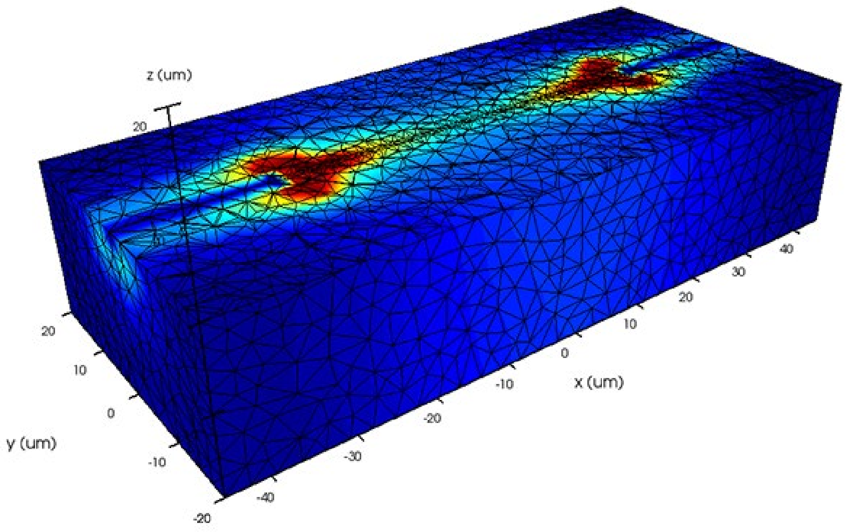
UNIVERSITY OF CAMBRIDGE

IIA Project SB4: Modeling of integrated photonic components



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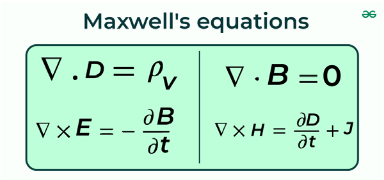
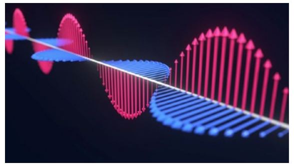
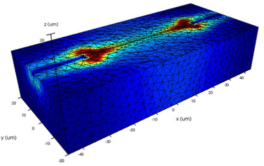
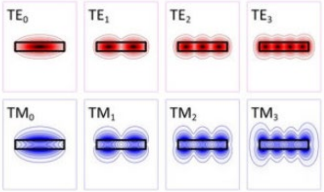
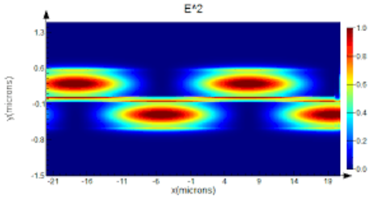
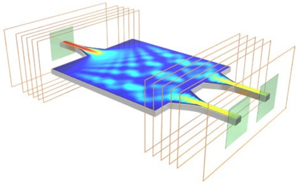
SB4: Modeling of integrated photonic components







AIMS & OBJECTIVES

- **Understand Fundamental Theories:** Gain a solid understanding of key concepts in photonics, including Maxwell's equations, waveguides, modes, FDTD models, and boundary conditions.
- **Master Eigenmode Analysis:** Learn to solve for eigenmodes in silicon waveguides using theoretical methods and Lumerical FDTD and understand their physical significance.
- **Develop Proficiency in Photonic Simulations:** Acquire hands-on experience with Lumerical FDTD to set up, run, and analyze simulations, including basic waveguides and complex photonic components.
- **Design, Simulation, and Validation:** Gain the ability to design, simulate, and analyze photonic components such as directional couplers, and validate simulation results by comparing them with mathematical models.

CONTENT

This four-week course introduces basic photonics theories and practical simulations with mathematical models and professional simulation tools. Students will individually design and simulate waveguide building blocks, and validate the simulation results against mathematical models, gaining proficiency in both theoretical concepts and hands-on simulation skills.

WEEKLY PLAN

- **Week 1**: Introduction to photonic theories, derive the waveguide mode with Maxwell’s equations, and perform basic simulations.
- **Week 2**: Eigenmode and mode propagation analysis in silicon waveguides with both theoretical calculations and Lumerical FDTD.
- **Week 3**: Design waveguide components, calculate their key structural parameters and construct initial simulations.
- **Week 4**: Optimize the component performance and validate the simulation results with mathematical models.

AIMS

The aims of the course are to:

- Gain a comprehensive understanding of essential photonic concepts, including Maxwell's equations governing electromagnetic waves, principles of waveguides, different modes of light propagation, boundary conditions, dispersion, and etc.
- Analyze optical modes and their propagation in photonic waveguides using both theoretical calculations and Lumerical FDTD simulations. Gain practical insights into mode profiles and relevant characteristics, such as propagation constant, effective index, and confinement factor, etc.
- Acquire practical skills in Lumerical FDTD simulations, including meshing techniques, defining material properties, configuring light sources, and understanding simulation outputs like field distributions and mode profiles.
- Understand the working principles and simulation methodologies for key photonic components — e.g., directional couplers, and learn the mode coupling theory.
- Design and simulate a 2x2 directional couplers with FDTD, optimizing their performance metrics such as coupling efficiency, insertion loss, and bandwidth.
- Validate simulation results by comparing them with analytical models and numerical methods, ensuring accuracy and reliability in predicting device behavior and performance. Discuss the current design limitation and possible improvement.
- Apply acquired knowledge and skills to practical scenarios, preparing for advanced studies or professional applications in photonics, such as communications, sensing, and signal processing.

IIA Project: Modeling of integrated photonic components

Content

This four-week course on photonics simulation, designed for bachelor students, provides a comprehensive introduction to both theoretical and practical aspects of photonics. The course begins with an overview of fundamental photonics concepts, including Maxwell's equations, waveguides, and eigenmodes. Students will learn to derive waveguide modes using Maxwell's equations and perform basic simulations.

In the second week, students will delve into eigenmode and mode propagation analysis in silicon waveguides, and design a single-mode waveguide utilizing both theoretical calculations and Lumerical FDTD simulations. This will provide a deeper understanding of mode characteristics and behavior in silicon waveguides.

The third week focuses on the design of two photonic components, i.e. a directional coupler. Students will calculate key structural parameters and construct initial simulations of these components, gaining practical experience in photonic design and simulation techniques.

In the final week, students will optimize the performance of the designed components and validate their simulation results with mathematical models to ensure accuracy and reliability in their simulations. By the end of the course, students will be proficient in both the theoretical understanding and practical application of photonics simulations, preparing them for advanced studies or professional work in the field.

IIA Project: Modeling of integrated photonic components

Content:

Weekly Plan:
Week 1: Introduce fundamental photonics theory and basic waveguide simulation with Lumerical software, focusing on understanding and setting up simple models.
Week 2: Dive into eigenmode analysis in silicon waveguides using both theoretical calculations and Lumerical FDTD. Design and simulate a single-mode waveguide, observe the mode propagation, and compare it with the calculated single-mode condition.
Week 3: Design and simulate waveguide photonic components — i.e., a directional coupler. Calculate their key structural parameters using theoretical models and simulate both components with Lumerical FDTD.
Week 4: Validate simulation results by comparing them with theoretical and numerical models, optimize their performance, ensuring accuracy and reliability of the simulations.

Mini Lectures:
Two mini lectures will be delivered to:

- Introduction to photonic fundamentals, Maxwell's equations, waveguide modes, and eigenmode analysis in photonic waveguides, such as silicon waveguide.
- Overview/tutorial of Lumerical FDTD software, including interface navigation, setting up simulations, and running and interpreting simulation results.

Coursework:

Coursework	Due date	Marks
Interim report 1	TBD	20
Interim report 2	TBD	20
Final summary report	TBD	40

* 100% of the marks will be given based on individual performance.

Weekly Plan (Detailed)

Week 1

1. Mini lecture 1, introduce fundamental concepts of photonics. Discuss Maxwell's equations and electromagnetic wave propagation. Explain waveguides, modes, boundary conditions, and etc. Cover the theory of eigenmodes in waveguides and the effective index method.
2. Guide students to calculate waveguide modes using Maxwell's equations, understand the origins of higher-order waveguide modes, and analyze the characteristics of different modes.
3. Use Lumerical FDTD to construct a basic silicon waveguide, learn to define the simulation region, configure the simulation parameters, including the mesh and boundary conditions, and set up the relevant monitors.

Week 2

1. Explore the eigenmode analysis in silicon waveguides, understand the propagation characteristics of different modes, including the effective index, group index, and confinement factor. Calculate the waveguide's single-mode cutoff condition and understand the impact of dispersion on waveguide modes.
2. Mini lecture 2, familiarize students with the Lumerical FDTD software. Overview of Lumerical FDTD capabilities and applications. Navigation through the software interface and main features. Introduction to setting up a basic simulation project.
3. Construct a silicon waveguide in Lumerical FDTD, simulate the propagation characteristics of different modes, and analyze their loss and dispersion.
4. Optimize the waveguide geometry to create a single-mode waveguide, and compare it with the theoretically calculated single-mode condition, and analyze any discrepancies.

Interim report 1

IIA Project: Modeling of integrated photonic components

Week 3

1. Understand the fundamental principles of directional couplers, i.e., mode coupling theory. Learn about their common applications in integrated optical platforms and discuss fabrication considerations.
2. Design a 2x2 directional coupler, both aiming to achieve a 50:50 split of the fundamental TE mode. Use theoretical calculations to determine key geometry parameters, such as the coupling length in the directional coupler.
3. Configure simulations in Lumerical FDTD for both components. Define the material properties and simulation settings and obtain initial simulation results.

Interim report 2

Week 4

1. Validate simulation results by comparing them with mathematical models. Discuss discrepancies and insights gained from the comparison.
2. Optimize the component performance, targeting for balanced splitting ratio, lower insertion loss, broader bandwidth, and etc.
3. Evaluate the device performance, discuss the current limitations and future improvements based on simulation findings.

Final summary report

IIA Project: Modeling of integrated photonic components

Practical steps in course implementation

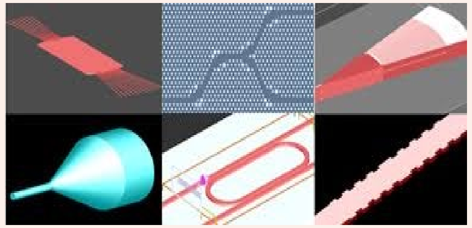
Basic photonic theories and simulation tools

T1-1 to 1-2

...ll's equations

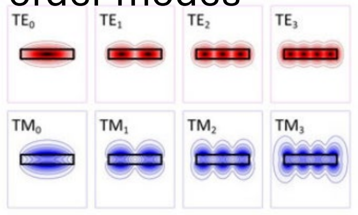
$$\nabla \cdot D = \rho_V \qquad \nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad \nabla \times H = \frac{\partial D}{\partial t} + J$$



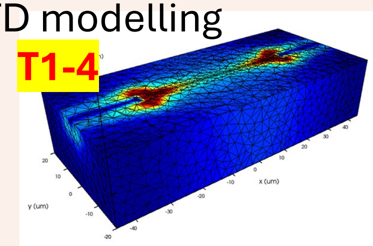
Higher order modes

T1-3



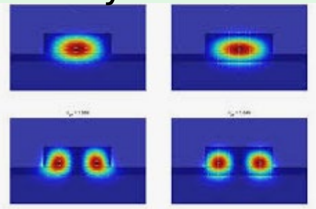
FDTD modelling

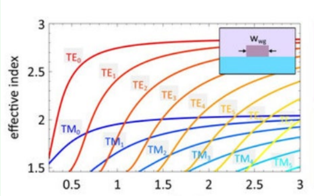
T1-4



Eigen mode analysis

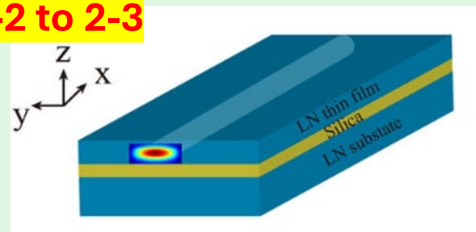
T2-1

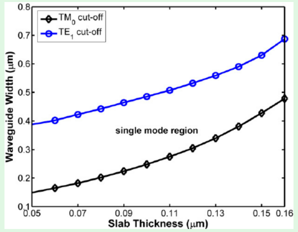




Design a single-mode waveguide

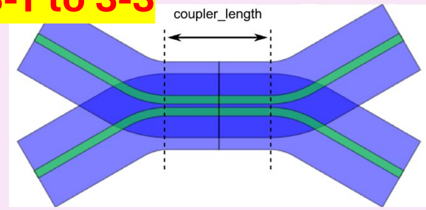
T2-2 to 2-3

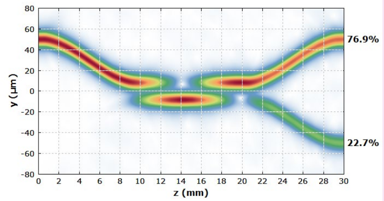


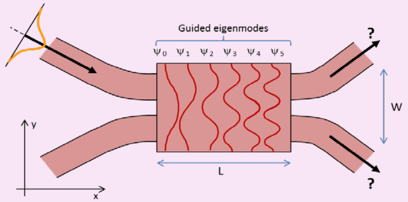


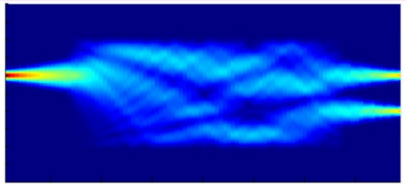
Design a 2x2 directional coupler

T3-1 to 3-3

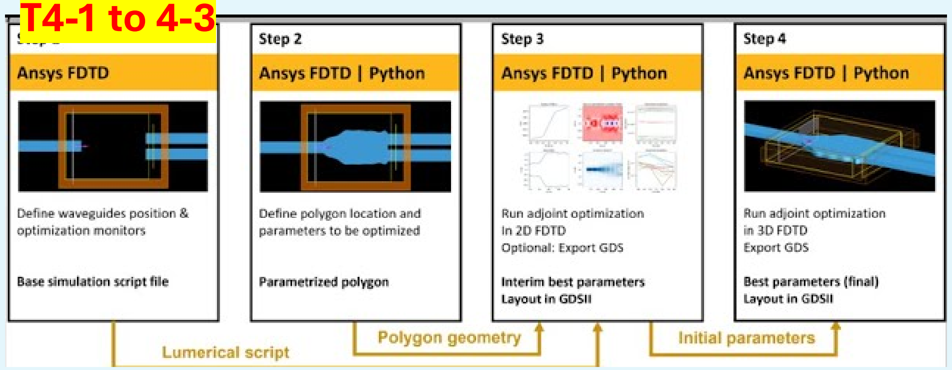








T4-1 to 4-3



Performance optimization and validation

IIA Project: Modeling of integrated photonic components

Practical steps in course implementation:

1. Introduce photonics fundamentals: Maxwell's equations, wave propagation, waveguides, modes, and boundary conditions.
2. Familiarize with Lumerical FDTD software: capabilities, interface, set up a basic simulation project.
3. Calculate waveguide modes using Maxwell’s equations: understand higher-order modes and analyze their characteristics.
4. Create a basic waveguide model in Lumerical FDTD: define region, set geometry, assign materials, configure parameters.
5. Understand the basic characteristics of waveguide modes, including effective index, group index, and confinement factor.
6. Calculate the single-mode cutoff condition for waveguides and understand the impact of dispersion on waveguide modes.
7. Design a single-mode waveguide, simulate it in Lumerical FDTD, and compare with the theoretical single-mode condition.
8. Understand the working principles of directional couplers (mode coupling theory).
9. Simulate directional couplers in Lumerical FDTD: define geometry, materials, settings.
10. Analyze simulation results: assess coupling efficiency, insertion loss, bandwidth, and etc.
11. Optimize the component performance, discuss insights.
12. Validate the simulation outcomes with theoretical results.
13. Summarize simulation findings: current limitations and future improvements.

IIA Project: Modeling of integrated photonic components

Weekly Plan

W1

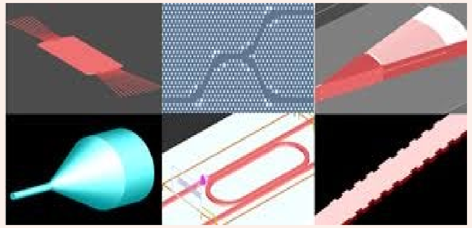
Basic photonic theories and simulation tools

1,2

Maxwell's equations

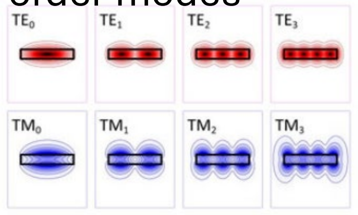
$$\nabla \cdot D = \rho_v \qquad \nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad \nabla \times H = \frac{\partial D}{\partial t} + J$$



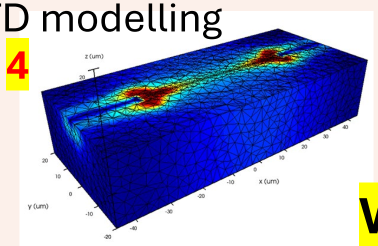
Higher order modes

3



FDTD modelling

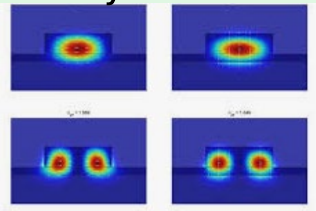
4

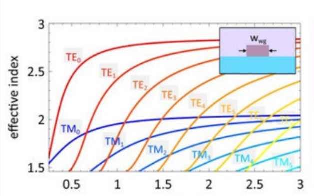


W2

Eigen mode analysis

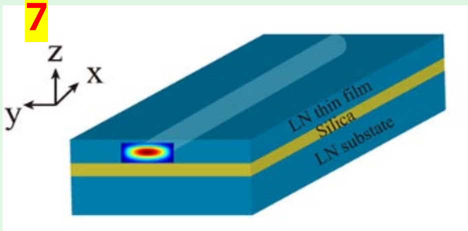
5,6

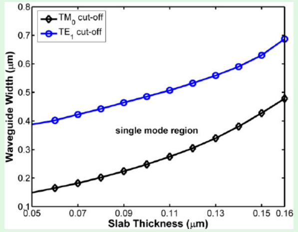




Design a single-mode waveguide

7

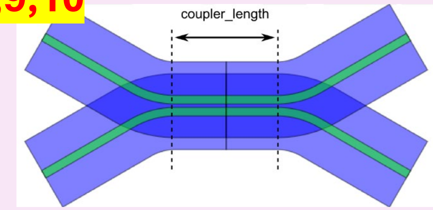


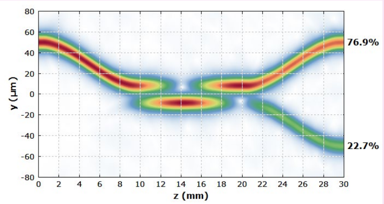


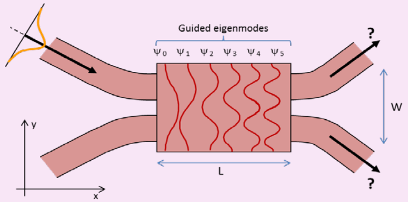
W3

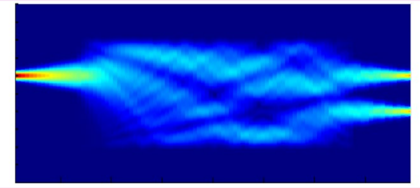
Design a 2x2 directional coupler

8,9,10



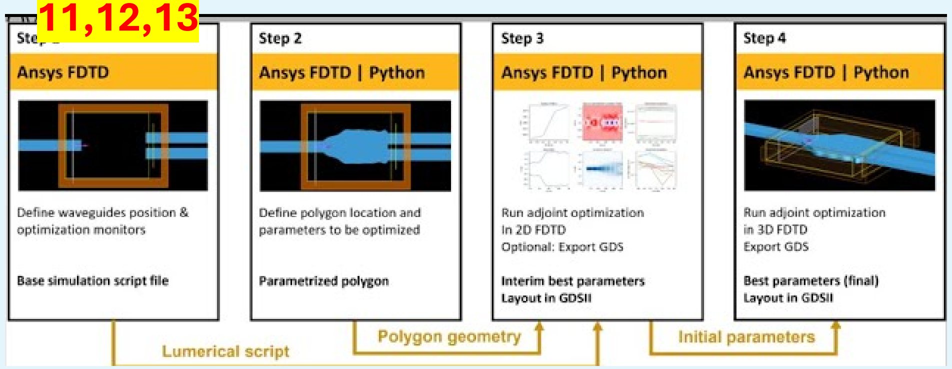






W4

11,12,13



Performance optimization and validation

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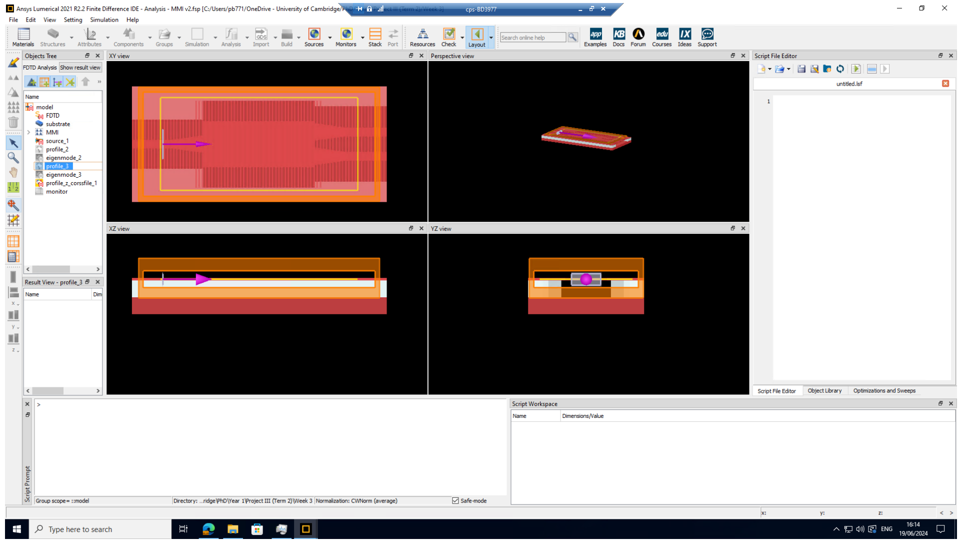
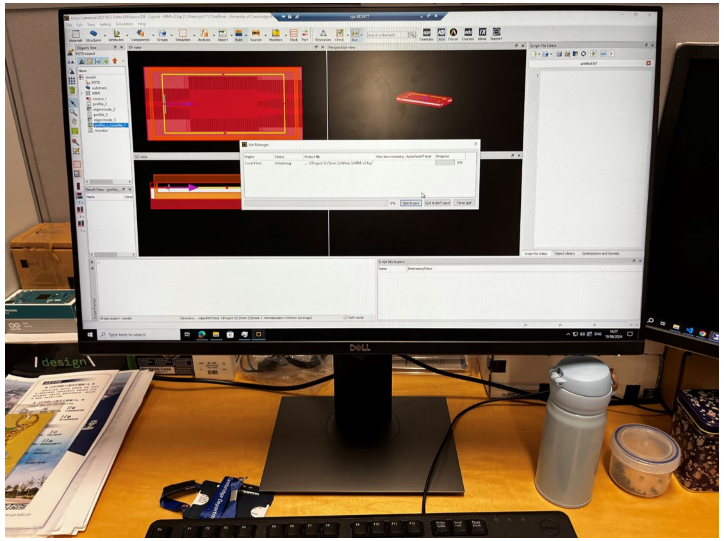
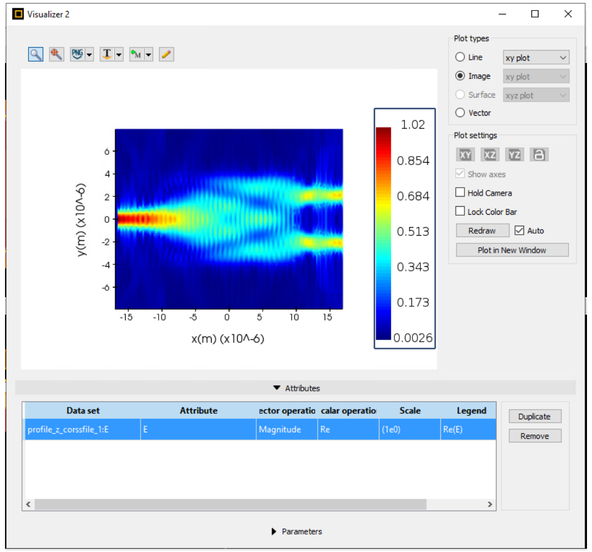




For example, a multi-mode interferometer in FDTD simulation

Practical steps in course implementation



Resultant electric field