Active

131
132
133

Override and Contribution

Equation

Port Properties

Port name:

3

Type of port:

Numeric

Wave excitation at this port:

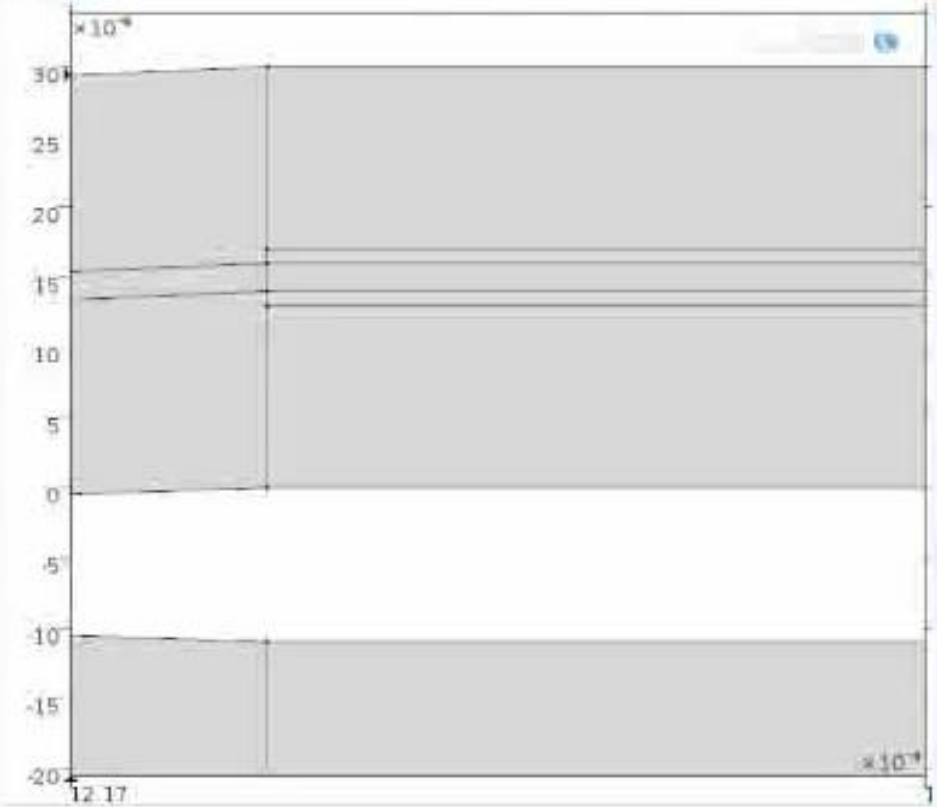
Off

Port phase:

θ_p 0 rad

Port Mode Settings

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electrostatics | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Global

Physics | Domain | Boundary | Point | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
      - Port 2
      - Port 3
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
      - Ground 1
    - Mesh 1
  - Study 1
  - Results

Ground

Boundary Selection

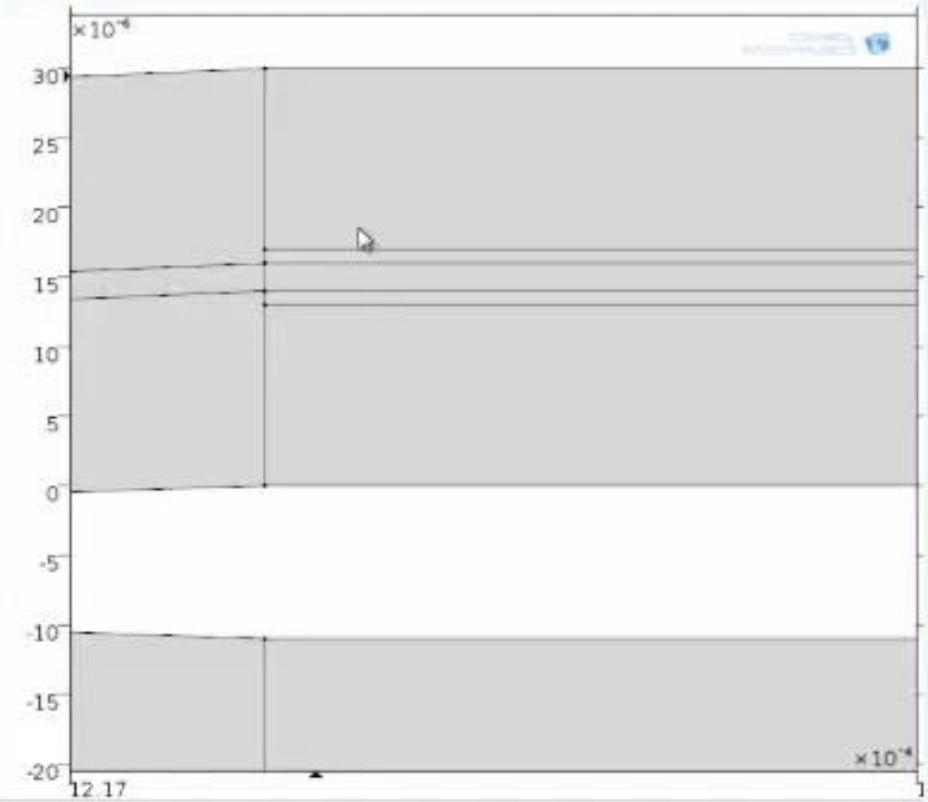
Selection: Manual

Active

Override and Contribution

Equation

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electrostatics | Add Physics | Domains | Boundaries | Pairs | Points | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
      - Port 2
      - Port 3
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
      - Ground 1
      - Electric Potential 1
    - Mesh 1
  - Study 1
  - Results

Electric Potential

Boundary Selection

Selection: Manual

Active

Override and Contribution

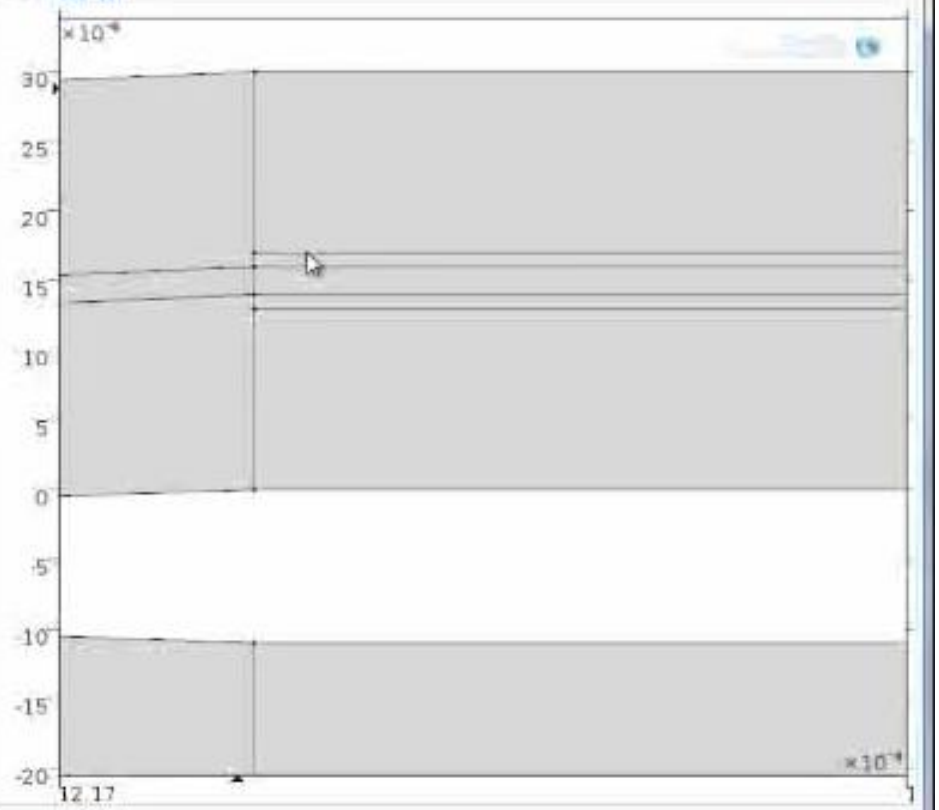
Equation

Electric Potential

Electric potential:

V_0 0 V

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electrostatics | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Global

Physics | Domain | Boundary | Point | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
      - Port 2
      - Port 3
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
      - Ground 1
      - Electric Potential 1
    - Mesh 1
  - Study 1
  - Results

Electric Potential

Boundary Selection

Selection: Manual

Active

72

Override and Contribution

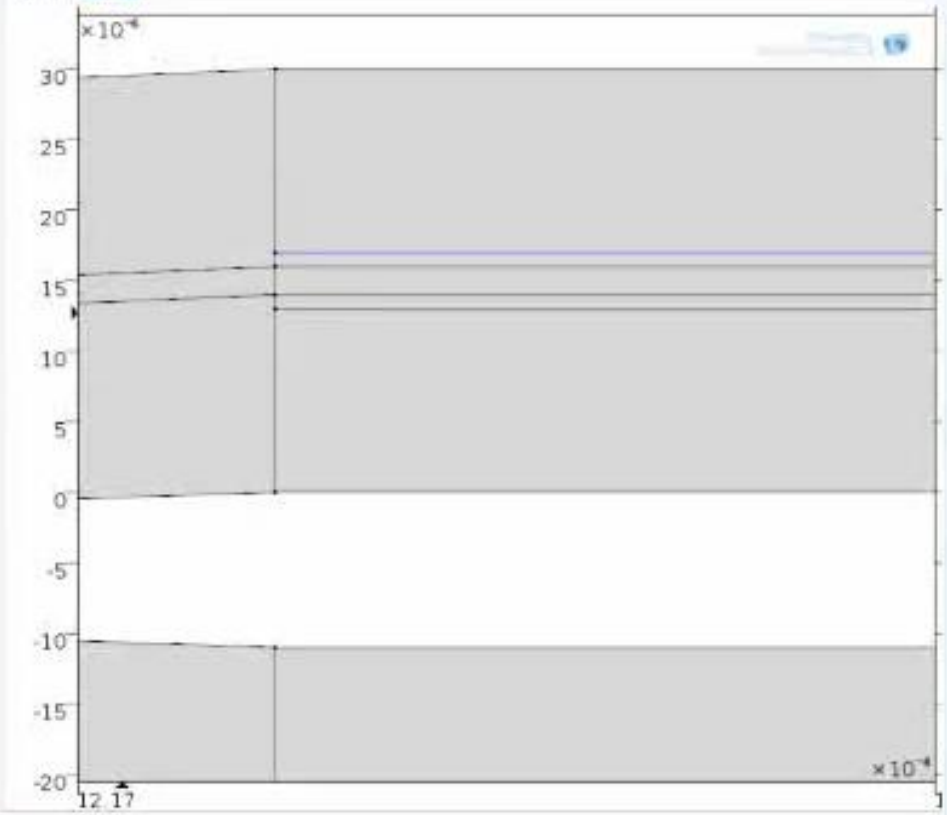
Equation

Electric Potential

Electric potential:

V_0 V0 V

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electrostatics | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Global

Physics | Domain | Boundary | Point | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
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    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
      - Port 2
      - Port 3
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
      - Ground 1
      - Electric Potential 1
    - Mesh 1
  - Study 1
  - Results

Parameters

Parameters

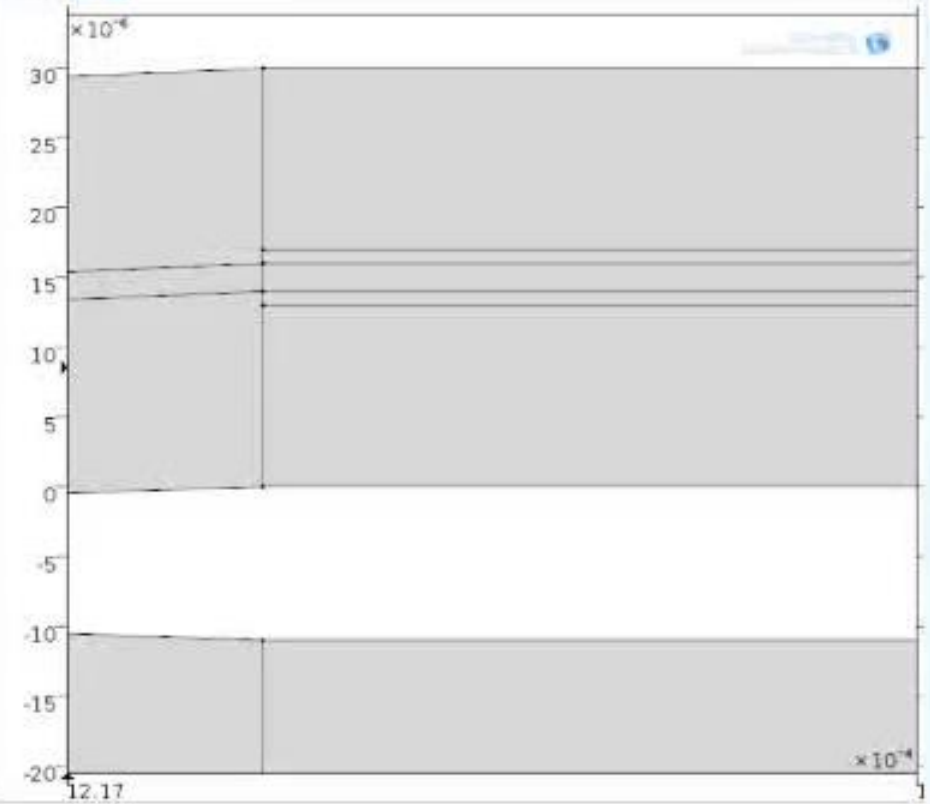
Name	Expression	Value
wl	1.55[um]	1.5500E-6 m
f0	c_const/wl	1.9341E14 1/s
w	2[um]	2.0000E-6 m
w_tot	30[um]	3.0000E-5 m
n_clad	2.2	2.2000
n_core	2.22	2.2200
d0	2*wl	3.1000E-6 m
dy_bend	0.6*w_tot	1.8000E-5 m
r0	2.5[mm]	0.0025000 m
alpha	acos((r0-dy_ben...	0.084878 rad
dx_bend	2*r0*sin(alpha)	4.2388E-4 m
d_dc	380[um]	3.8000E-4 m
d_mz	2[cm]	0.020000 m
hx	wl/(6*n_core)/(1...	3.2324E-5 m
hy	wl/(6*n_core)/si...	1.3726E-6 m
dy_wg	3[um]	3.0000E-6 m

Name:

Expression:

Description:

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electrostatics | Add Physics | Domains | Boundaries | Pairs | Points

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
      - Port 2
      - Port 3
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
      - Ground 1
      - Electric Potential 1
    - Mesh 1
  - Study 1
  - Results

Parameters

Parameters

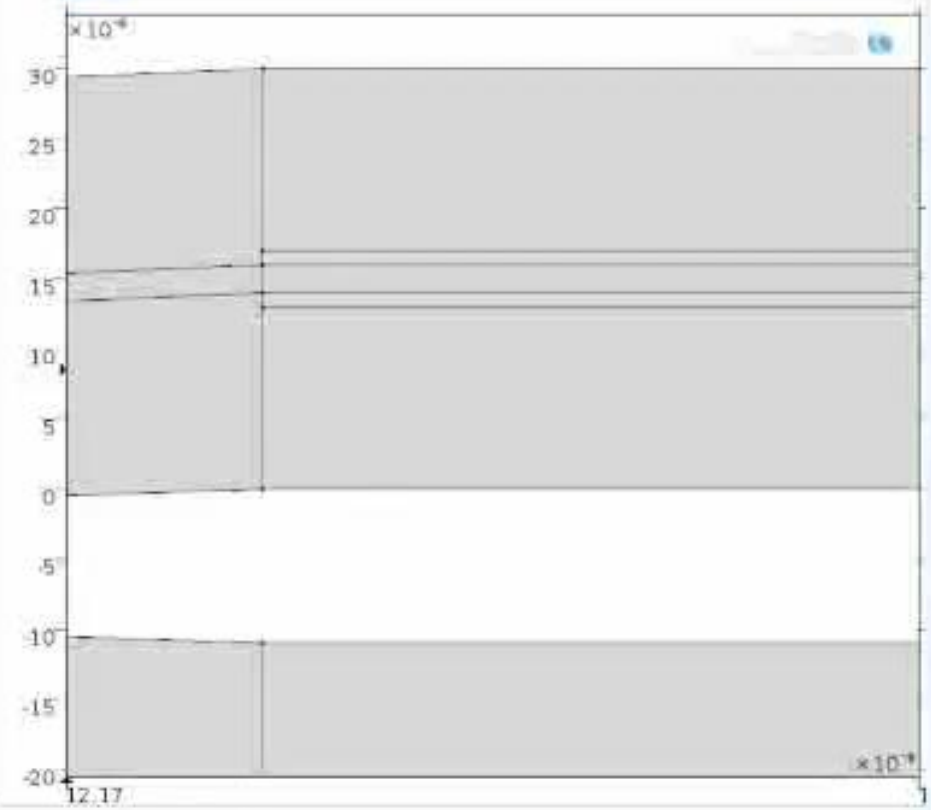
Name	Expression	Value
w_tot	30[um]	3.0000E-5 m
n_clad	2.2	2.2000
n_core	2.27	2.2200
d0	2*wl	3.1000E-6 m
dy_bend	0.6*w_tot	1.8000E-5 m
r0	2.5[mm]	0.0025000 m
alpha	acos((r0-dy_ben...	0.084878 rad
dx_bend	2*r0*sin(alpha)	4.2388E-4 m
d_dc	380[um]	3.8000E-4 m
d_mz	2[cm]	0.020000 m
hx	wl/(6*n_core)/(1...	3.2324E-5 m
hy	wl/(6*n_core)/si...	1.3726E-6 m
dy_wg	3[um]	3.0000E-6 m
V0	100[V]	100.00 V
epsr	35	35.000

Name:

Expression:

Description:

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electrostatics | Add Physics | Domains | Boundaries | Pairs | Points | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
      - Port 2
      - Port 3
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
      - Ground 1
      - Electric Potential 1
    - Mesh 1
  - Study 1
  - Results

Parameters

Parameters

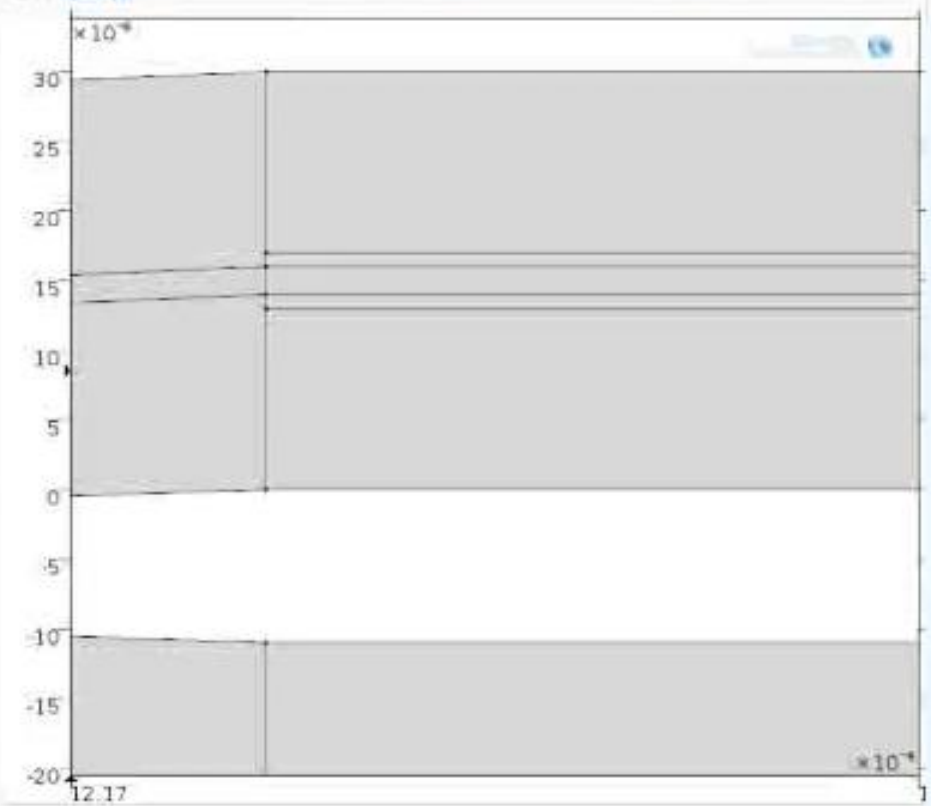
Name	Expression	Value
w_tot	30[um]	3.0000E-5 m
n_clad	2.2	2.2000
n_core	2.22	2.2200
d0	2*wl	3.1000E-6 m
dy_bend	0.6*w_tot	1.8000E-5 m
r0	2.5[mm]	0.0025000 m
alpha	acos((r0-dy_ben...	0.084878 rad
dx_bend	2*r0*sin(alpha)	4.2388E-4 m
d_dc	380[um]	3.8000E-4 m
d_mz	2[cm]	0.020000 m
hx	wl/(6*n_core)/(1...	3.2324E-5 m
hy	wl/(6*n_core)/si...	1.3726E-6 m
dy_wg	3[um]	3.0000E-6 m
V0	100[V]	100.00 V
epsr	35	35.000
r13	30[pm	

Name: r13

Expression:

Description:

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electrostatics | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
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    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
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      - Port 3
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
      - Ground 1
      - Electric Potential 1
    - Mesh 1
  - Study 1
  - Results

Parameters

Parameters

Value	Description
3.0000E-5 m	Total waveguide width
2.2000	Cladding refractive index
2.2200	Core refractive index
3.1000E-6 m	Initial straight waveguide
1.8000E-5 m	Total displacement in y-di...
0.0025000 m	Bend radius
0.084878 rad	Bend angle
4.7388E-4 m	Total length in the x-direc...
3.8000E-4 m	Length of directional cou...
0.020000 m	Length of Mach-Zehnder...
3.2324E-5 m	Maximum element size in...
1.3776E-6 m	Maximum element size in...
3.0000E-6 m	Distance between directio...
100.00 V	Applied voltage
35.000	Low-frequency relative pe...
3.0000E-11 C/N	Electro-optic coefficient

Name:

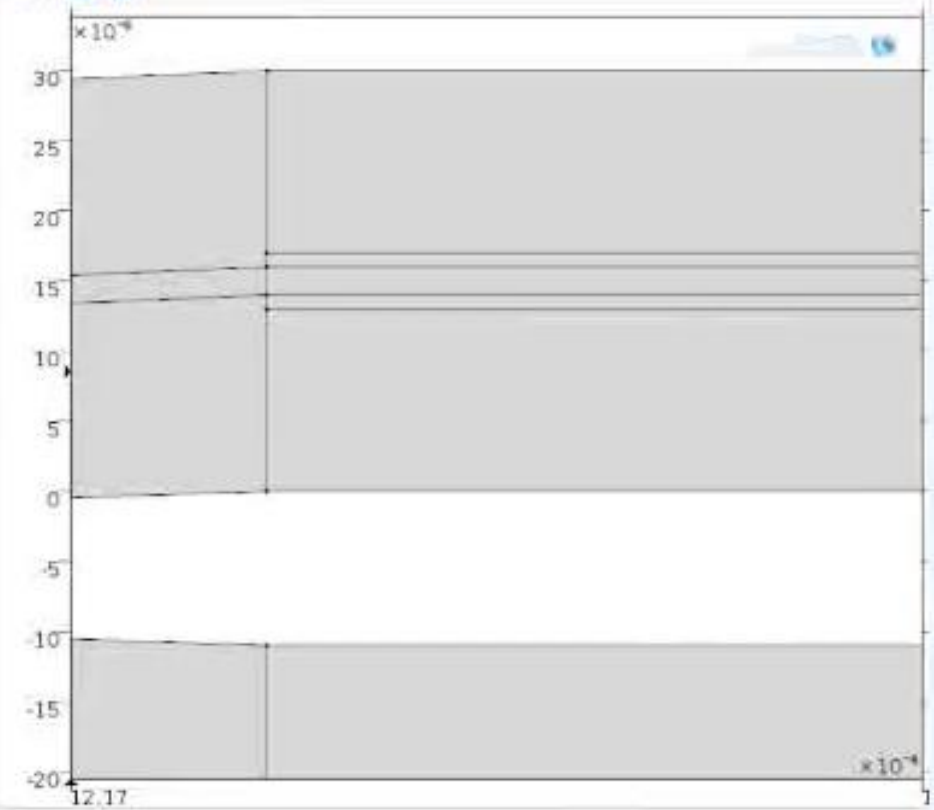
r13

Expression:

30[pm/V]

Description:

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electrostatics | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Global

Physics | Domain | Boundary | Point | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
      - Core (mat2)
      - Cladding (mat1)
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelopc
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
      - Port 2
      - Port 3
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
      - Ground 1
      - Electric Potential 1
    - Mesh 1
  - Study 1
  - Results

Material

Geometric Entity Selection

Geometric entity level: Domain

Selection: Core

Active

2
5
8
11
15
16
20

Override

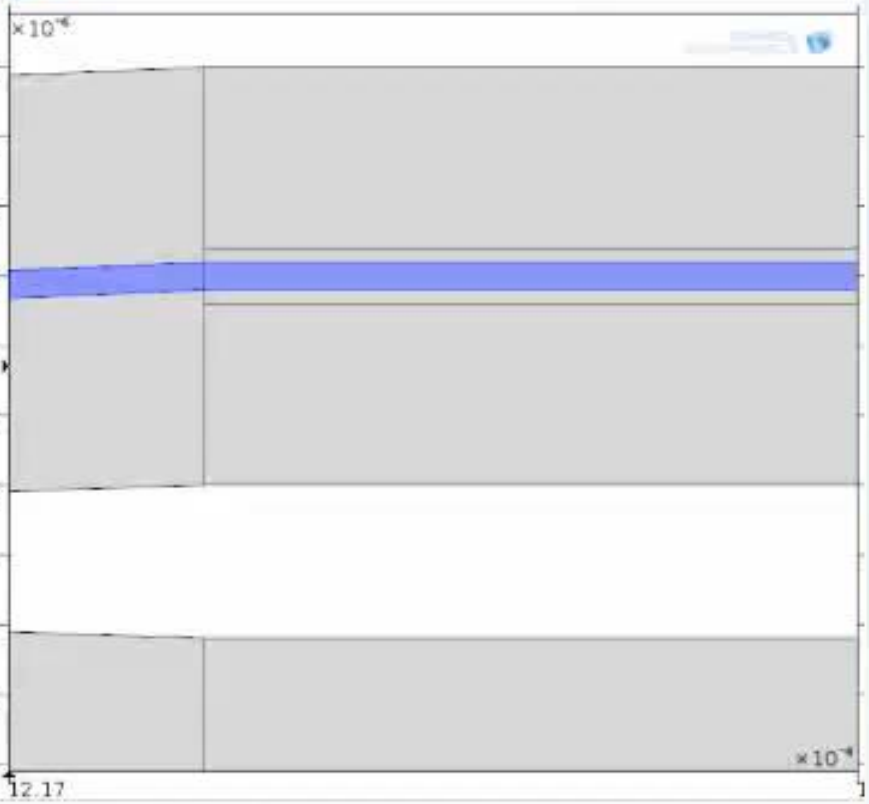
Material Properties

Material Contents

roperty	Name	Value
lative permittivity	epsilonr	epsr
fractive index	n	re-0.5*n
fractive index, imaginary part	ki	0

Appearance

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electrostatics | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
      - Core (mat2)
      - Cladding (mat1)
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelope
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      - Port 3
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
      - Ground 1
      - Electric Potential 1
    - Mesh 1
  - Study 1
  - Results

Material

Geometric Entity Selection

Geometric entity level: Domain

Selection: Core

Active

2
5
8
11
15
16
20

Override

Material Properties

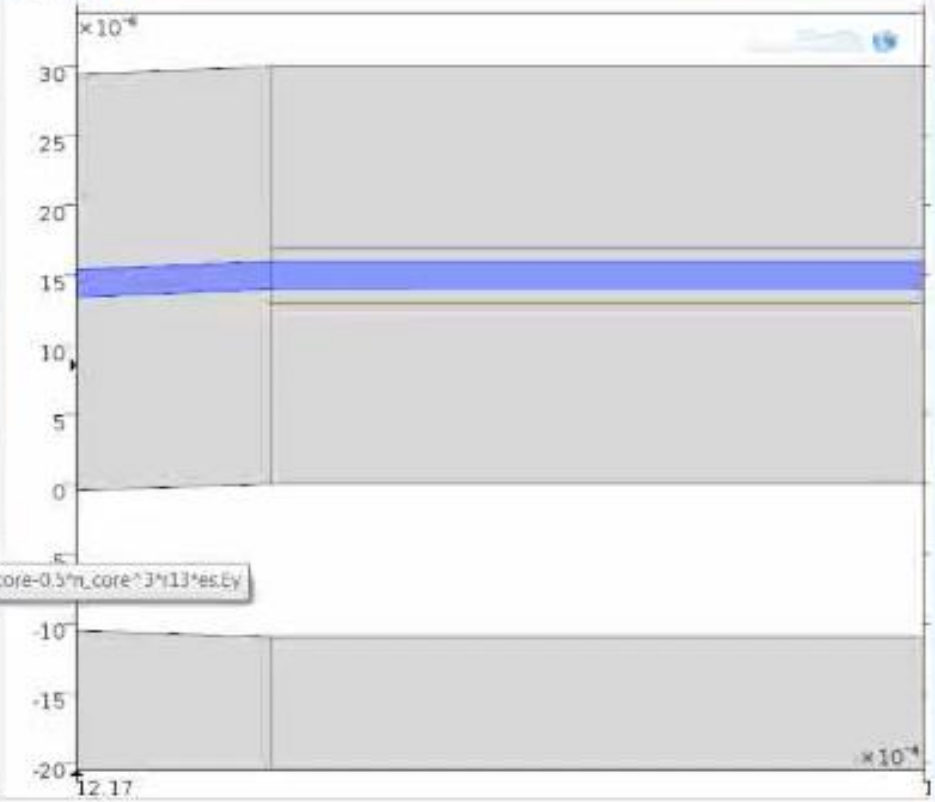
Material Contents

Property	Name	Value
Relative permittivity	epsilonr	epsr
Refractive index	n	n_core-0.
Refractive index, imaginary part	ki	0

n_core-0.5*n_core^3*r13*es.Ey

Appearance

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electrostatics | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Global

Physics | Domain | Boundary | Point | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
      - Core (mat2)
      - Cladding (mat1)
    - Electromagnetic Waves, Beam Enve
      - Wave Equation, Beam Envelopc
      - Perfect Electric Conductor 1
      - Initial Values 1
      - Scattering Boundary Condition
      - Port 1
      - Port 2
      - Port 3
    - Electrostatics (es)
      - Charge Conservation 1
      - Zero Charge 1
      - Initial Values 1
      - Ground 1
      - Electric Potential 1
    - Mesh 1
  - Study 1
  - Results

Material

Geometric Entity Selection

Geometric entity level: Domain

Selection: Cladding

Active

1, 3, 4, 6, 7, 9, 10

Override

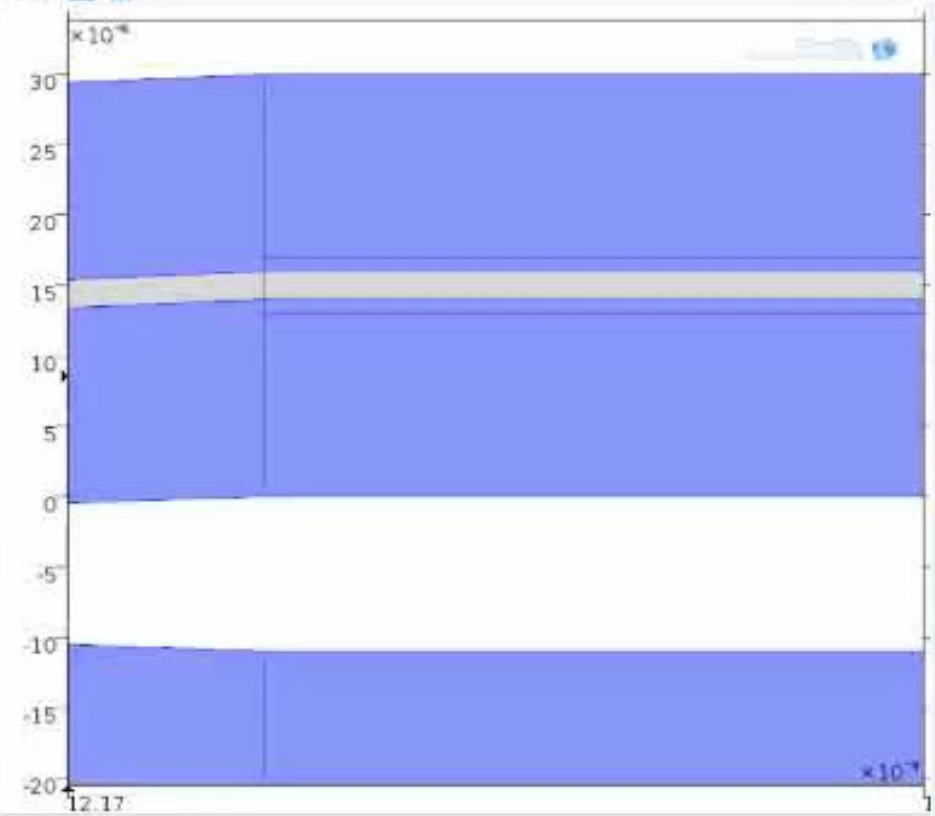
Material Properties

Material Contents

Property	Name	Value
Relative permittivity	epsilonr	epsr
Refractive index	n	n_clad
Refractive index, imaginary part	ki	0

Appearance

Graphics



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Electrostatics | Add Physics | Domains | Boundaries | Pairs | Points | Pairs | Global

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
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      - Core (mat2)
      - Cladding (mat1)
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      - Zero Charge 1
      - Initial Values 1
      - Ground 1
      - Electric Potential 1
    - Mesh 1
  - Study 1
  - Results

Material

Geometric Entity Selection

Geometric entity level: Domain

Selection: Cladding

Active

1, 3, 4, 6, 7, 9, 10

Override

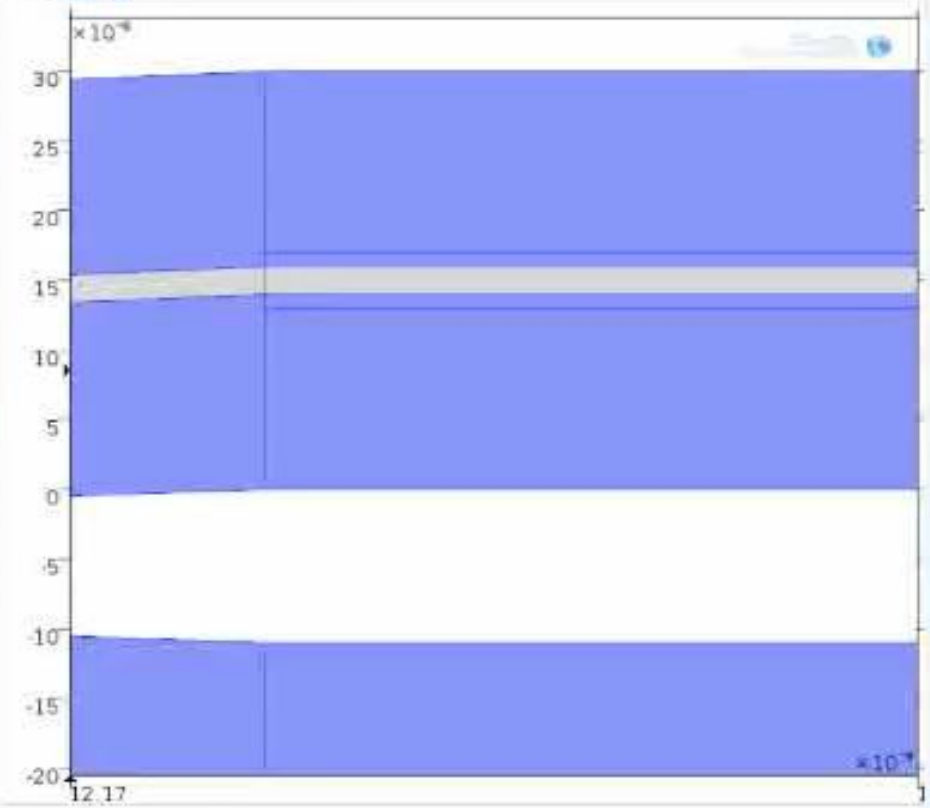
Material Properties

Material Contents

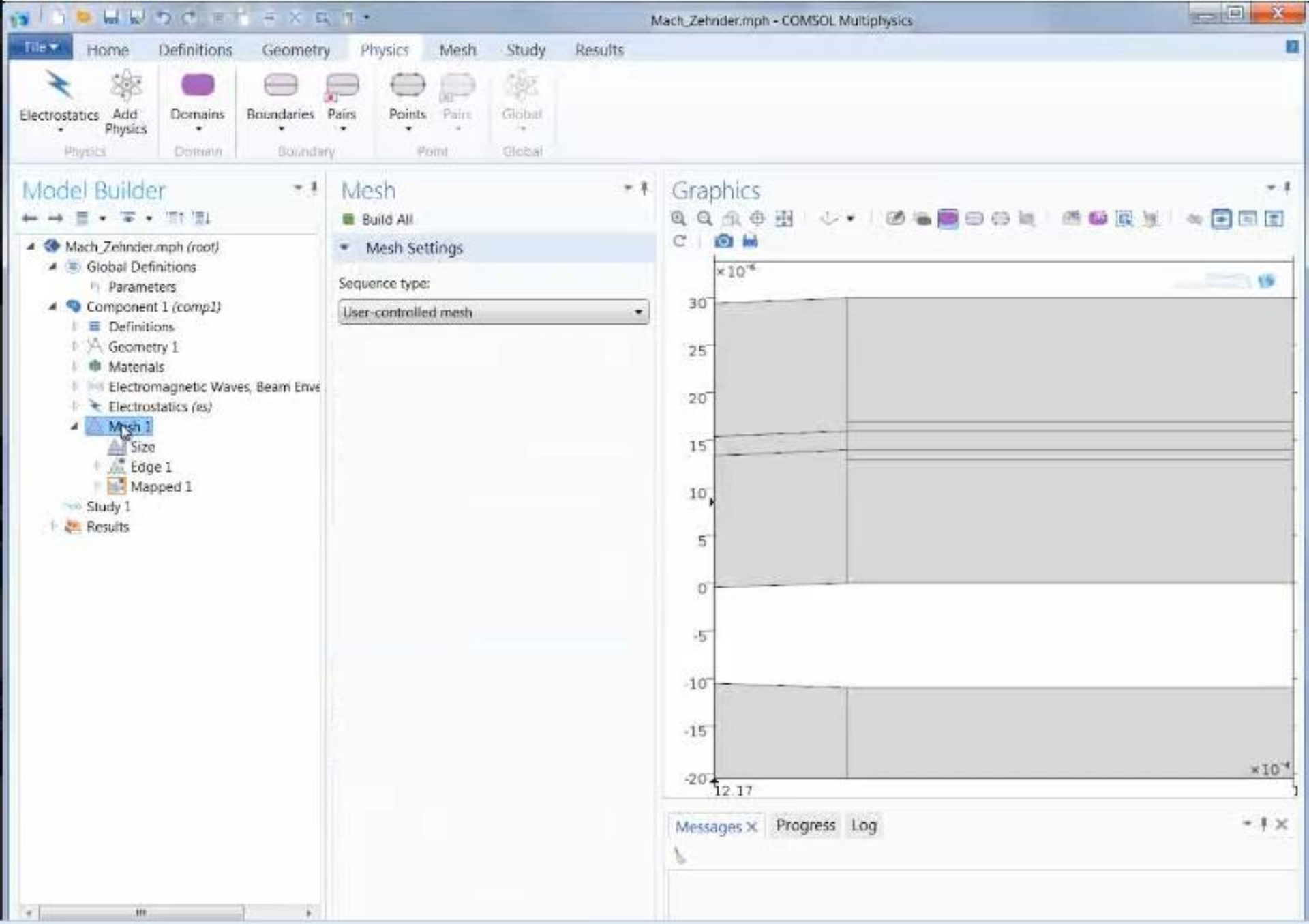
Property	Name	Value
Relative permittivity	epsilonr	epsr
Refractive index	n	3*n13*es
Refractive index, imaginary part	ki	0

Appearance

Graphics



Messages | Progress | Log


Mach_Zehnder.mph - COMSOL Multiphysics
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Electrostatics
Add Physics
Domains
Boundaries
Pairs
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Pairs
Global
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Domain
Boundary
Point
Global
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Mach_Zehnder.mph (root)
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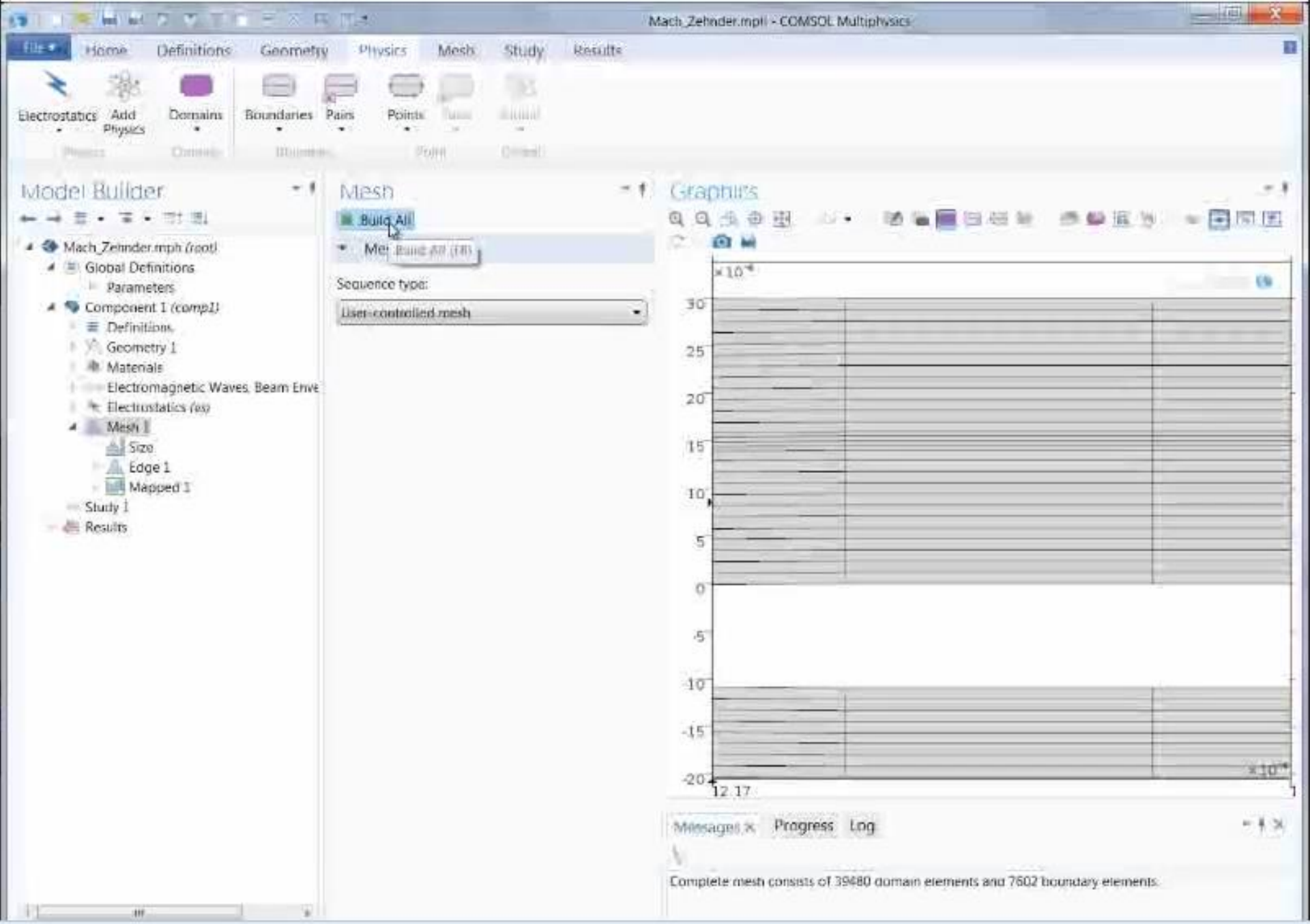
Electromagnetic Waves, Beam Enve
Electrostatics (es)
Mesh 1
Size
Edge 1
Mapped 1
Study 1
Results
Mesh
Build All
Mesh Settings
Sequence type:
User-controlled mesh
Graphics
×10⁻⁶
30
25
20
15
10
5
0
-5
-10
-15
-20
12.17
×10⁻⁶
Messages
Progress
Log


Mach_Zehnder.mph - COMSOL Multiphysics
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Study
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Electrostatics
Add Physics
Domains
Boundaries
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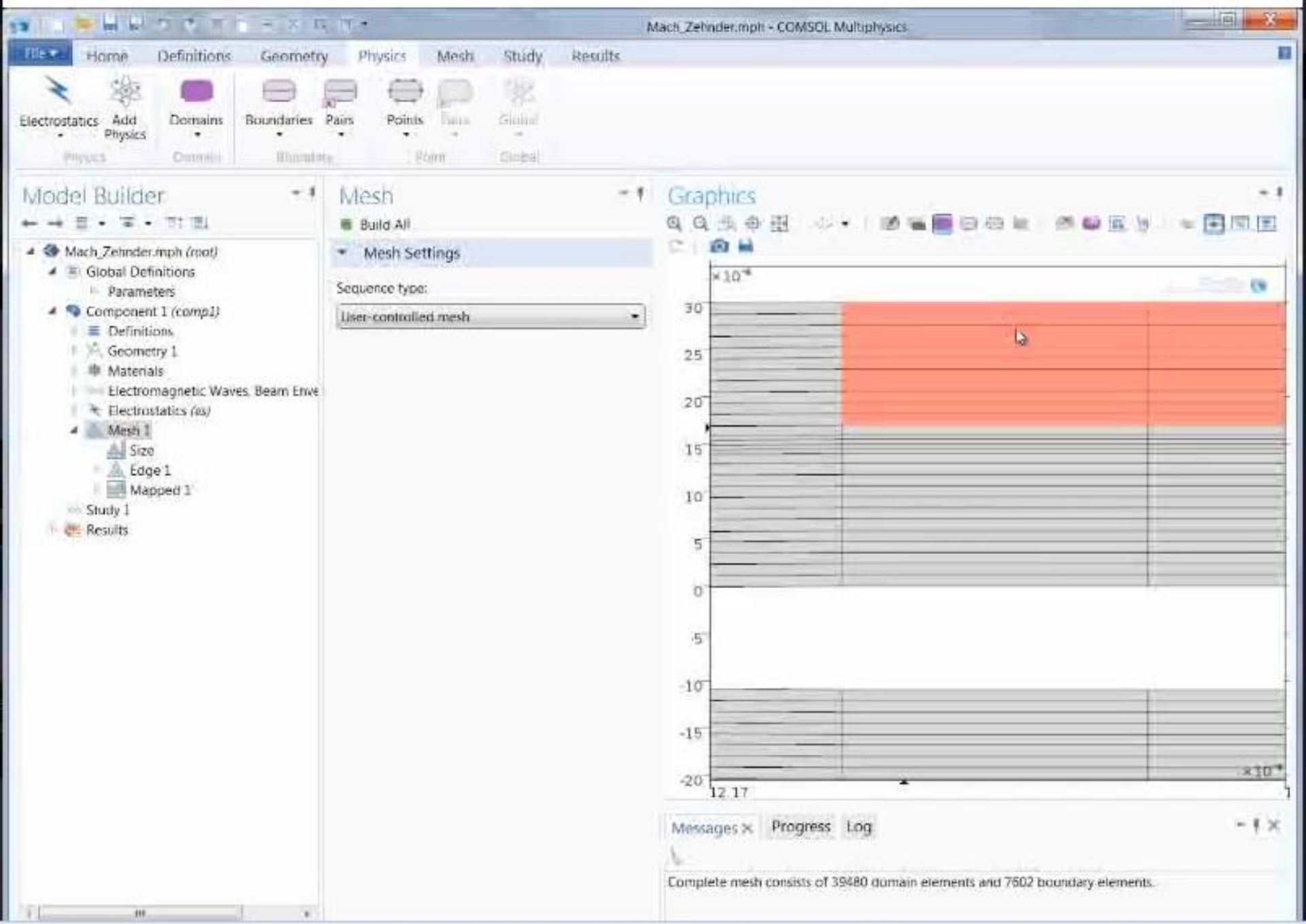
Points
Model Builder
Mach_Zehnder.mph (root)
Global Definitions
Parameters
Component 1 (comp1)
Definitions
Geometry 1
Materials
Electromagnetic Waves, Beam Enve
Electrostatics (es)
Mesh 1
Size
Edge 1
Mapped 1
Study 1
Results
Mesh
Build All
Sequence type:
User-controlled mesh
Graphics
Messages
Progress
Log
Complete mesh consists of 39480 domain elements and 7602 boundary elements.


Mach_Zehnder.mph - COMSOL Multiphysics
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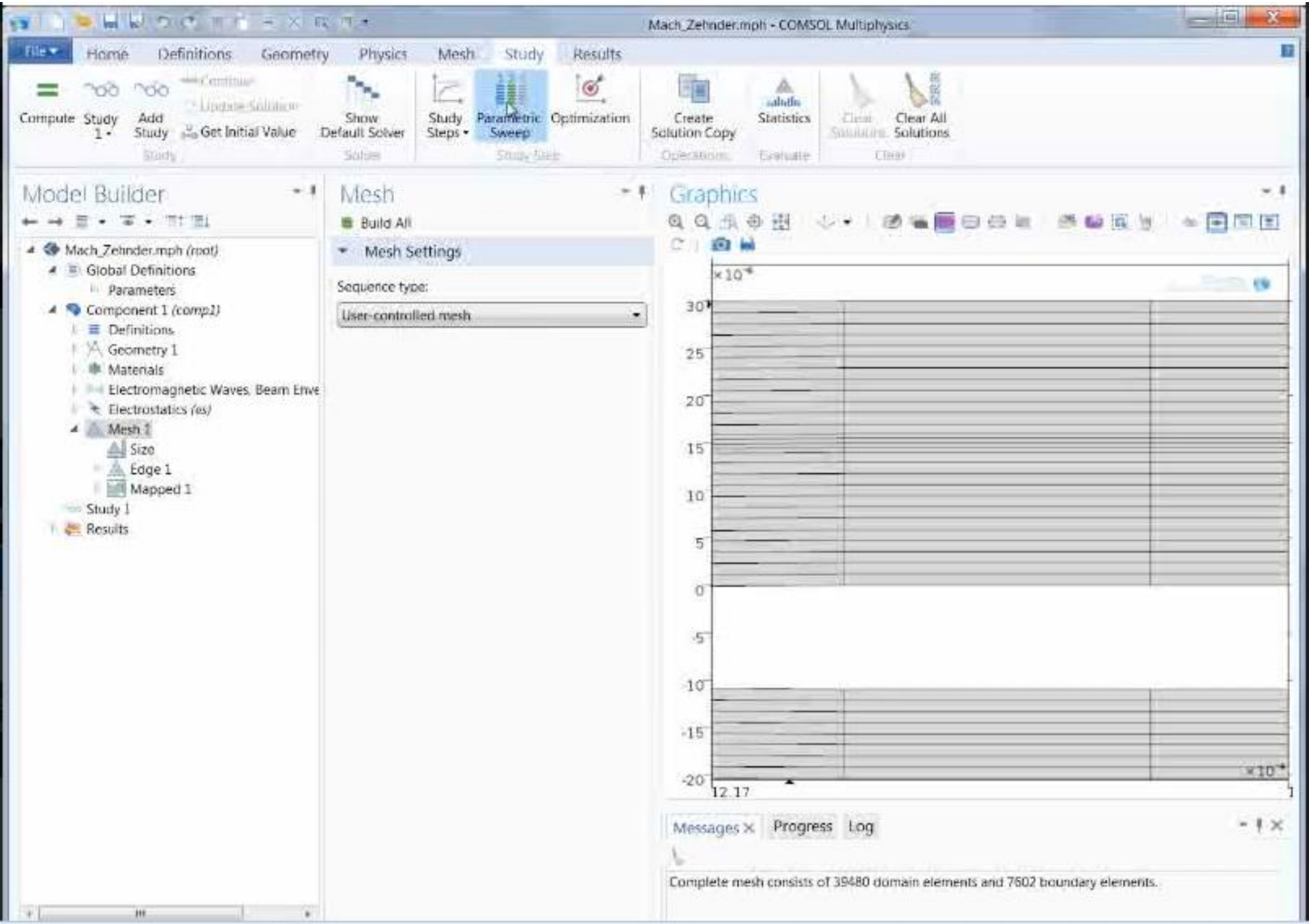
Definitions
Geometry
Physics
Mesh
Study
Results
Electrostatics
Add Physics
Domains
Boundaries
Pairs
Points
Model Builder
Mach_Zehnder.mph (root)
Global Definitions
Parameters
Component 1 (comp1)
Definitions
Geometry 1
Materials
Electromagnetic Waves, Beam Enve
Electrostatics (es)
Mesh 1
Size
Edge 1
Mapped 1
Study 1
Results
Mesh
Build All
Mesh Settings
Sequence type:
User-controlled mesh
Graphics
Messages
Progress
Log
Complete mesh consists of 39480 domain elements and 7602 boundary elements.


Mach_Zehnder.mph - COMSOL Multiphysics
File
Home
Definitions
Geometry
Physics
Mesh
Study
Results
Compute
Study 1
Add Study
Continue
Update Solution
Get Initial Value
Show Default Solver
Study Steps
Parametric Sweep
Optimization
Create Solution Copy
Statistics
Clear Solutions
Clear All Solutions
Model Builder
Mach_Zehnder.mph (root)
Global Definitions
Parameters
Component 1 (comp1)
Definitions
Geometry 1
Materials
Electromagnetic Waves, Beam Enve
Electrostatics (es)
Mesh 1
Size
Edge 1
Mapped 1
Study 1
Results
Mesh
Build All
Mesh Settings
Sequence type:
User-controlled mesh
Graphics
Messages
Progress
Log
Complete mesh consists of 39480 domain elements and 7602 boundary elements.

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Compute | Study 1 | Add Study | Continue | Update Solution | Get Initial Value | Show Default Solver | Study Steps | Parametric Sweep | Optimization | Create Solution Copy | Statistics | Clear Solution | Clear All Solutions

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
      - Size
      - Edge 1
      - Mapped 1
  - Study 1
    - Parametric Sweep
  - Results

Parametric Sweep

Study Settings

Sweep type: Specified combinations

Parameter names	Parameter value list

Add

Output While Solving

Plot

Plot group:

Probes: All

Accumulated probe table

Output table: New

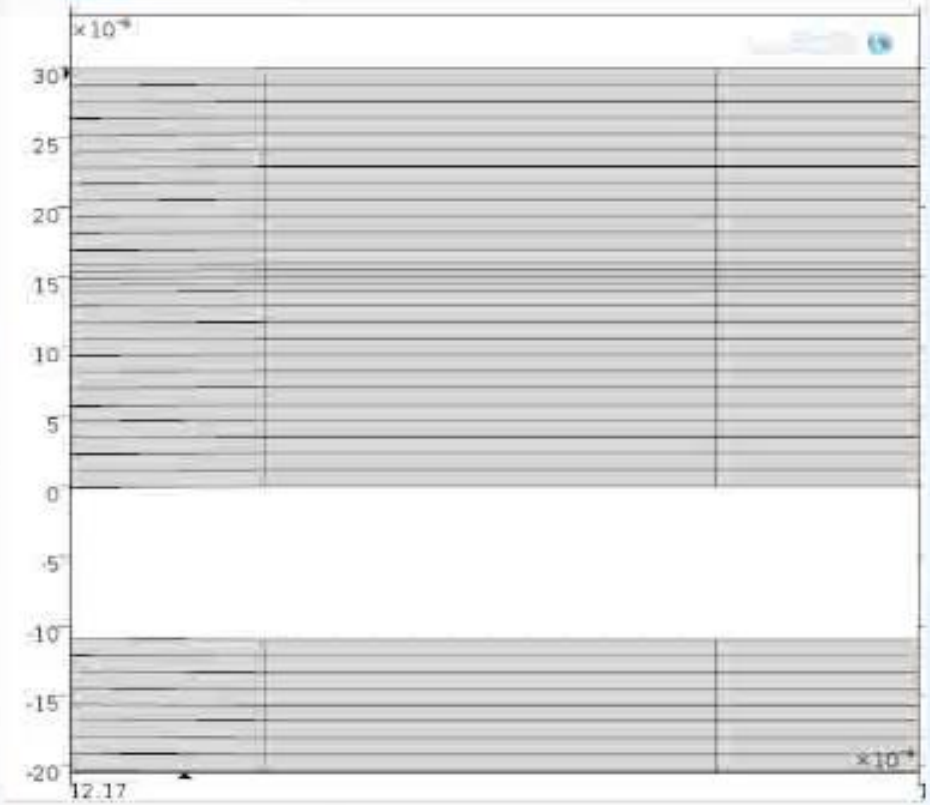
Use all probes

Memory settings for jobs

Keep solutions in memory: All

Study Extensions

Graphics



Messages | Progress | Log

Complete mesh consists of 39480 domain elements and 7602 boundary elements.

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Compute | Study 1 | Add Study | Continue | Update Solution | Get Initial Value | Show Default Solver | Study Steps | Parametric Sweep | Optimization | Create Solution Copy | Statistics | Clear Solution | Clear All Solutions

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
      - Size
      - Edge 1
      - Mapped 1
  - Study 1
    - Parametric Sweep
  - Results

Parametric Sweep

Study Settings

Sweep type: Specified combinations

Parameter names	Parameter value list
V0 (Applied voltag	

Output While Solving

Plot

Plot group:

Probes: All

Accumulated probe table

Output table: New

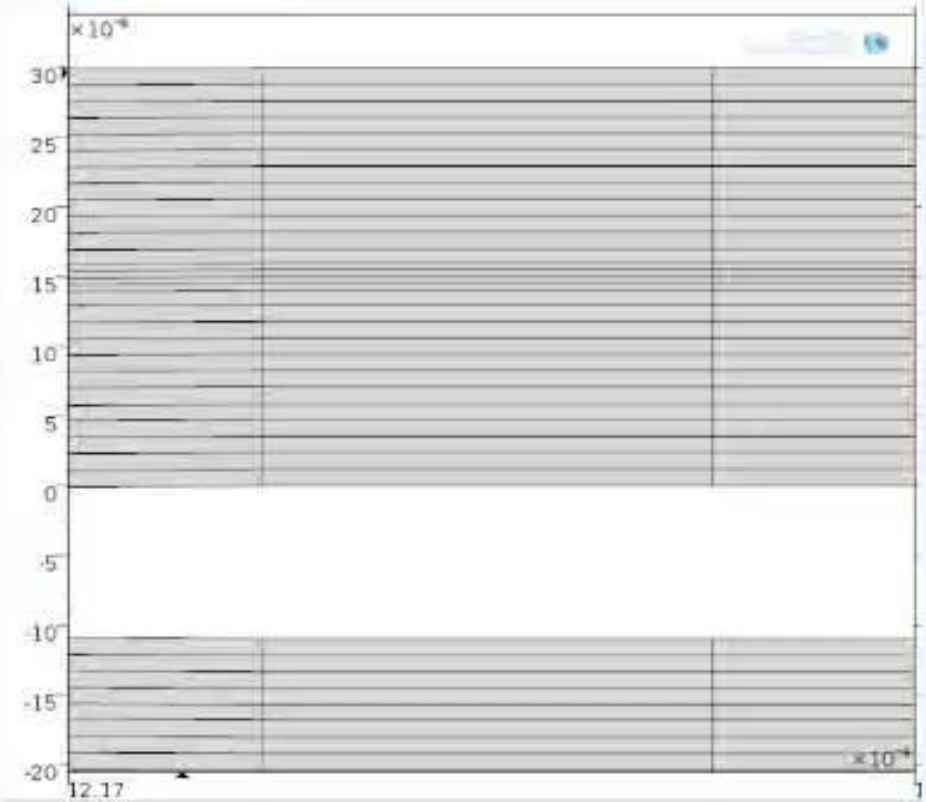
Use all probes

Memory settings for jobs

Keep solutions in memory: All

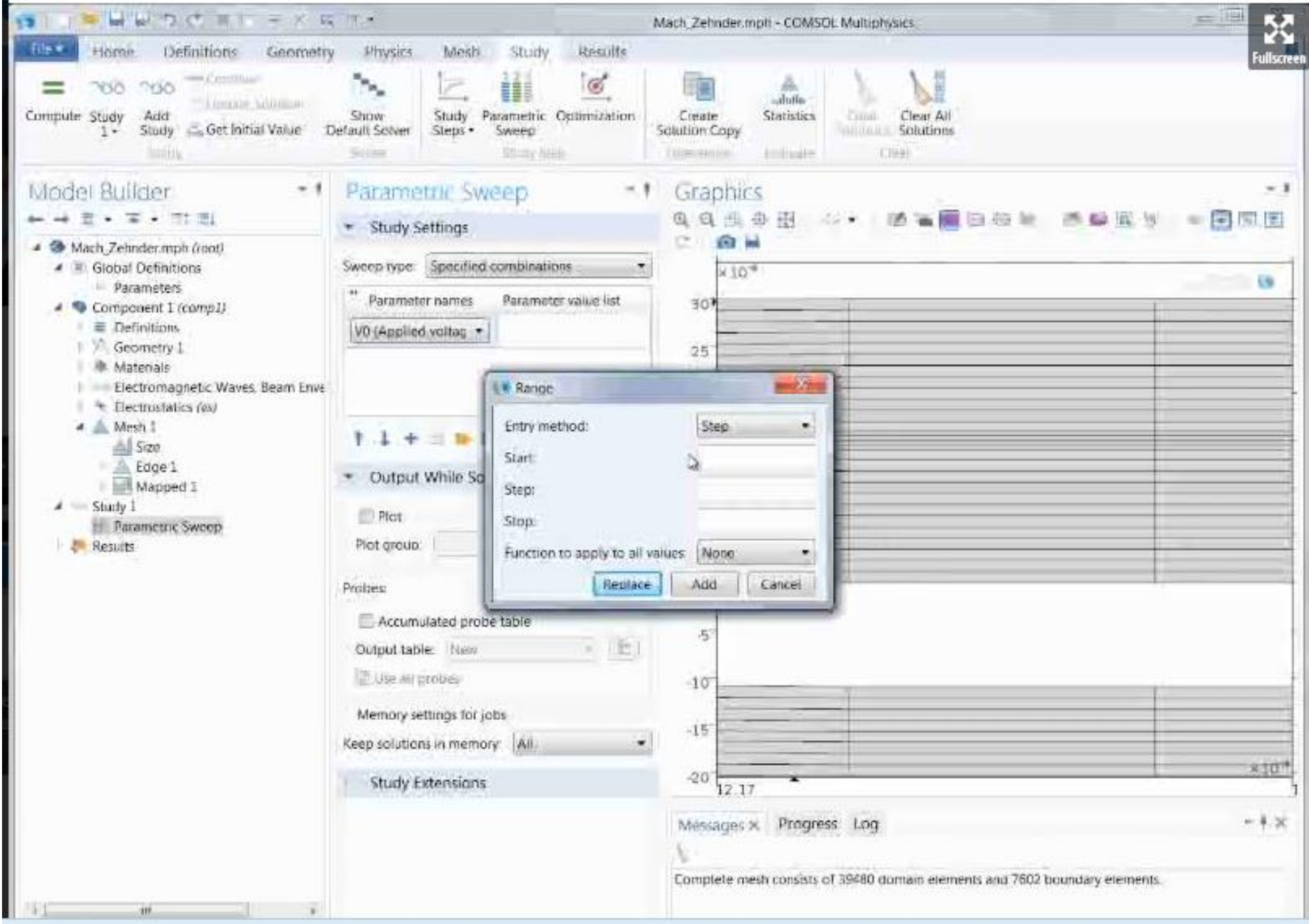
Study Extensions

Graphics



Messages | Progress | Log

Complete mesh consists of 39480 domain elements and 7602 boundary elements.


Mach_Zehnder.mph - COMSOL Multiphysics
Fullscreen
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Mesh
Study
Results
Compute
Study 1
Add Study
Get Initial Value
Show Default Solver
Study Steps
Parametric Sweep
Optimization
Create Solution Copy
Statistics
Clear All Solutions
Model Builder
Mach_Zehnder.mph (root)
Global Definitions
Parameters
Component 1 (comp1)
Definitions
Geometry 1
Materials
Electromagnetic Waves, Beam Enve
Electrostatics (es)
Mesh 1
Size
Edge 1
Mapped 1
Study 1
Parametric Sweep
Results
Parametric Sweep
Study Settings
Sweep type: Specified combinations
Parameter names
Parameter value list
V0 (Applied voltag
Output While So
Plot
Plot group:
Probes:
Accumulated probe table
Output table: New
Use all probes
Memory settings for jobs
Keep solutions in memory: All
Study Extensions
Range
Entry method: Step
Start:
Step:
Stop:
Function to apply to all values: None
Replace
Add
Cancel
Graphics
Messages
Progress
Log
Complete mesh consists of 39480 domain elements and 7602 boundary elements.

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Compute | Study 1 | Add Study | Continue | Update Solution | Get Initial Value | Show Default Solver | Study Steps | Parametric Sweep | Optimization | Create Solution Copy | Statistics | Clear Solutions | Clear All Solutions

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
      - Size
      - Edge 1
      - Mapped 1
  - Study 1
    - Parametric Sweep
  - Results

Parametric Sweep

Study Settings

Sweep type: Specified combinations

Parameter names	Parameter value list
V0 (Applied voltag	

Output While So

Plot

Plot group:

Probes:

Accumulated probe table

Output table: New

Use all probes

Memory settings for jobs

Keep solutions in memory: All

Study Extensions

Range

Entry method: Step

Start: 0[V]

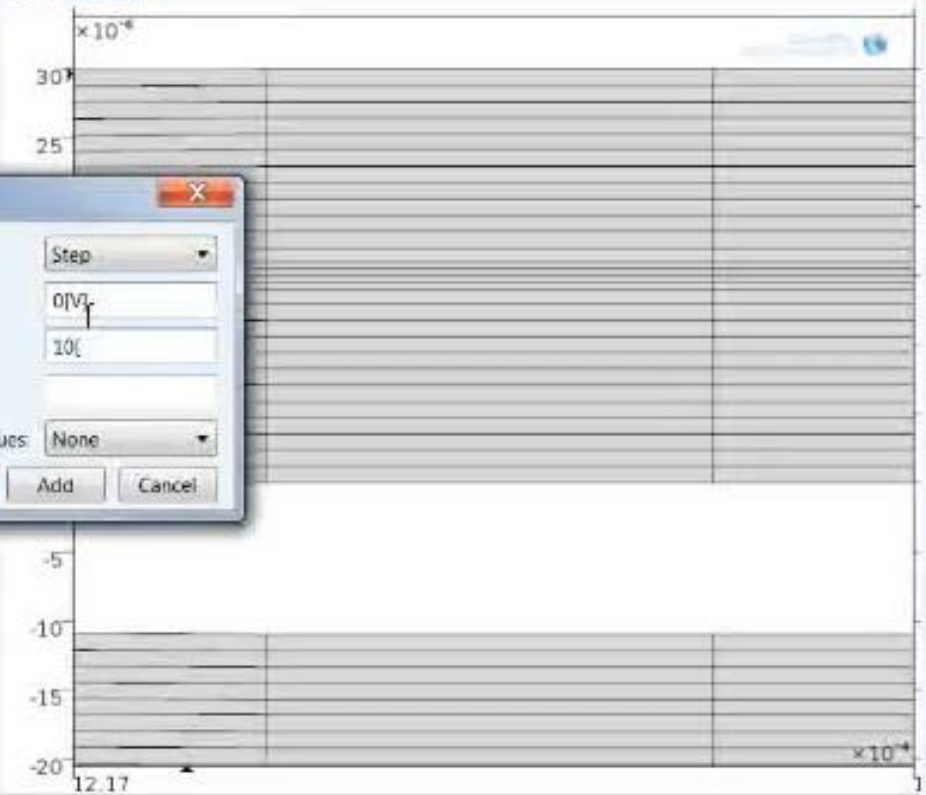
Step: 10[

Stop:

Function to apply to all values: None

Replace | Add | Cancel

Graphics



Messages | Progress | Log

Complete mesh consists of 39480 domain elements and 7602 boundary elements.

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Compute | Study 1 | Add Study | Continue | Update Solution | Get Initial Value | Show Default Solver | Study Steps | Parametric Sweep | Optimization | Create Solution Copy | Statistics | Clear Solution | Clear All Solutions

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
      - Size
      - Edge 1
      - Mapped 1
  - Study 1
    - Parametric Sweep
  - Results

Parametric Sweep

Study Settings

Sweep type: Specified combinations

Parameter names	Parameter value list
V0 (Applied voltag	

Output While So

Plot

Plot group:

Probes:

Accumulated probe table

Output table: New

Use all probes

Memory settings for jobs

Keep solutions in memory: All

Study Extensions

Range

Entry method: Step

Start: 0[V]

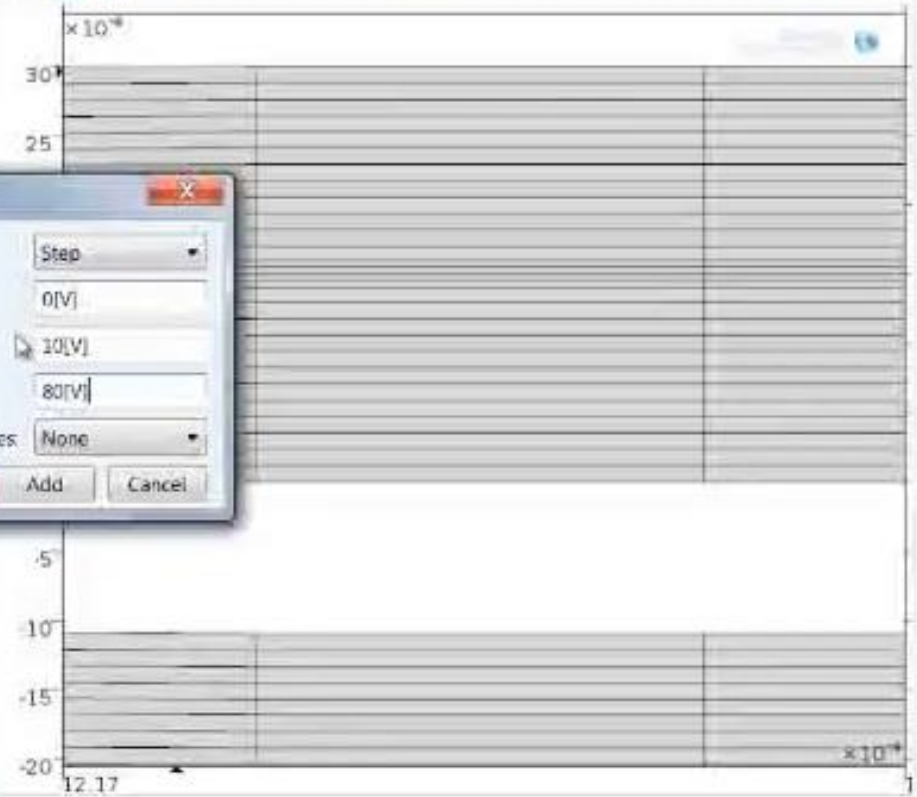
Step: 10[V]

Stop: 80[V]

Function to apply to all values: None

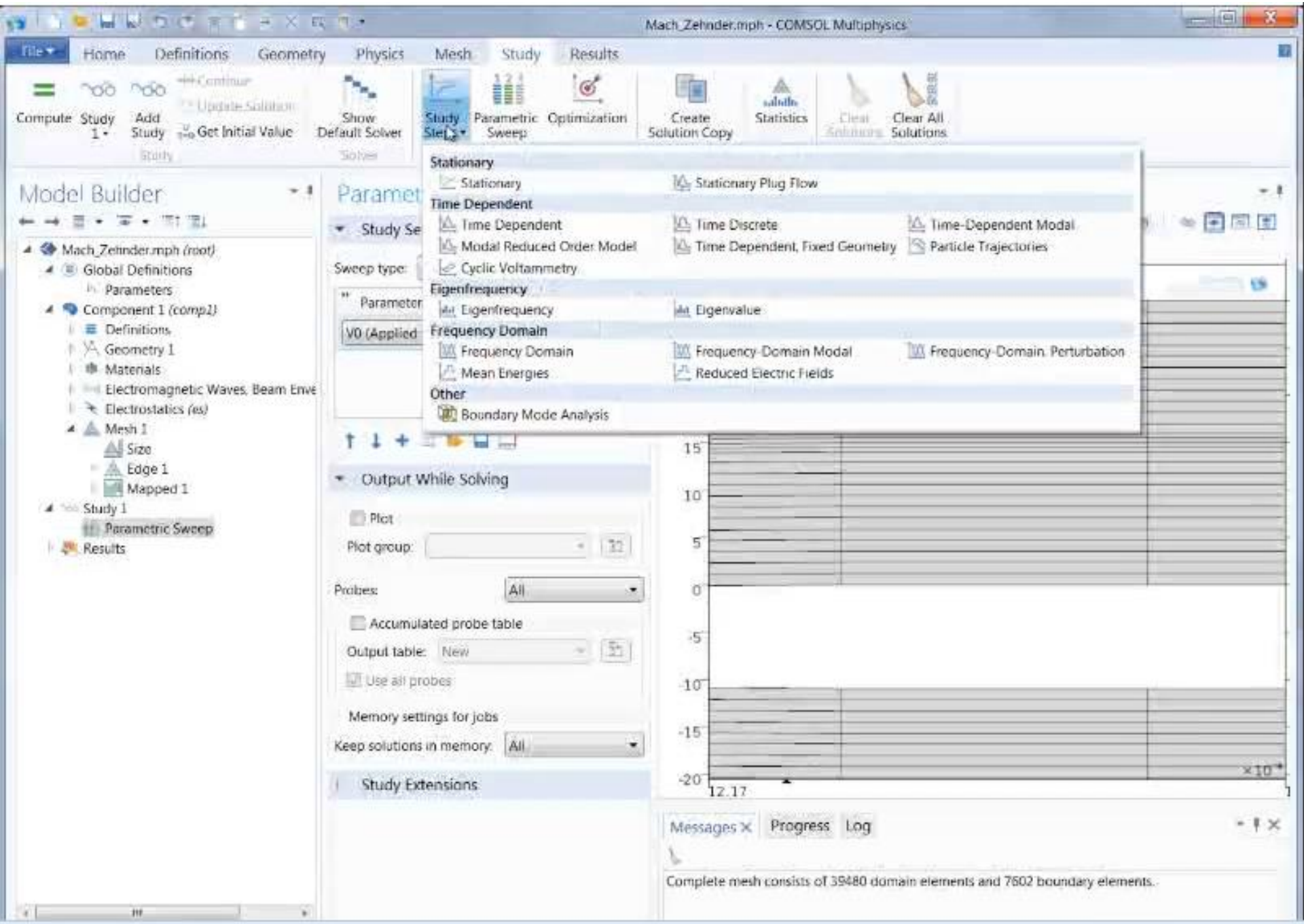
Replace | Add | Cancel

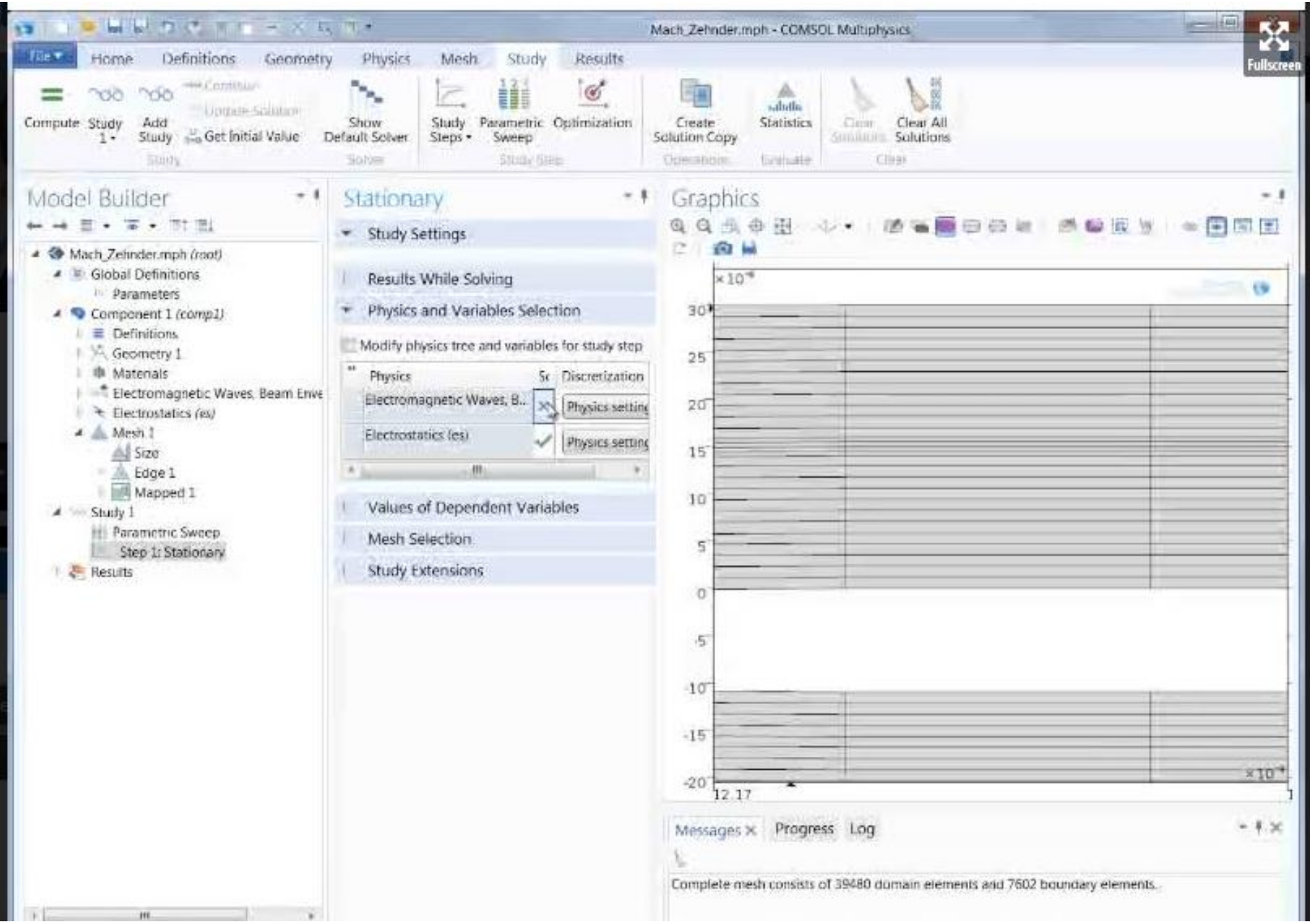
Graphics



Messages | Progress | Log

Complete mesh consists of 39480 domain elements and 7602 boundary elements.


Mach_Zehnder.mph - COMSOL Multiphysics
File
Home
Definitions
Geometry
Physics
Mesh
Study
Results
Compute
Study 1
Add Study
Continue
Update Solution
Get Initial Value
Show Default Solver
Study Steps
Parametric Sweep
Optimization
Create Solution Copy
Statistics
Clear Solutions
Clear All Solutions
Stationary
Stationary
Stationary Plug Flow
Time Dependent
Time Dependent
Time Discrete
Time-Dependent Modal
Modal Reduced Order Model
Time Dependent, Fixed Geometry
Particle Trajectories
Cyclic Voltammetry
Eigenfrequency
Eigenfrequency
Eigenvalue
Frequency Domain
Frequency Domain
Frequency-Domain Modal
Frequency-Domain Perturbation
Mean Energies
Reduced Electric Fields
Other
Boundary Mode Analysis
Model Builder
Mach_Zehnder.mph (root)
Global Definitions
Parameters
Component 1 (comp1)
Definitions
Geometry 1
Materials
Electromagnetic Waves, Beam Enve
Electrostatics (es)
Mesh 1
Size
Edge 1
Mapped 1
Study 1
Parametric Sweep
Results
Study Se
Sweep type:
Parameter
V0 (Applied
Output While Solving
Plot
Plot group:
Probes:
All
Accumulated probe table
Output table:
New
Use all probes
Memory settings for jobs
Keep solutions in memory:
All
Study Extensions
15
10
5
0
-5
-10
-15
-20
12.17
×10
Messages
Progress
Log
Complete mesh consists of 39480 domain elements and 7602 boundary elements.


Mach_Zehnder.mph - COMSOL Multiphysics
File
Home
Definitions
Geometry
Physics
Mesh
Study
Results
Fullscreen
Compute
Study 1
Add Study
Get Initial Value
Show Default Solver
Study Steps
Parametric Sweep
Optimization
Create Solution Copy
Statistics
Clear All Solutions
Model Builder
Mach_Zehnder.mph (root)
Global Definitions
Parameters
Component 1 (comp1)
Definitions
Geometry 1
Materials
Electromagnetic Waves, Beam Enve
Electrostatics (es)
Mesh 1
Size
Edge 1
Mapped 1
Study 1
Parametric Sweep
Step 1: Stationary
Results
Stationary
Study Settings
Results While Solving
Physics and Variables Selection
Modify physics tree and variables for study step
Physics
Discretization
Electromagnetic Waves, B...
Physics setting
Electrostatics (es)
Physics setting
Values of Dependent Variables
Mesh Selection
Study Extensions
Graphics
×10⁻⁴
30
25
20
15
10
5
0
-5
-10
-15
-20
12.17
×10⁻⁴
Messages
Progress
Log
Complete mesh consists of 39480 domain elements and 7602 boundary elements.

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Compute | Study 1 | Add Study | Continue | Update Solution | Get Initial Value | Show Default Solver | Study Steps | Parametric Sweep | Optimization | Create Solution Copy | Statistics | Clear Solutions | Clear All Solutions

Stationary
- Stationary
- Stationary Plug Flow

Time Dependent
- Time Dependent
- Time Discrete
- Time-Dependent Modal
- Modal Reduced Order Model
- Time Dependent, Fixed Geometry
- Particle Trajectories
- Cyclic Voltammetry

Eigenfrequency
- Eigenfrequency
- Eigenvalue

Frequency Domain
- Frequency Domain
- Frequency-Domain Modal
- Frequency-Domain, Perturbation
- Mean Energies
- Reduced Electric Fields

Other
- Boundary Mode Analysis

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
      - Size
      - Edge 1
      - Mapped 1
  - Study 1
    - Parametric Sweep
    - Step 1: Stationary
  - Results

Stationar

Study Se

Results V

Physics a

Modify phy

Physics | Physics setting

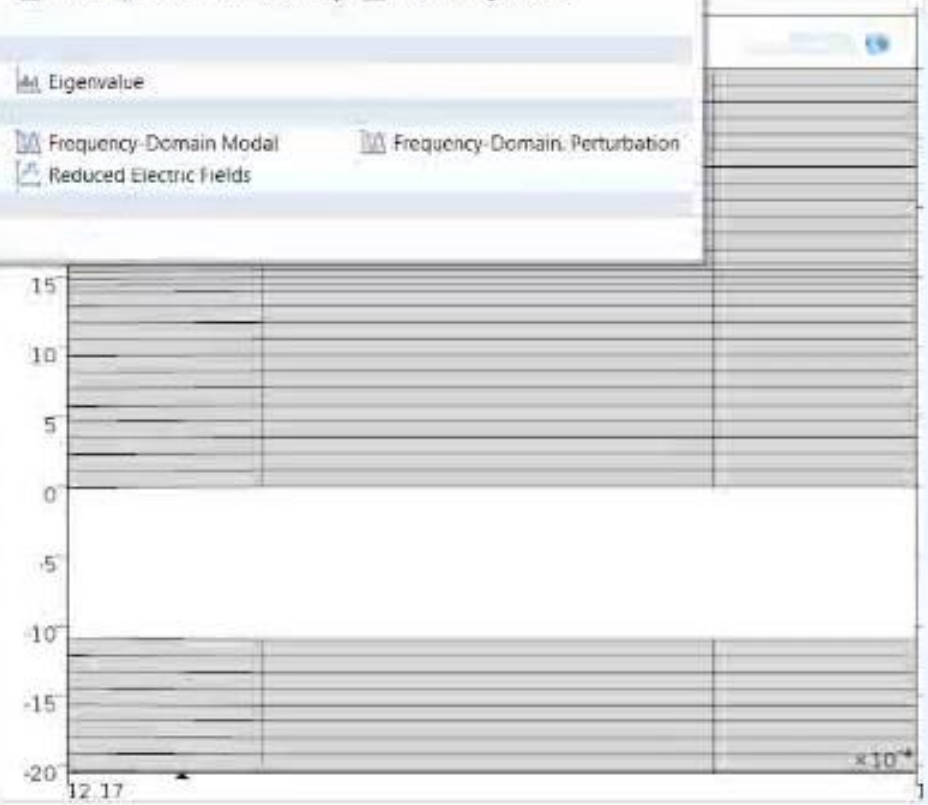
Electroma

Electrostat

Values of Dependent Variables

Mesh Selection

Study Extensions



Messages | Progress | Log

Complete mesh consists of 39480 domain elements and 7602 boundary elements.

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Compute | Study 1 | Add Study | Get Initial Value | Show Default Solver | Study Steps | Parametric Sweep | Optimization | Create Solution Copy | Statistics | Clear All Solutions

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
      - Size
      - Edge 1
      - Mapped 1
  - Study 1
    - Parametric Sweep
    - Step 1: Stationary
    - Step 2: Boundary Mode Analysis
  - Results

Boundary Mode Analysis

Study Settings

Desired number of modes: 1

Transform: Effect

Search for modes around: n_core

Port name: 1

Mode analysis frequency: 1 [kHz] Hz

Mode search method around shift: Closer

Physics and Variables Selection

Modify physics tree and variables for study step

Physics	Discretization
Electromagnetic Waves, B...	Physics settin
Electrostatics (es)	Physics settin

Values of Dependent Variables

Mesh Selection

Study Extensions

Graphics

Messages | Progress | Log

Complete mesh consists of 39480 domain elements and 7602 boundary elements.

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Compute | Study 1 | Add Study | Continue | Update Solution | Get Initial Value | Show Default Solver | Study Steps | Parametric Sweep | Optimization | Create Solution Copy | Statistics | Clear Solutions | Clear All Solutions

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
      - Size
      - Edge 1
      - Mapped 1
  - Study 1
    - Parametric Sweep
    - Step 1: Stationary
    - Step 2: Boundary Mode Analysis
  - Results

Boundary Mode Analysis

Study Settings

Desired number of modes: 1

Transform: Effect

Search for modes around: n_core

Port name: 1

Mode analysis frequency: f0 Hz

Mode search method around shift: Closest

Physics and Variables Selection

Modify physics tree and variables for study step

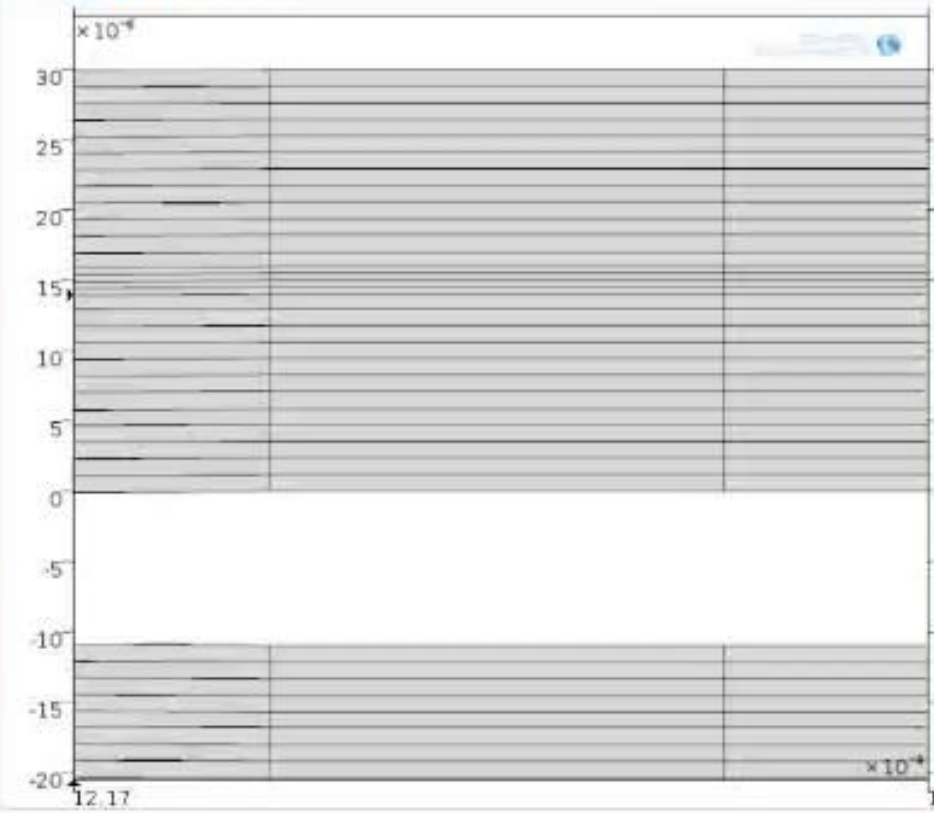
Physics	Sc	Discretization
Electromagnetic Waves, B...	✓	Physics setting
Electrostatics (es)	✓	Physics setting

Values of Dependent Variables

Mesh Selection

Study Extensions

Graphics



Messages | Progress | Log

Complete mesh consists of 39480 domain elements and 7602 boundary elements.

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Compute | Study 1 | Add Study | Get Initial Value | Show Default Solver | Study Steps | Parametric Sweep | Optimization | Create Solution Copy | Statistics | Clear All Solutions

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
      - Size
      - Edge 1
      - Mapped 1
  - Study 1
    - Parametric Sweep
    - Step 1: Stationary
    - Step 2: Boundary Mode Analysis
  - Results

Boundary Mode Analysis

Study Settings

Desired number of modes: 1

Transform: Effect

Search for modes around: n_core

Port name: 1

Mode analysis frequency: f0 Hz

Mode search method around shift: Closest

Physics and Variables Selection

Modify physics tree and variables for study step

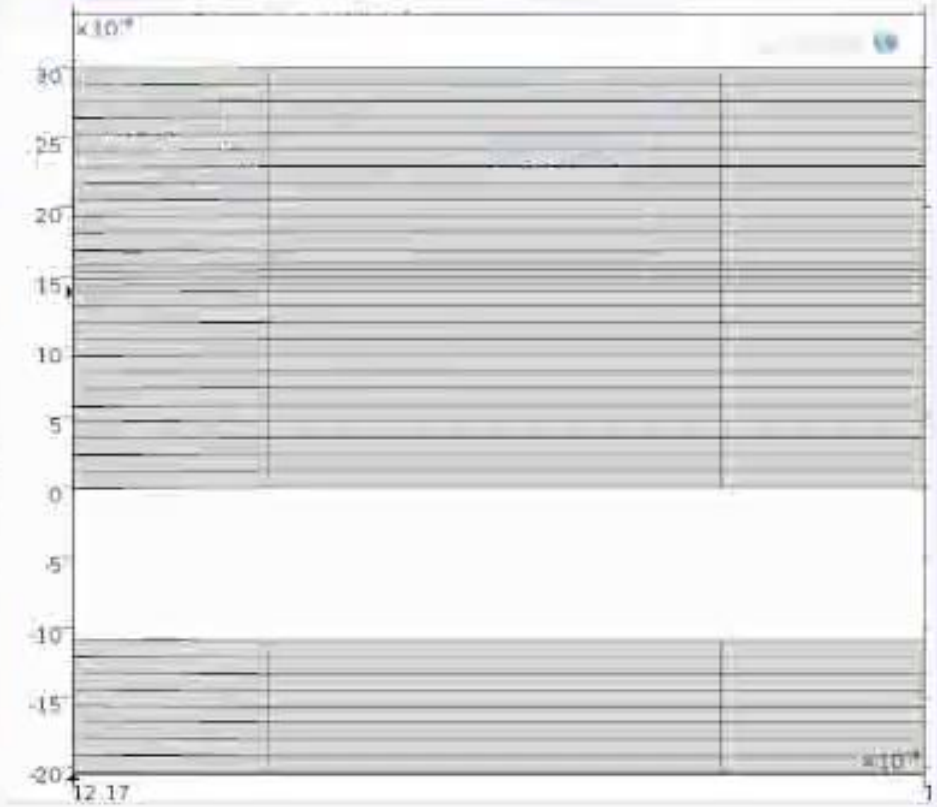
Physics	Sc	Discretization
Electromagnetic Waves, B...	✓	Physics setting
Electrostatics (es)	✗	Physics setting

Values of Dependent Variables

Mesh Selection

Study Extensions

Graphics



Messages | Progress | Log

Complete mesh consists of 39480 domain elements and 7602 boundary elements.

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Compute | Study 1 | Add Study | Get Initial Value | Show Default Solver | Study Steps | Parametric Sweep | Optimization | Create Solution Copy | Statistics | Clear All Solutions

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
      - Size
      - Edge 1
      - Mapped 1
  - Study 1
    - Parametric Sweep
    - Step 1: Stationary
    - Step 2: Boundary Mode Analysis
    - Step 3: Boundary Mode Analysis 2
  - Results

Boundary Mode Analysis

Study Settings

Desired number of modes: 1

Transform: Effect

Search for modes around: n_core

Port name: 2

Mode analysis frequency: f0 Hz

Mode search method around shift: Closest

Physics and Variables Selection

Modify physics tree and variables for study step

Physics	Discretization
Electromagnetic Waves, B...	Physics setting
Electrostatics (es)	Physics setting

Values of Dependent Variables

Mesh Selection

Study Extensions

Graphics

Messages | Progress | Log

Complete mesh consists of 39480 domain elements and 7602 boundary elements.

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results

Compute | Study 1 | Add Study | Continue | Update Solution | Get Initial Value | Show Default Solver | Study Steps | Parametric Sweep | Optimization | Create Solution Copy | Statistics | Clear Solutions | Clear All Solutions

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
    - Parameters
  - Component 1 (comp1)
    - Definitions
    - Geometry 1
    - Materials
    - Electromagnetic Waves, Beam Enve
    - Electrostatics (es)
    - Mesh 1
      - Size
      - Edge 1
      - Mapped 1
  - Study 1
    - Parametric Sweep
    - Step 1: Stationary
    - Step 2: Boundary Mode Analysis
    - Step 3: Boundary Mode Analysis 2
    - Step 4: Boundary Mode Analysis 3
  - Results

Boundary Mode Analysis

Study Settings

Desired number of modes:	1
Transform:	Effect
Search for modes around:	n_core
Port name:	3
Mode analysis frequency:	f0 Hz
Mode search method around shift:	Closer

Physics and Variables Selection

Modify physics tree and variables for study step

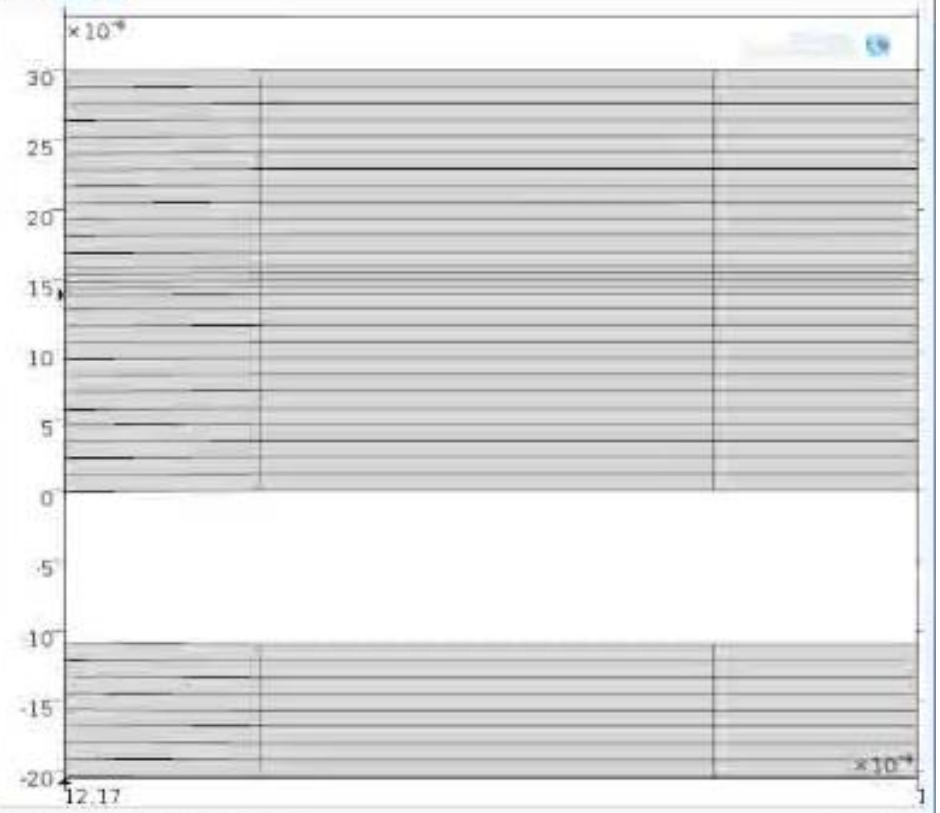
Physics	Sc	Discretization
Electromagnetic Waves, B...	✓	Physics settin
Electrostatics (es)		Physics settin

Values of Dependent Variables

Mesh Selection

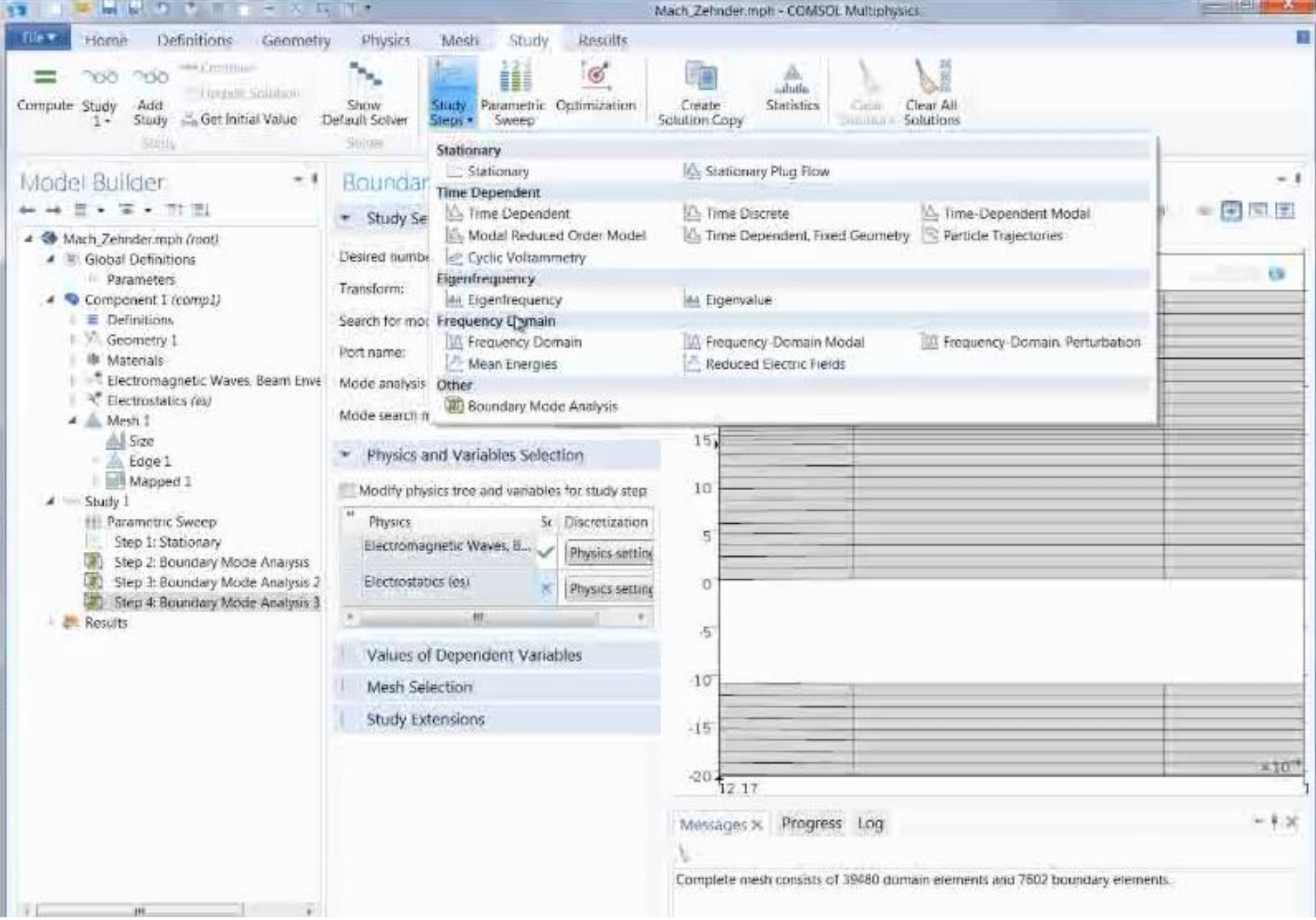
Study Extensions

Graphics



Messages | Progress | Log

Complete mesh consists of 39480 domain elements and 7602 boundary elements.


Mach_Zehnder.mph - COMSOL Multiphysics
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Stationary
Stationary
Stationary Plug Flow
Time Dependent
Time Dependent
Time Discrete
Time-Dependent Modal
Modal Reduced Order Model
Time Dependent, Fixed Geometry
Particle Trajectories
Cyclic Voltammetry
Eigenfrequency
Eigenfrequency
Eigenvalue
Frequency Domain
Frequency Domain
Frequency-Domain Modal
Frequency-Domain, Perturbation
Mean Energies
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Other
Boundary Mode Analysis
Model Builder
Mach_Zehnder.mph (root)
Global Definitions
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Component 1 (comp1)
Definitions
Geometry 1
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Electrostatics (es)
Mesh 1
Size
Edge 1
Mapped 1
Study 1
Parametric Sweep
Step 1: Stationary
Step 2: Boundary Mode Analysis
Step 3: Boundary Mode Analysis 2
Step 4: Boundary Mode Analysis 3
Results
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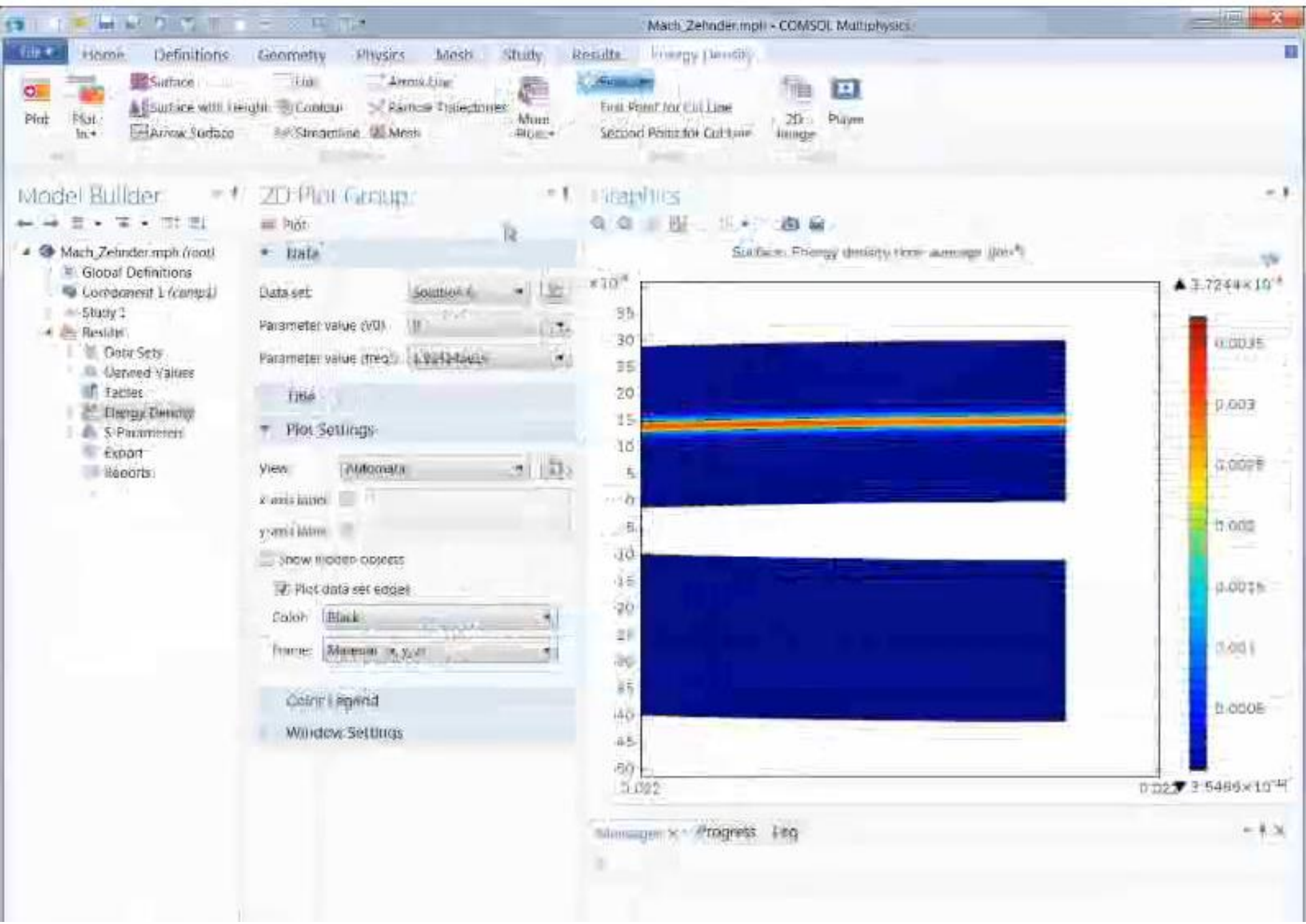
Physics and Variables Selection
Modify physics tree and variables for study step
Physics
Discretization
Electromagnetic Waves, B...
Physics setting
Electrostatics (es)
Physics setting
Values of Dependent Variables
Mesh Selection
Study Extensions
15
10
5
0
-5
-10
-15
-20
12.17
Messages
Progress
Log
Complete mesh consists of 39480 domain elements and 7602 boundary elements.


Mach_Zehnder.mph - COMSOL Multiphysics
Home
Definitions
Geometry
Physics
Mesh
Study
Results
Model Builder
Mach_Zehnder.mph (root)
Global Definitions
Component 1 (comp1)
Study 1
Results
Data Sets
Derived Values
Tables
Energy Density
S-Parameters
Export
Reports
2D Plot Group
Data
Data set:
Parameter value (V0)
Title
Plot Settings
View
Plot data set edges
Color
Black
Color Legend
Window Settings
Graphics
Messages
Progress
Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results | Energy Density

Plot | Plot In | Surface | Surface with Height | Arrow Surface | Line | Contour | Streamline | Arrow Line | Particle Trajectories | Mesh | More Plots | Evaluate | First Point for Cut Line | Second Point for Cut Line | 2D Image | Player

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
  - Component 1 (comp1)
  - Study 1
  - Results
    - Data Sets
    - Derived Values
    - Tables
    - Energy Density
    - S-Parameters
    - Export
    - Reports

2D Plot Group

Plot

Data

Data set: Solution 6

Parameter value (V0): 30

Parameter value (freq): 1.93414Se14

Title

Plot Settings

View: Automatic

x-axis label:

y-axis label:

Show hidden objects

Plot data set edges

Color: Black

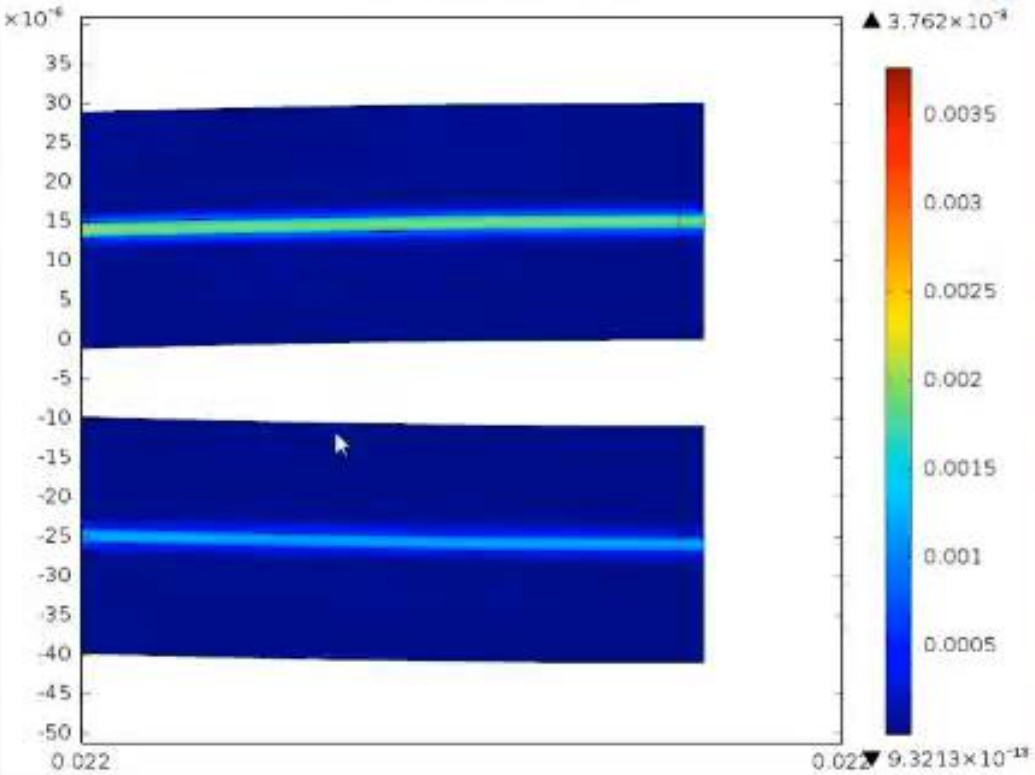
Frame: Material (x, y, z)

Color Legend

Window Settings

Graphics

Surface: Energy density time average (J/m³)



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results | Energy Density

Plot | Plot In | Surface | Surface with Height | Arrow Surface | Line | Contour | Streamline | Arrow Line | Particle Trajectories | Mesh | More Plots | Evaluate | First Point for Cut Line | Second Point for Cut Line | 2D Image | Player

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
  - Component 1 (comp1)
  - Study 1
  - Results
    - Data Sets
    - Derived Values
    - Tables
    - Energy Density
    - S-Parameters
    - Export
    - Reports

2D Plot Group

Plot

Data

Data set: Solution 6

Parameter value (V0): 60

Parameter value (freq): 1.934145e14

Title

Plot Settings

View: Automatic

x-axis label:

y-axis label:

Show hidden objects

Plot data set edges

Color: Black

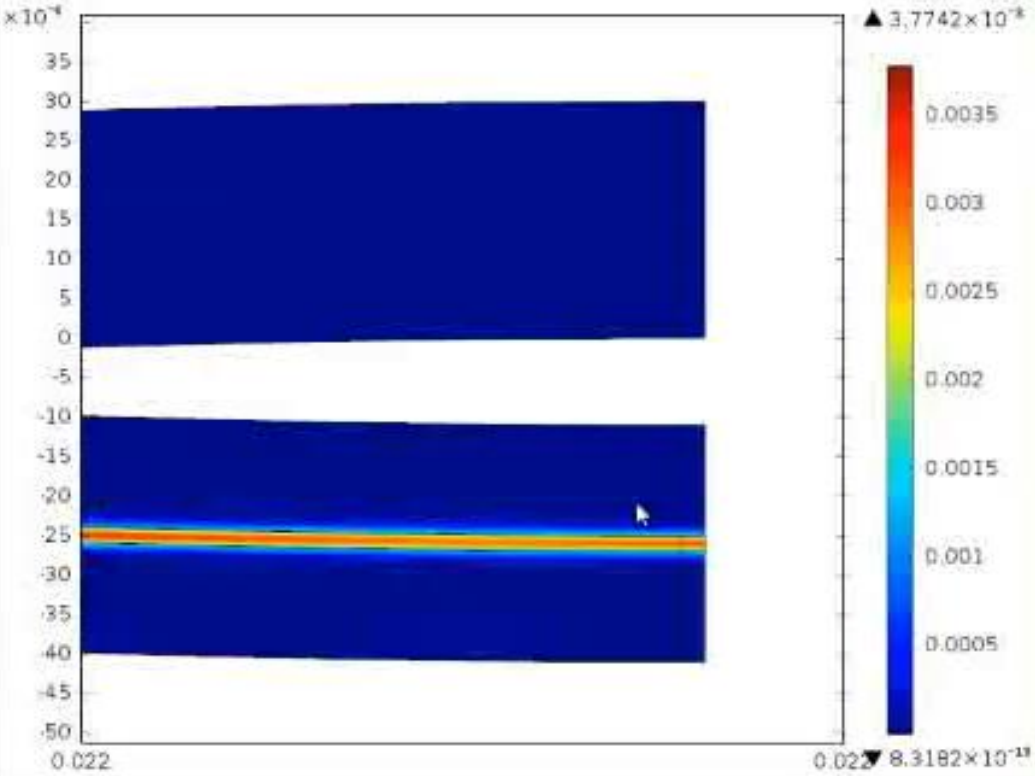
Frame: Material (x, y, z)

Color Legend

Window Settings

Graphics

Surface: Energy density time average (J/m³)



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results | Energy Density

Plot | Plot In | Surface | Surface with Height | Arrow Surface | Line | Contour | Streamline | Arrow Line | Particle Trajectories | Mesh | More Plots | Evaluate | First Point for Cut Line | Second Point for Cut Line | 2D Image | Player

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
  - Component 1 (comp1)
  - Study 1
  - Results
    - Data Sets
    - Derived Values
    - Tables
    - Energy Density
    - S-Parameters
    - Export
    - Reports

2D Plot Group

Plot

Data

Data set: Solution 6

Parameter value (V0): 60

Parameter value (freq): 1.934145e14

Title

Plot Settings

View: Automatic

x-axis label:

y-axis label:

Show hidden objects

Plot data set edges

Color: Black

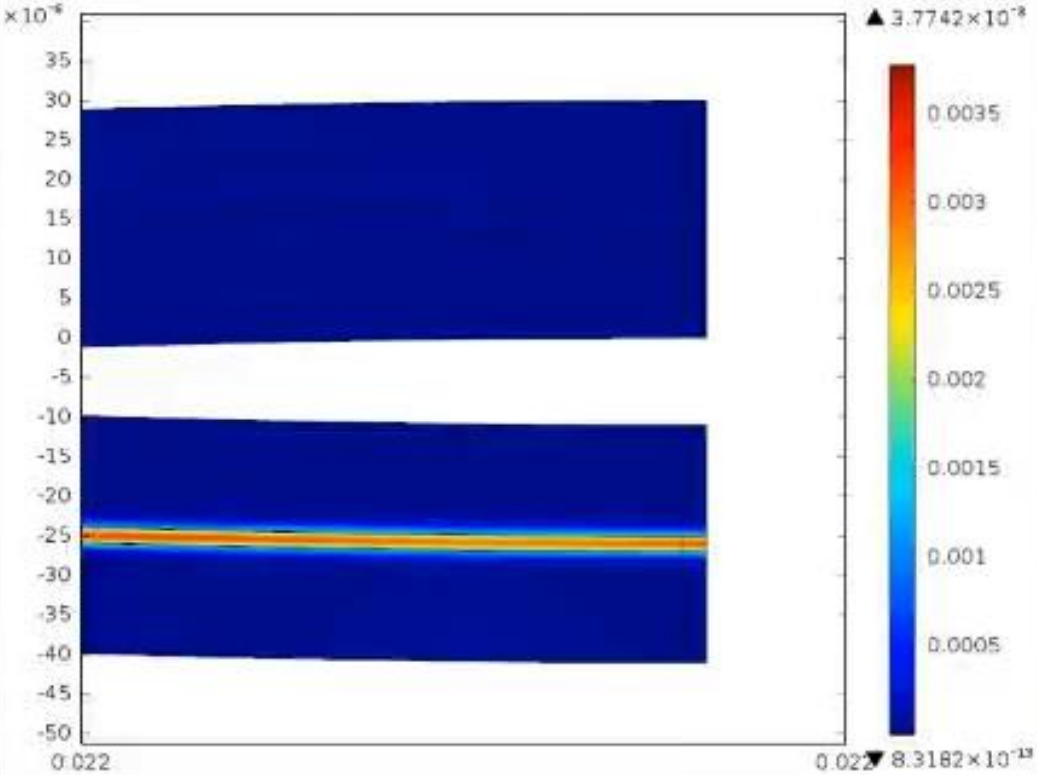
Frame: Material (x, y, z)

Color Legend

Window Settings

Graphics

Surface: Energy density time average (J/m³)



Messages | Progress | Log

Mach_Zehnder.mph - COMSOL Multiphysics

File | Home | Definitions | Geometry | Physics | Mesh | Study | Results | S-Parameters

Plot | Plot In | Line Graph | Point Graph | Global | Table Graph | Histogram | Nyquist Plot | Far Field | Export Data | Player

Model Builder

- Mach_Zehnder.mph (root)
  - Global Definitions
  - Component 1 (comp1)
  - Study 1
  - Results
    - Data Sets
    - Derived Values
    - Tables
    - Energy Density
    - S-Parameters
    - Export
    - Reports

1D Plot Group

Plot

Data

Data set: Solution

Parameter selection (V0): All

Parameter selection (freq): All

Title

Plot Settings

x-axis label: V0

y-axis label:

Axis

Manual axis limits

x minimum: -0.8

x maximum: 80.8

y minimum: 26.07809

y maximum: 0.04095

Preserve aspect ratio

x-axis log scale

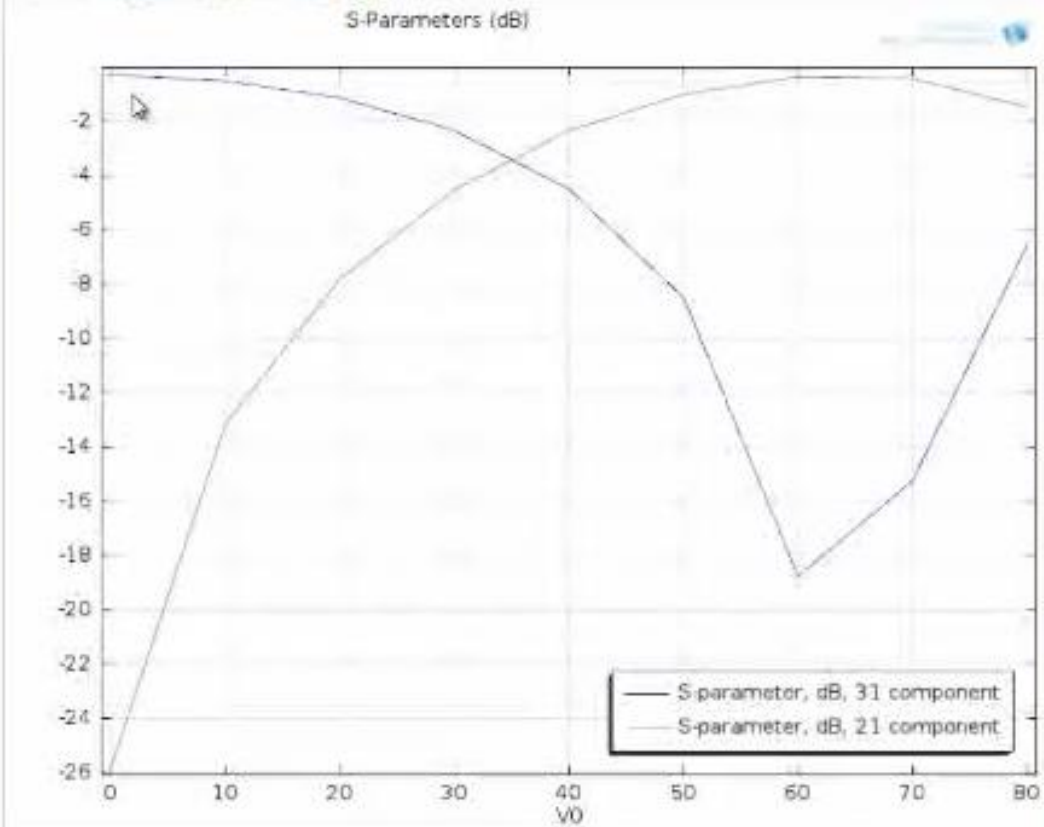
y-axis log scale

Grid

Manual spacing

x spacing: 1

Graphics



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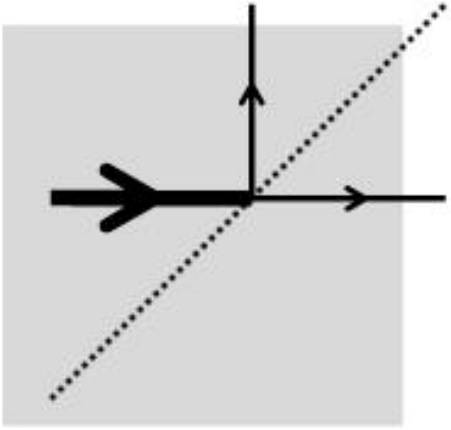
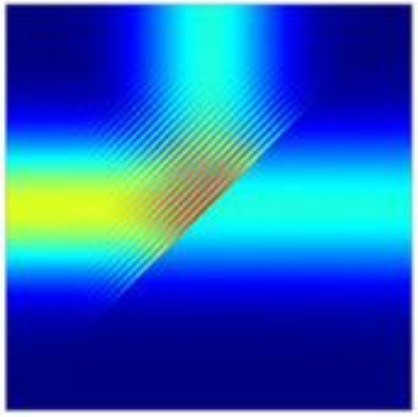
Demo: Mach-Zehnder Modulator

- Energy density at $V_0 = 0$

Example: Beam Splitter

- Thin silver layer between two glass prisms
- Incident Gaussian beam gets split in two
- Use transition boundary condition to model silver layer





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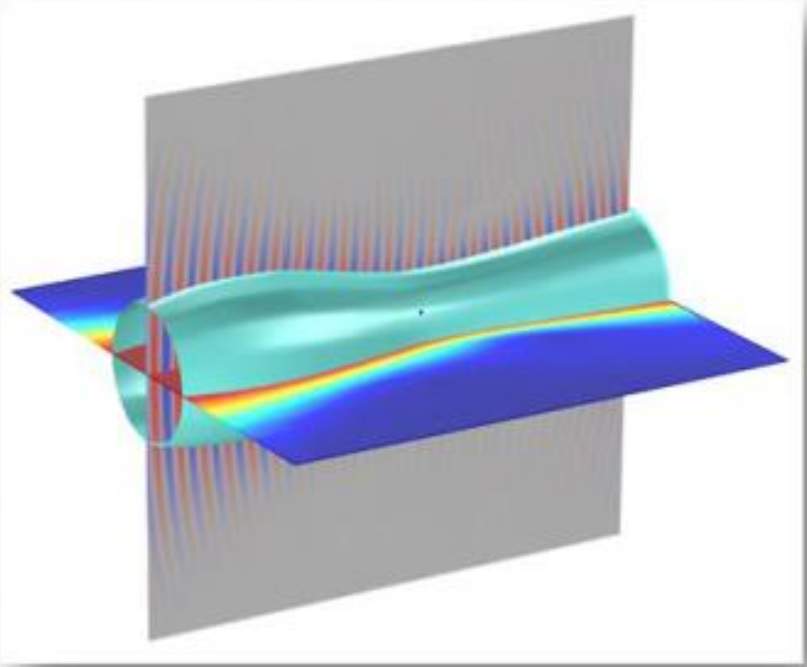
Example: Self-focusing Beam

- BK-7 optical glass: Refractive index increases with intensity
- Diffraction counteracted, Gaussian beam focuses itself



Compressed view of electric field, refractive index isosurface

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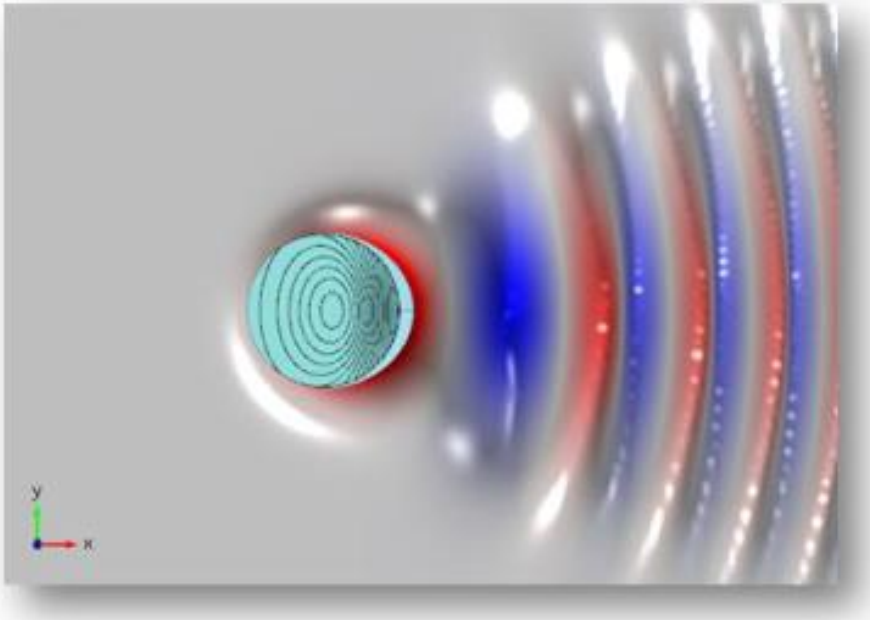
Example: Step-Index Fiber Bend

- 2D cross section of a curved fiber
- Study mode shape, radiation losses



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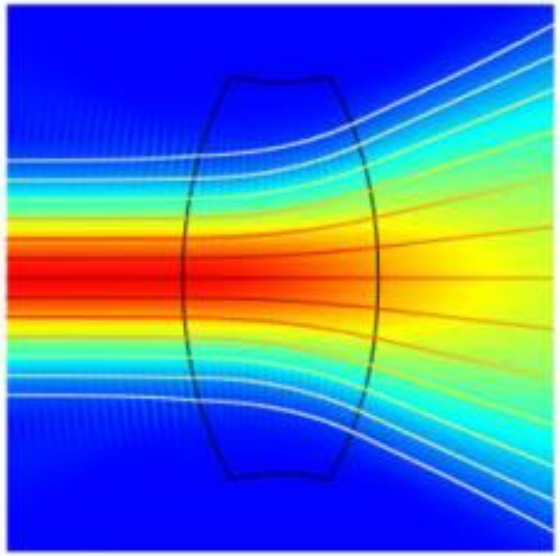
Example: Metamaterial Lens

- Convex lens, yet diverging beams
- Permittivity distribution defined on rectangular frame and mapped to lens shape

Permittivity distribution



Power flow, electric field norm

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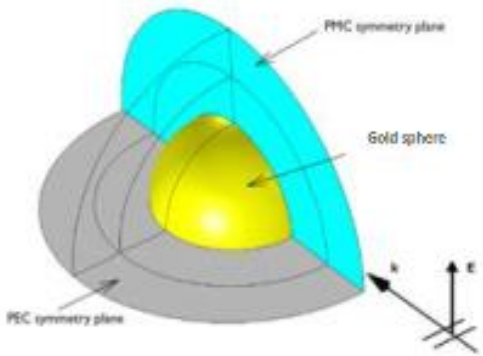
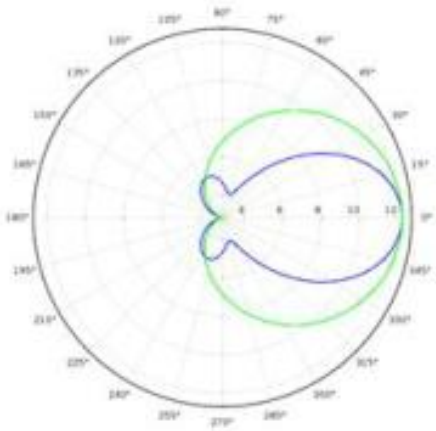
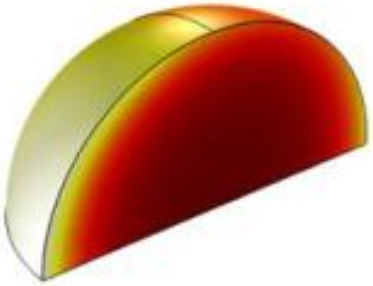
Example: Scattering off a Gold Sphere

- Gold sphere illuminated by 400-700 nm light
- Symmetry reduces problem size
- Perfectly Matched Layer (PML) truncates model domain
- Gold modeled with negative, complex-valued permittivity
- Far fields, losses in sphere computed







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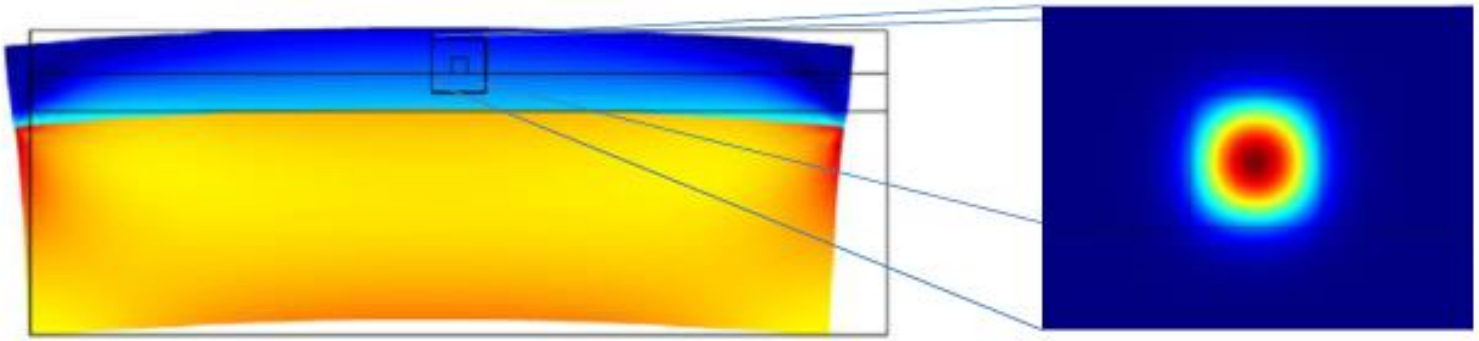
Example: Stress-Optical Effect

- Ridge waveguide
- Structural stress causes birefringence
- Solve for local stresses
- Apply anisotropic stress-dependent refractive indices
- Find out how modes, propagation constants change



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Feature Overview: Material Models

- Material properties can be
  - Constant or nonlinearly dependent on the fields
  - Isotropic, diagonal, or fully anisotropic
  - Defined via rule-of-mixtures models
  - Bi-directionally coupled to any other physics, e.g. temperature, strain
  - Fully user-definable
- Loss tangents and dispersion models supported
  - Drude-Lorentz
  - Sellmeier
  - Debye dispersion
  - User-defined

$$\mathbf{D} = \varepsilon_0 \varepsilon_r \mathbf{E}$$
$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}$$
$$\mathbf{D} = \varepsilon_0 \varepsilon_r \mathbf{E} + \mathbf{D}_r$$

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H}$$
$$\mathbf{B} = \mu_0 \mathbf{H} + \mu_0 \mathbf{M}$$
$$\mathbf{B} = \mu_0 \mu_r \mathbf{H} + \mathbf{B}_r$$

$$\mathbf{J} = \sigma \mathbf{E}$$

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Feature Overview: Boundary Conditions

- Thick volumes of electrically resistive or conductive materials
- Thin layers of electrically resistive or conductive materials
- Perfectly conducting boundaries
- Periodicity conditions, with optional phase shift
- Waveguide feeds
- Electromagnetic wave excitations
- Absorbing (radiating) boundaries

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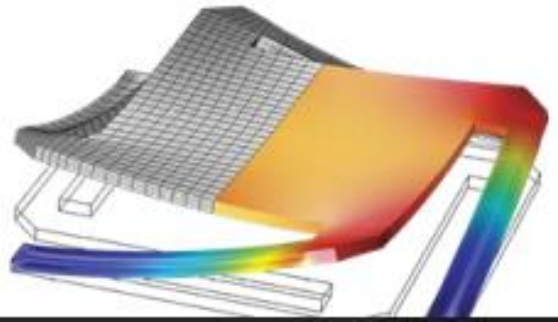

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