lumerical

illuminating the way

FDTD *Solutions*

Introductory Training

探索业界领先的光子设计工具套包

免费试用评估

Lumerical 工具使光子器件、芯片和系统的设计得以实现

FDTD Solutions	MODE Solutions	DEVICE	INTERCONNECT
微纳光学设计环境	波导设计环境	多物理场光子设计平台	集成光学设计和仿真平台

浏览全部产品

Product Overview

Optical Simulation

FDTD Solutions

Nanophotonic Design Environment

- Finite Difference Time-Domain Solver
- Finite Difference Eigenmode Solver

MODE Solutions

Waveguide Design Environment

- Finite Difference Eigenmode Solver
- Eigenmode Expansion Solver
- Variational FDTD Solver

Data Exchange:
Lumerical Scripting
MATLAB API
Python API

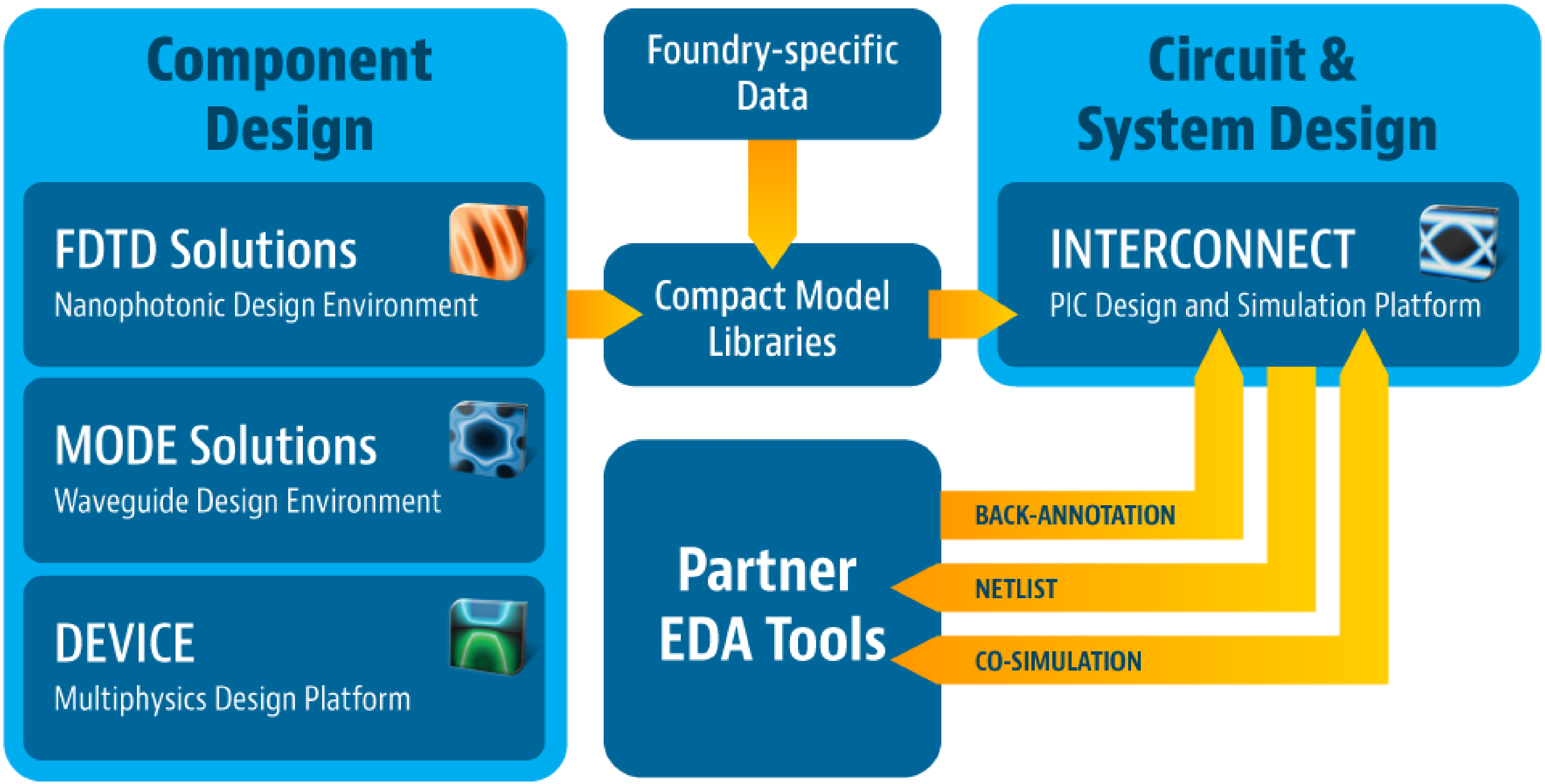
Multiphysics

DEVICE

Multiphysics Photonics Design Platform

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

Product Overview



Outline

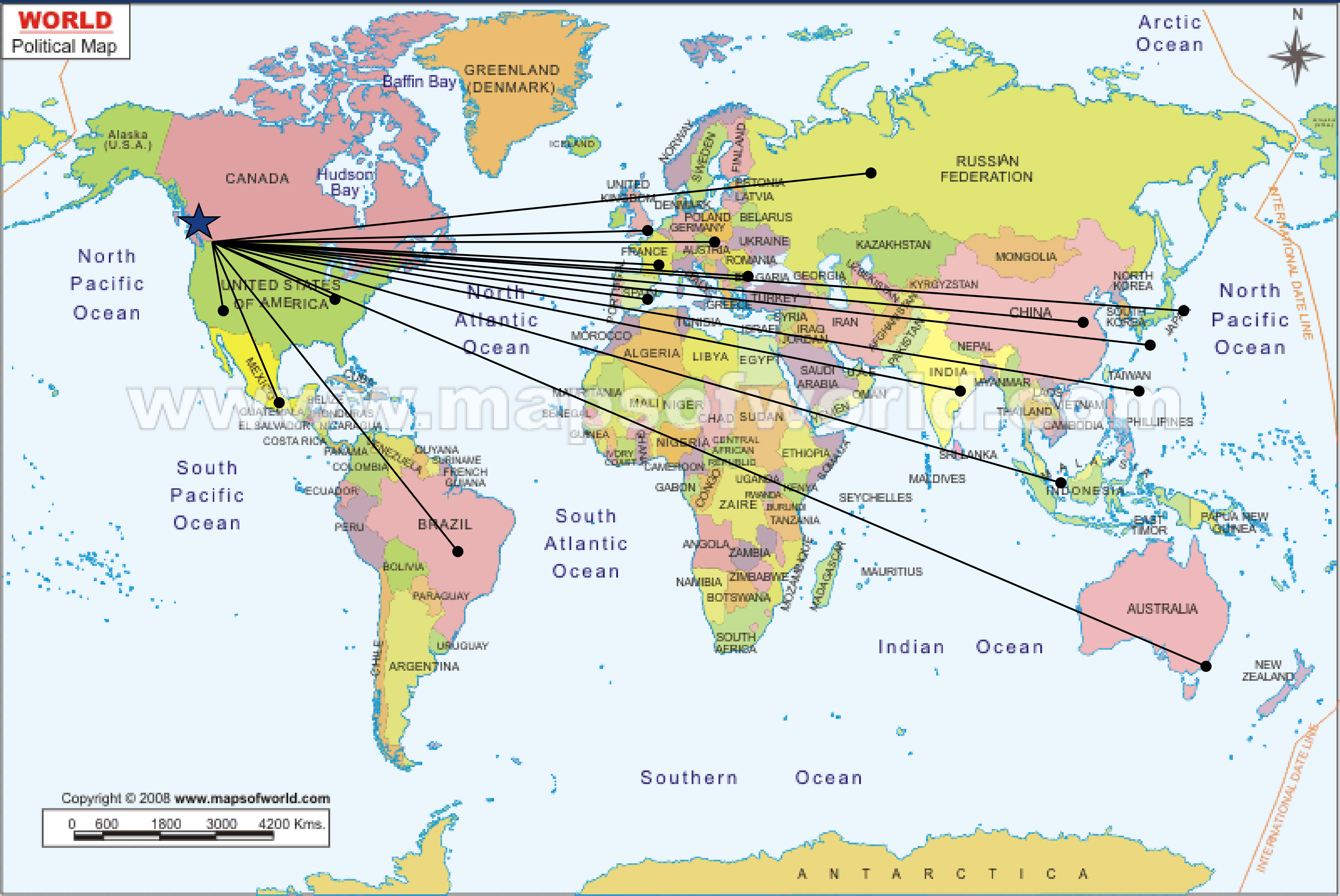
- Introduction: history background, application areas
- Overview of FDTD method
- Install FDTD Solutions
- Features of FDTD Solutions

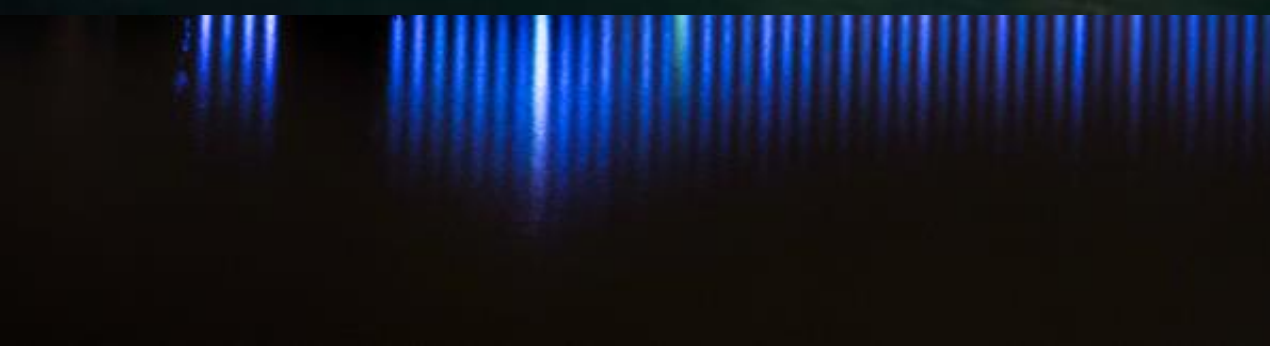
- FDTD Solutions work flow and examples
- Simple example
- Advanced example
- Workshop
- Review and tips

Goals

- **Understand the types of problems that require FDTD Solutions.**
- **Learn the fundamentals of the FDTD algorithm**
- **Learn the basic features of FDTD Solutions**
- **Gain initial experience using FDTD Solutions**

Introduction: History and Background





国际日期变更线

150°
东经180°西经
150°
北
冰
洋
北极圈
亚
洲
北
美
洲
国
际
日
期
变
更
线
不变
阿留申群岛
太
北回归线
中途岛
夏威夷群岛
马绍尔群岛
平
赤道
−1
+1
斐济群岛
萨摩亚群岛
南回归线
洋
大
洋
洲
150°
东经180°西经
150°

鄂霍次克海
白令海
帝王槽
伊尔库茨克
太平洋
乌兰巴托
哈尔滨
帝王海山
札幌
沈阳
敦煌
北京
兰州
郑州
济南
釜山
大阪
东京
成都
首页
高度:
10972 米
到郑州所需距离:
813 公里

Introduction: History and Background

Lumerical's tools enable the design of photonic components, circuits and systems. Learn more

Our Products

FDTD Solutions
3D/2D Maxwell's solver for optical design

MODE Solutions
Waveguide design environment

INTERCONNECT
Photonic integrated circuit (PIC) simulation and analysis

DEVICE
Multiphysics modeling of charge and heat transport

Trusted Technology

Lumerical software is used in over 50 countries and has been referenced in more than 5000 academic publications and patents.

Upcoming Workshops

Photonics Summit & Workshop 2016
San Jose, CA — October 19 & 20

Multiproduct Training
Seoul, KR — November 28-30

PIC Workshop
Pyeongchang, KR — December 1

Upcoming Webinars

Defect Detection & Optical Inspection Technology — October 24 & 25

Introduction: Example Application Areas

- Biophotonics
  - Surface plasmon devices
  - Nano-particle scattering
  - Integrated optical sensors
- Lighting applications
  - OLED/LED light extraction optimization
  - Emissive calculations
- Display technology
  - Nanowire grid polarizers
  - Digital micro-mirror devices
- Optical communications
  - Ring resonators
  - Optical waveguides
  - Optical filters
  - Photonic crystal micro-cavities
  - Photonic crystals vertical cavity surface emitting laser (PCs-VCSEL)
- Optical sensing and imaging
  - CMOS/CCD image sensor pixels
  - Near-field microscopy
  - Micro-optic tips
  - Phase contrast microscope
- Optical storage
  - DVD surface design, Blue-ray
- Semiconductor manufacturing
  - DUV lithography simulation
  - Surface plasmon resonance interference nanolithography
  - Metrology for wafer and reticles inspection
- Solar cells and photo-voltaic cells
- NRI-based components
- Optical tweezers
- ...

Wave Optics vs. Ray tracing

Commercial software for Wave Optics vs. Ray tracing:

Code-V, Zemax, OSLO, ASAP etc.

Question:

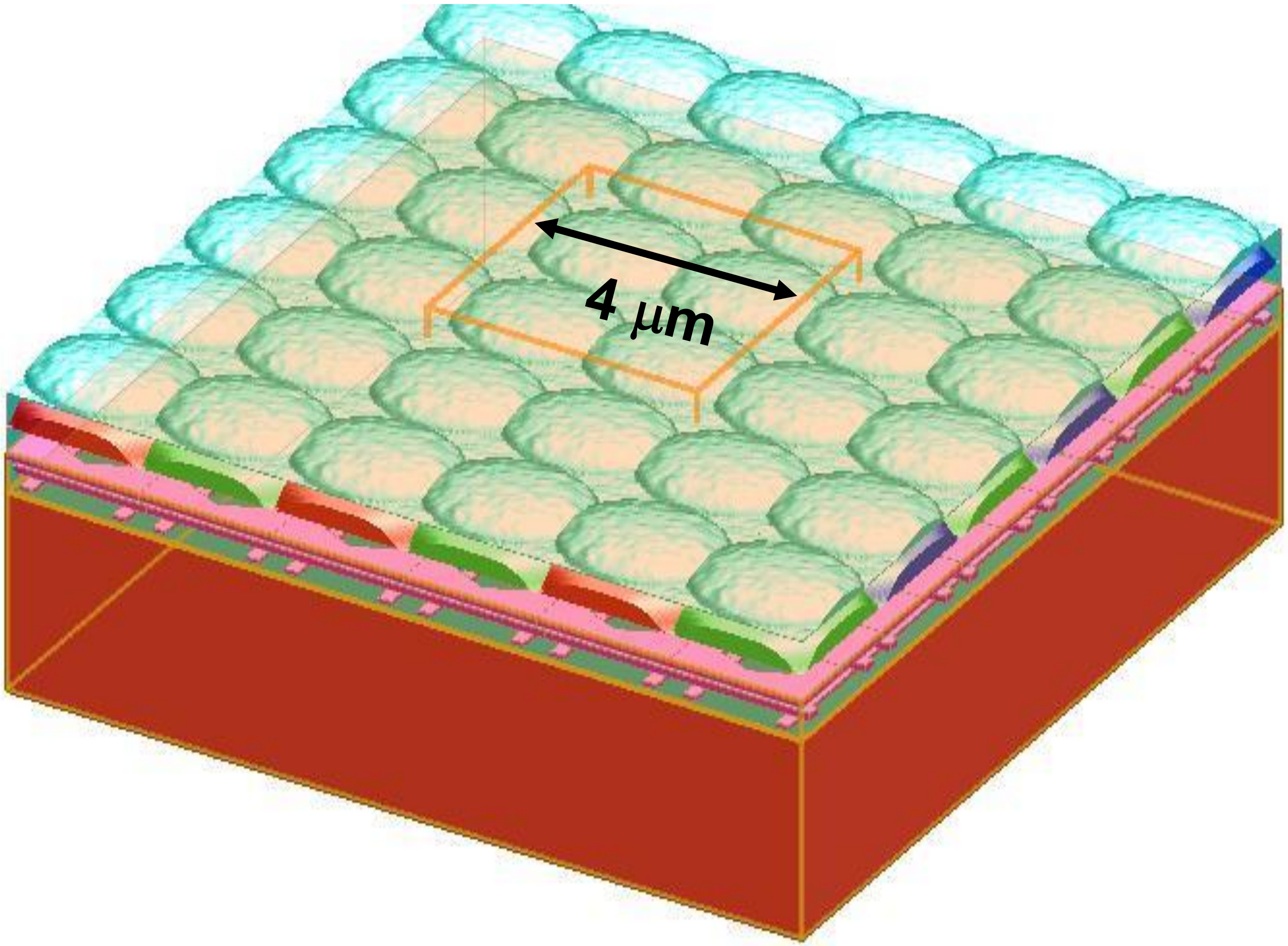
What features are common points among these applications?

(When do you need to use FDTD Solutions?)

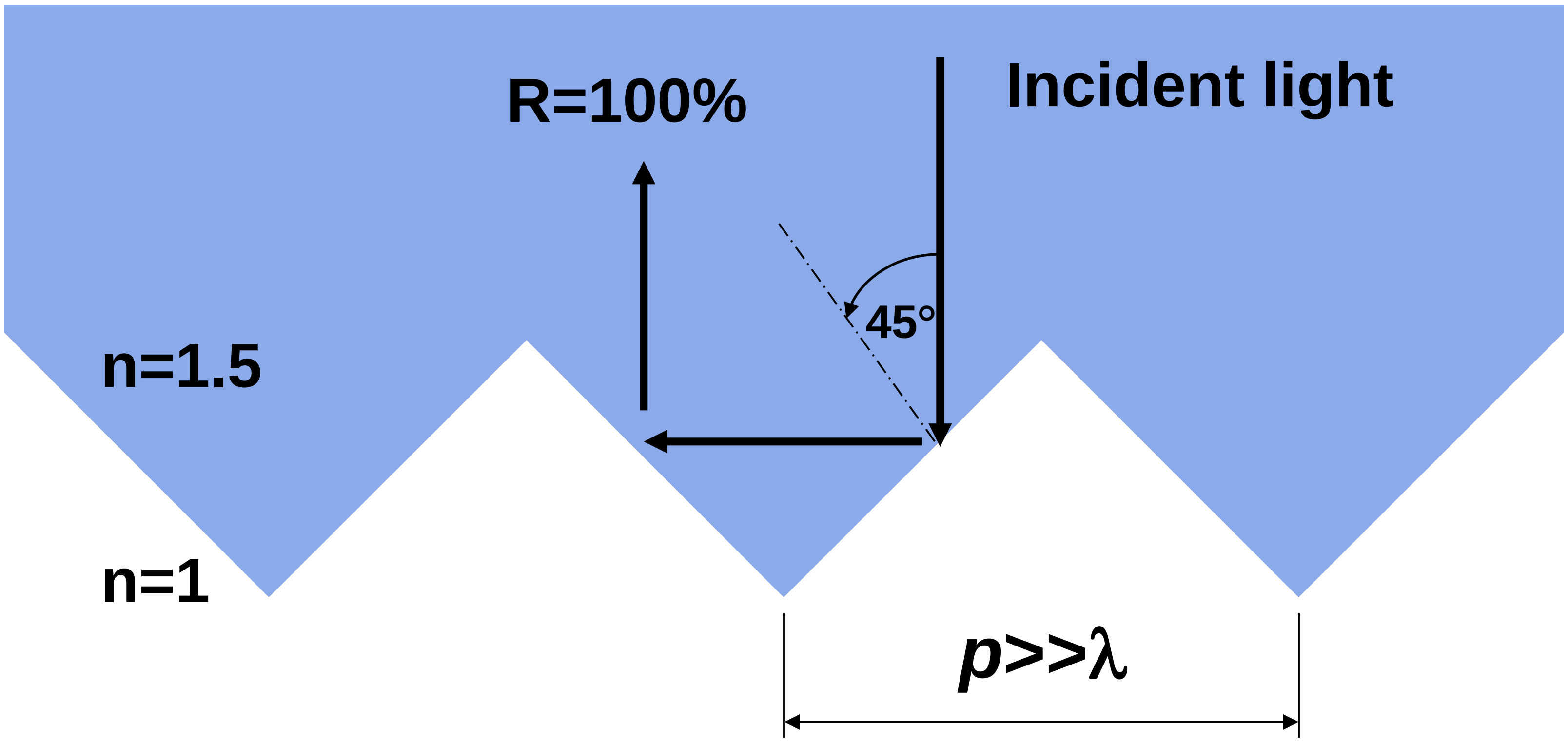
Answer: ???

Wave Optics vs. Ray tracing

Source λ = 0.55 μm



Wave Optics vs. Ray tracing

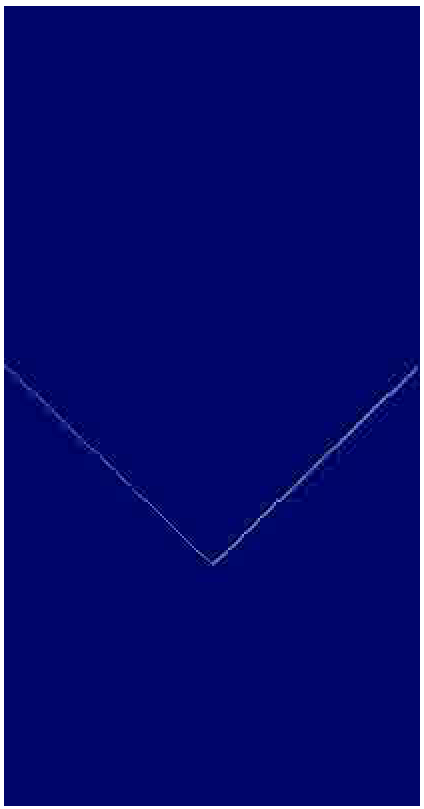


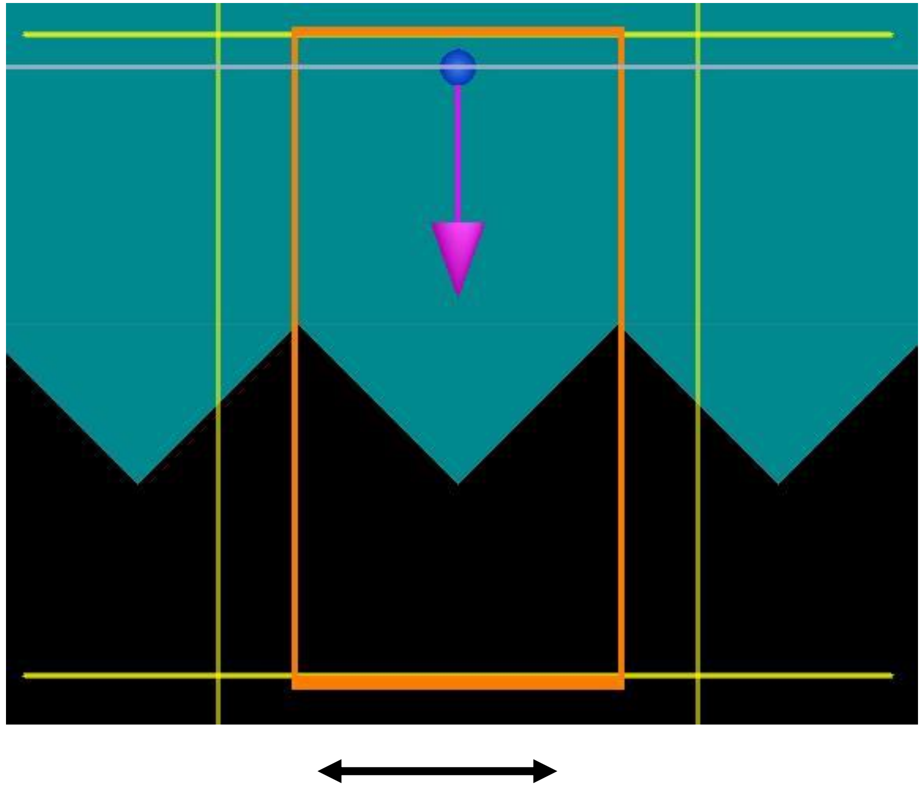
Snell's Law gives

θ_c: 41.8°

Wave Optics vs. Ray tracing

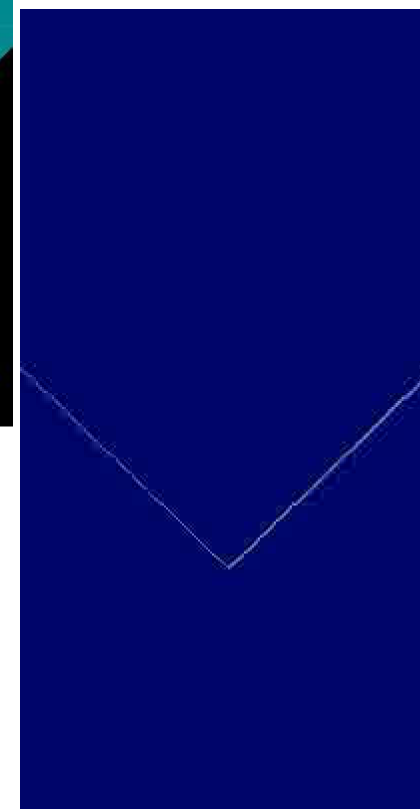
λ = 0.4 μm





20 μm

λ = 4 μm



Wave Optics vs. Ray tracing

Conclusion:

You need FDTD Solutions when feature sizes *p* are on the order of a wavelength *p*~λ, and *p*<λ.

Overview of FDTD algorithm

TOPICS:

- Maxwell equations
- Yee cell
- Time domain technique
- Fourier transform
- Requirements of computational memory size/time
- 2D vs. 3D
- Advantages of the FDTD method

Maxwell's Equations

Describe the behavior of both the electric and magnetic fields, as well as their interactions with matter.

Name	Differential form	Integral form
Gauss' law	$\nabla \cdot \mathbf{D} = \rho$	$\oint_S \mathbf{D} \cdot d\mathbf{A} = \int_V \rho \cdot dV$
Gauss' law for magnetism (absence of magnetic monopoles):	$\nabla \cdot \mathbf{B} = 0$	$\oint_S \mathbf{B} \cdot d\mathbf{A} = 0$
Faraday's law of induction:	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d}{dt} \int_S \mathbf{B} \cdot d\mathbf{A}$
Ampère's law (with Maxwell's extension):	$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$	$\oint_C \mathbf{H} \cdot d\mathbf{l} = \int_S \mathbf{J} \cdot d\mathbf{A} + \frac{d}{dt} \int_S \mathbf{D} \cdot d\mathbf{A}$

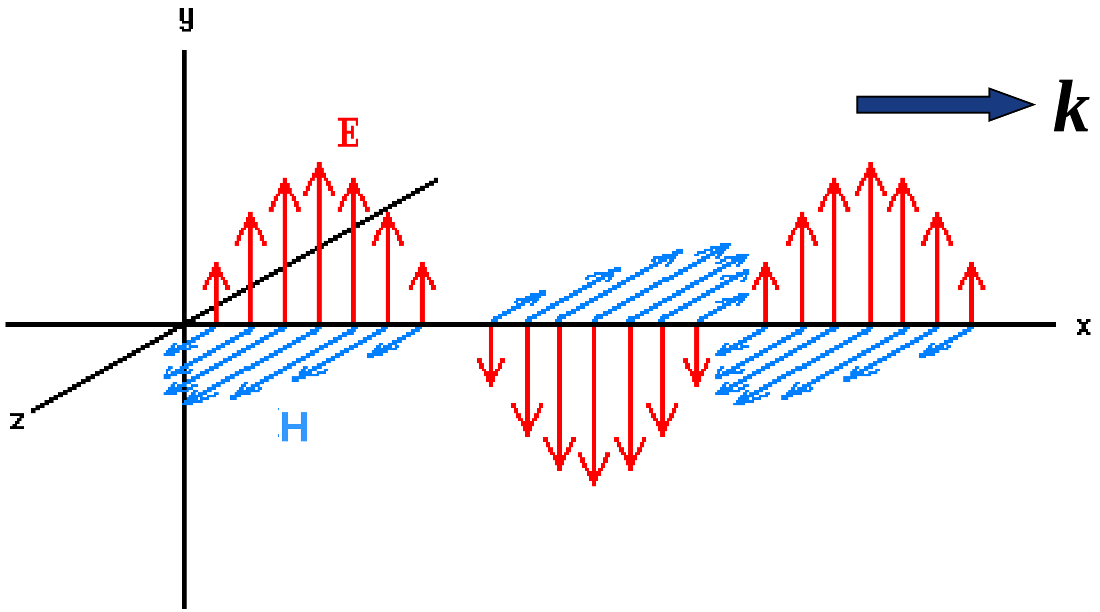
Maxwell's Equations

Symbol	Meaning	SI Unit of Measure
$\mathbf{E}$	electric field	Volt per meter
$\mathbf{H}$	magnetic field also called the auxiliary field	Ampere per meter
$\mathbf{D}$	electric displacement field also called the electric flux density	Coulomb per square meter
$\mathbf{B}$	magnetic flux density also called the magnetic induction also called the magnetic field	Tesla, or equivalently, Weber per square meter
ρ	*free* electric charge density, not including dipole charges bound in a material	Coulomb per cubic meter
$\mathbf{J}$	*free* current density, not including polarization or magnetization currents bound in a material	Ampere per square meter

Wave Optics – Free space plane wave

In vacuum, without charges (ρ=0) or currents (J=0)(无源空间)

- Maxwell's equations have a simple solution in terms of traveling sinusoidal plane waves.
- The electric and magnetic field directions are orthogonal to one another and the direction of travel *k*
- The **E**, **H** fields are in phase, traveling at the speed *c*



Wave Optics - Simple Materials

In linear materials, the **electric flux density D** and **magnetic flux density B** fields are related to **E** and **H** by:

$$D = \varepsilon E$$

$$B = \mu_0 H$$

where:

ε is the electrical permittivity of the material, and

$\boldsymbol{\mu_0}$ is the permeability of free space, μ_0=1 here.

Note: **FDTD Solutions does not allow for magnetic materials**

FDTD 简单概念介绍

- **FDTD算法：**K.S.Yee于1966年提出的，它直接对麦克斯韦方程作差分处理，来解决电磁脉冲在电磁介质中传播和反射、透射等问题的一种算法.

- **基本思想：****基于有限元的思路**，采用Yee元胞的方法计算域空间节点，同时电场和磁场节点空间与时间上都采用交错抽样；因而使得麦克斯韦旋度方程离散后构成显式差分方程，与前面的波动方程求解相比较，计算得到大大简化。

具体实现方法：

FDTD算法直接将有限差分式代替麦克斯韦时域场旋度方程中的微分式，得到关于场分量的有限差分式，用具有相同电参量的空间网格去模拟被研究体，选取合适的场初始值和计算空间的边界条件，得到包括时间变量的麦克斯韦方程的四维数值解，通过傅里叶变换可求得三维空间的频域解。

FDTD基本原理

Maxwell方程组

矢量方程：

$$\begin{cases} \dfrac{\partial \vec{H}}{\partial t} = -\dfrac{1}{\mu}\left[\nabla \times \vec{E} + s\vec{H}\right] \\ \dfrac{\partial \vec{E}}{\partial t} = \dfrac{1}{\varepsilon}\left[\nabla \times \vec{H} - \sigma\vec{E}\right] \end{cases}$$

即

$$\begin{cases} \nabla \times \vec{H} = \dfrac{\partial \vec{D}}{\partial t} + \sigma\vec{E} \\ \nabla \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t} - s\vec{H} \end{cases}$$

6个标量方程：

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} - sH_x\right)$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} - sH_y\right)$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} - sH_z\right)$$

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - \sigma E_x\right)$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - \sigma E_y\right)$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \sigma E_z\right)$$

Maxwell旋度方程可以推出此六个耦合方程

FDTD 简单概念介绍

FDTD 基本方程

$$\frac{H_{z(t;x,y+\Delta y,z)}-H_{z(t;x,y-\Delta y,z)}}{2\Delta y}-\frac{H_{y(t;x,y,z+\Delta z)}-H_{y(t;x,y,z-\Delta z)}}{2\Delta z}=\tilde{\varepsilon}(x,y,z)\frac{E_{x(t+\Delta t;x,y,z)}-E_{x(t-\Delta t;x,y,z)}}{\Delta t}$$

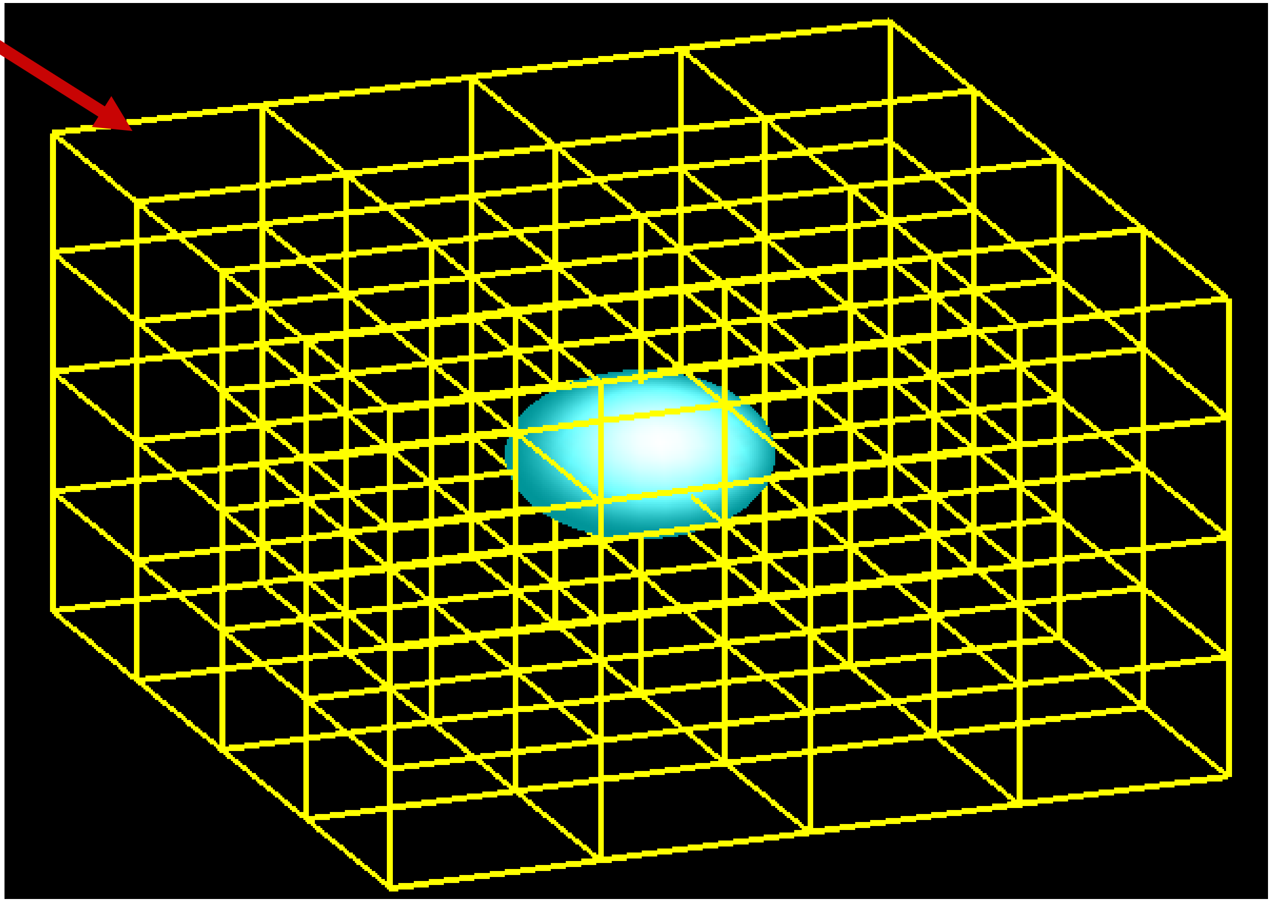
$$\frac{H_{y(t;x+\Delta x,y,z)}-H_{y(t;x-\Delta x,y,z)}}{2\Delta x}-\frac{H_{x(t;x,y+\Delta y,z)}-H_{x(t;x,y-\Delta y,z)}}{2\Delta y}=\tilde{\varepsilon}(x,y,z)\frac{E_{z(t\_\Delta t;x,y,z)}-E_{z(t-\Delta t;x,y,z)}}{\Delta t}$$

$$\frac{H_{x(t;x,y,z+\Delta z)}-H_{x(t;x,y,z-\Delta z)}}{2\Delta z}-\frac{H_{z((t;x+\Delta x,y,z)}-H_{z(t;x-\Delta x,y,z)}}{2\Delta x}=\tilde{\varepsilon}(x,y,z)\frac{E_{y(t+\Delta t;x,y,z)}-E_{y(t-\Delta t;x,y,z)}}{\Delta t}$$

Maxwell Equations on a mesh

Yee cell

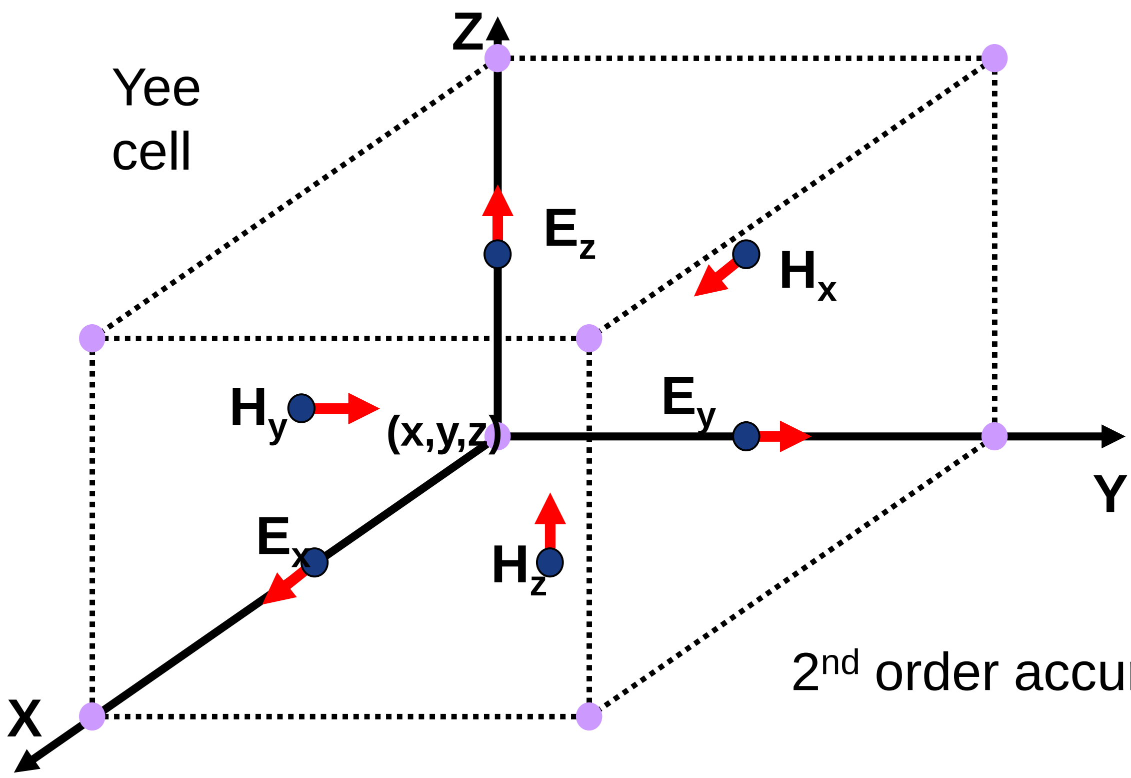
⇨ **E** and **H** are discrete in space



Originating from FEM

The Yee cell

Spatially stagger the vector components of the E-field and H-field about rectangular unit cells of a Cartesian computational grid.



2nd order accurate in space

Kane Yee (1966). "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media". *Antennas and Propagation, IEEE Transactions on* **14**: 302–307.

FDTD—Finite-Difference Time-Domain method

FDTD直接求解麦克斯韦方程: 全矢量法

$$\frac{\partial B}{\partial t} = -\nabla \times E \quad \frac{\partial D}{\partial t} = \nabla \times H \quad \nabla \bullet D = \rho \quad \nabla \bullet B = 0 \quad D = \varepsilon E \quad B = \mu H$$

首先**E 和 H** 在时域离散化

$$E(t) \rightarrow E^{n\Delta t} \quad H(t) \rightarrow H^{(n+1/2)\Delta t}$$

FDTD 最基本的时间步进关系：

$$E^{n+1} = E^{n} + \alpha \nabla \times H^{n+1/2}$$

$$H^{n+3/2} = H^{n+1/2} + \beta \nabla \times E^{n+1}$$

蛙跳式—数据直接迭代，不需要求解矩阵。

$$E^{0} \rightarrow H^{1/2} \rightarrow E^{1} \rightarrow H^{3/2} \rightarrow \cdots$$

时间上是二次方精度： ~ Δt^2

How the FDTD method works?

为确保算法在较长时间步长上运行的稳定性，时间增量**Δt**应满足下列关系式：

$$\Delta t = \frac{min.(\Delta x_{min.}, \Delta y_{min.}, \Delta z_{min.})}{2c}$$

即：当沿三个轴向的网格元是可变时，则应取每个轴向上的最小值，再选三者之中最小者。

FDTD Solution中有“Auto shutoff”功能来保证。

FDTD Solutions: unique features

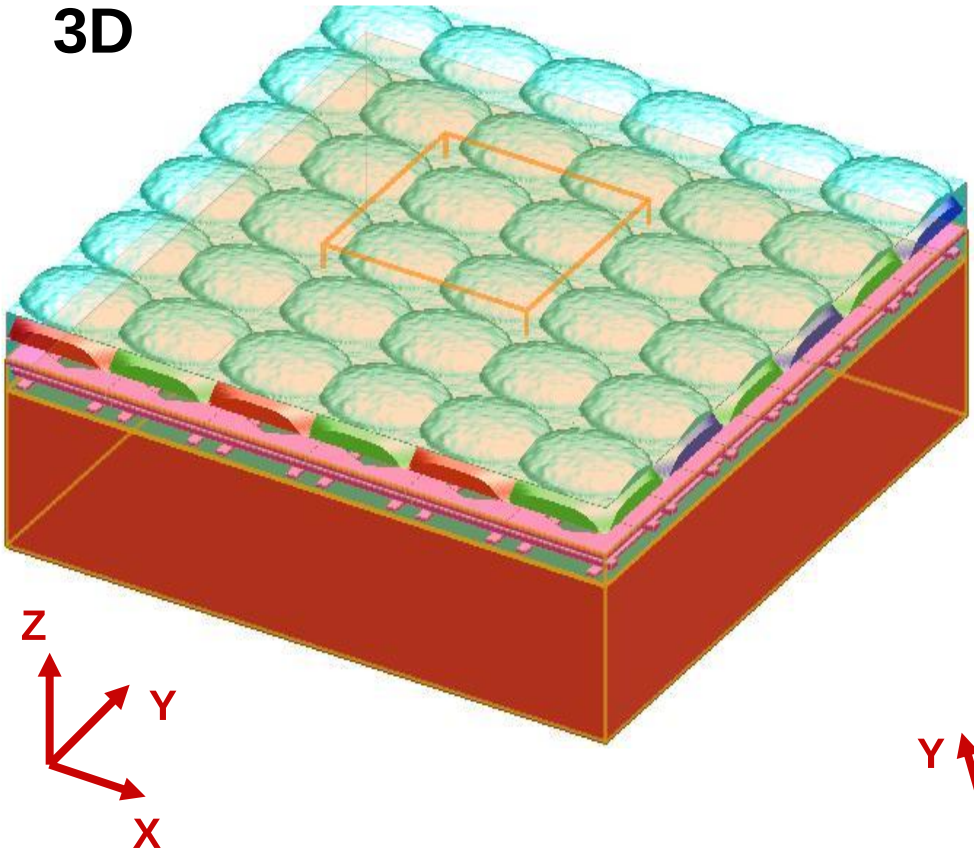
- *Fastest* 高速、精确、宽谱、多功能、自动材料建模，易学易用
  - ：Parallelism/very short pulse/*automatic grading mesh*/BCs/(real E,H)
- Accurate
  - ：Full-vectorial accuracy (staircasing: average & 1/0?)
- Multi-wavelength analysis & Broadband
  - ：Accurate *broadband modeling* of dispersive materials and devices
- Geometric objects
  - ：Representation of idealized and *manufactured* devices (surface roughness, from images of the fabricated structures, AFM, GDSII)
- *Multimedia* and other monitors (*Much smaller* resulting *file size* !)
- User-friendly interface, better data input/output
- Ability run and analyze many simulations
  - Parameter sweeps
  - Optimization
  - Yield calculations

- *Various excitation sources*
  - *Focused light beams*
- Coherent, *Incoherent*
- Polarized, *unpolaried*

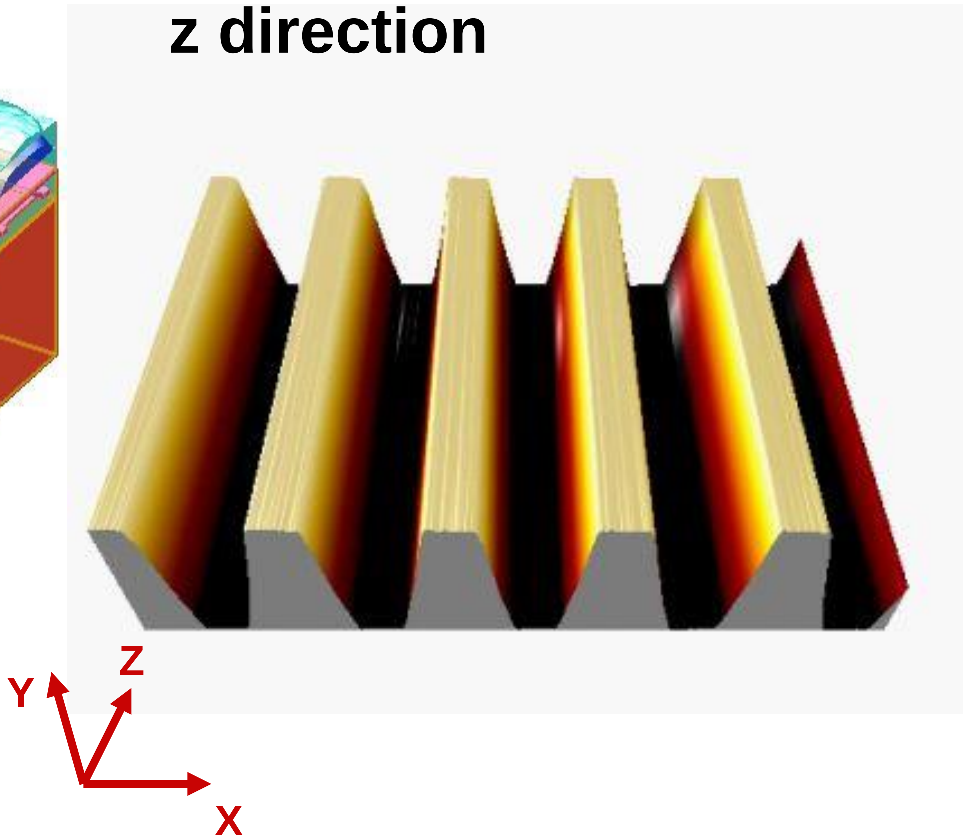
2D vs. 3D

- **FDTD simulations can be run in 2D or 3D**

3D



2D: Structure is infinite in z direction



Computational Resource Requirements

How can I estimate the computational resources needed for a given simulation?

Items	**3D**	**2D**
Memory Requirements	$\sim V \cdot (\lambda/dx)^3$	$\sim A \cdot (\lambda/dx)^2$
Simulation Time	$\sim V \cdot (\lambda/dx)^4$	$\sim A \cdot (\lambda/dx)^3$
Example	(8λx8λx8λ) box : 50 MB : ~30 seconds	(100λx100λ) area : 25 MB : ~30 seconds

***Procedures Using FDTD Solutions*: four steps**

- **Define the physical structures**
  - : This will be used to create **ε** (permittivity) for each cell within the computational domain.
  - : Typically, the material is either **free-space** (air), **dielectric** (glass, polymer,…) or **dispersive** (metal, semi-conductor,…)
- **Define a simulation region**
  - : This is the physical region over which the simulation will be performed.
- **Define a source of light**
  - : A light beam or a dipole source
- **Define monitors to record data**

FDTD is a time domain technique!

- The simulation is running to solve Maxwell's equations in time to obtain **E**(t) and **H**(t).
- Most users want to know the field as a function of wavelength, **E**(λ), or equivalently frequency, **E**(ω).
- The steady state, continuous wave (CW) field **E**(ω) is calculated from **E**(t) by Fourier transform during the simulation.

$$\vec{E}(\omega) = \int_0^{T_{Sim}} e^{i\omega t} \vec{E}(t)\,dt$$

See section on Units and Normalization of Reference Manual for more details:
http://www.lumerical.com/fdtd_online_help/ref_fdtd_units_units_and_normalization.php

Advantages of the FDTD method

Advantages

- Few inherent approximations = **accurate**
- A very **general technique** that can deal with many types of problems.
- Arbitrarily complex geometries
- One simulation gives broadband results.

由于整个计算过程中极少采用近似处理，所以计算精度高。

New version improvements

FDTD Solution7.0:

1. Parameter sweeps
2. Optimization
3. Object library
4. Mac OS X support
5. Windows 7.0 support
6. Conformal mesh
7. Simplified installation and licensing
8. More flexible PML configuration options
9. Improved GDSII import
10. Analytic material model
11. Other new script commands

FDTD Solution7.5:

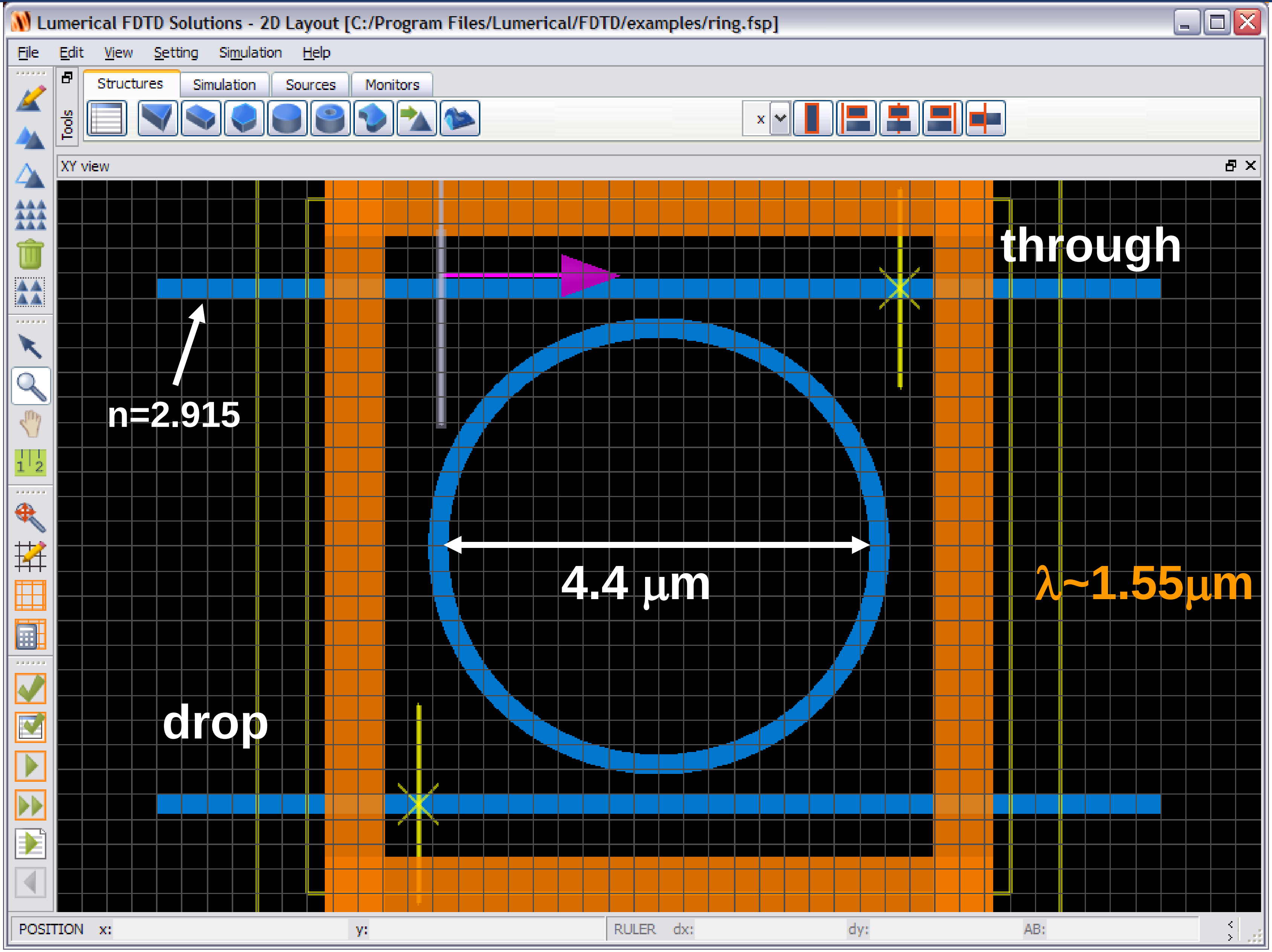
1. Ability to distribute optimizations and parameter sweeps
2. Movie monitors in parallel simulations
3. New script commands

New version improvements

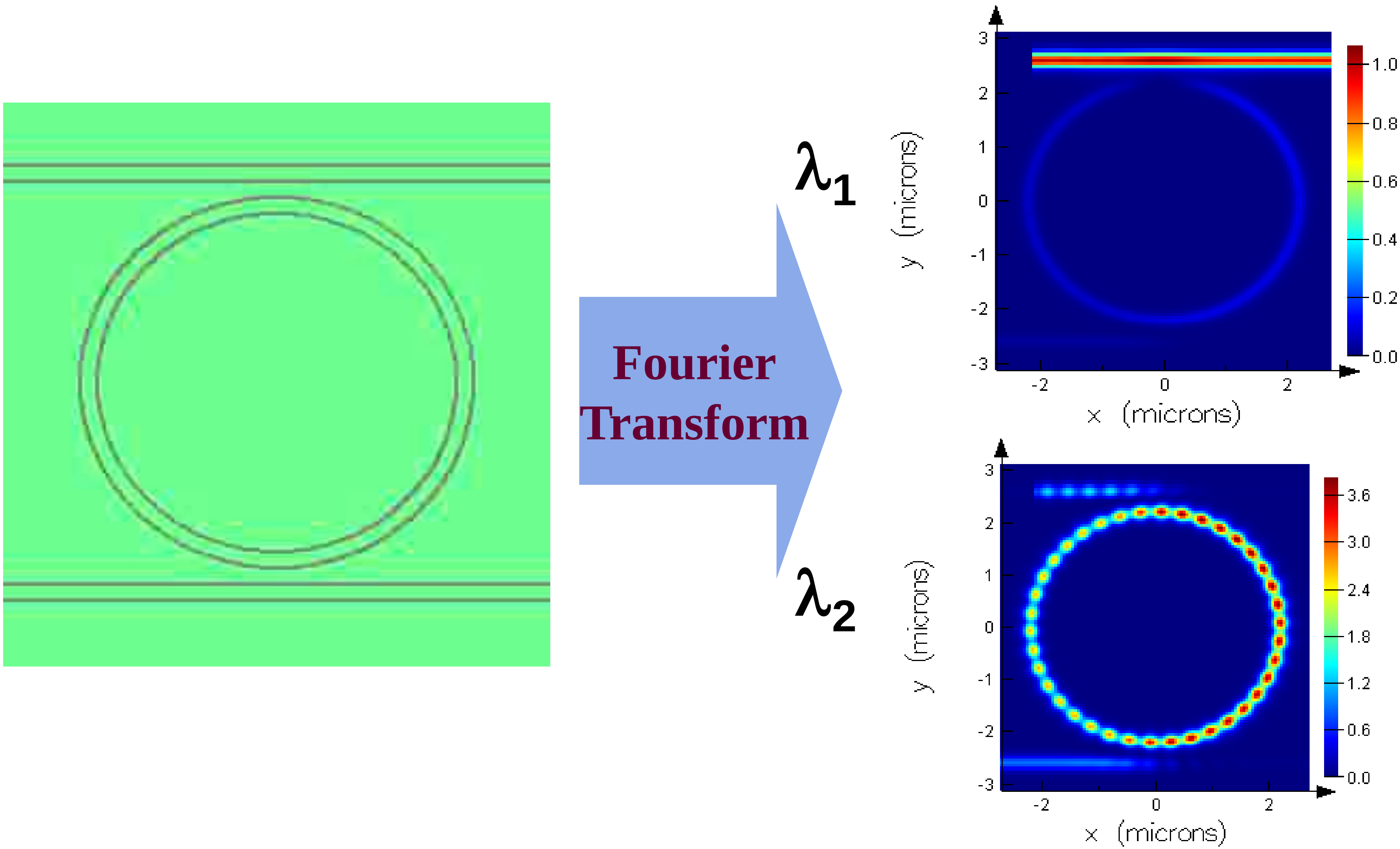
FDTD Solution 8.0:

1. User-defined dispersive, gain, anisotropic & nonlinear materials.
2. Built-in $\chi(2)$ and paramagnetic materials
3. Non-diagonal anisotropic materials including liquid crystals and magneto-optical materials.
4. Improved analysis and visualization tools with the Results Manager and Visualizer
5. Modal expansion monitors with arbitrary rotation.
6. Mode sources with arbitrary rotation

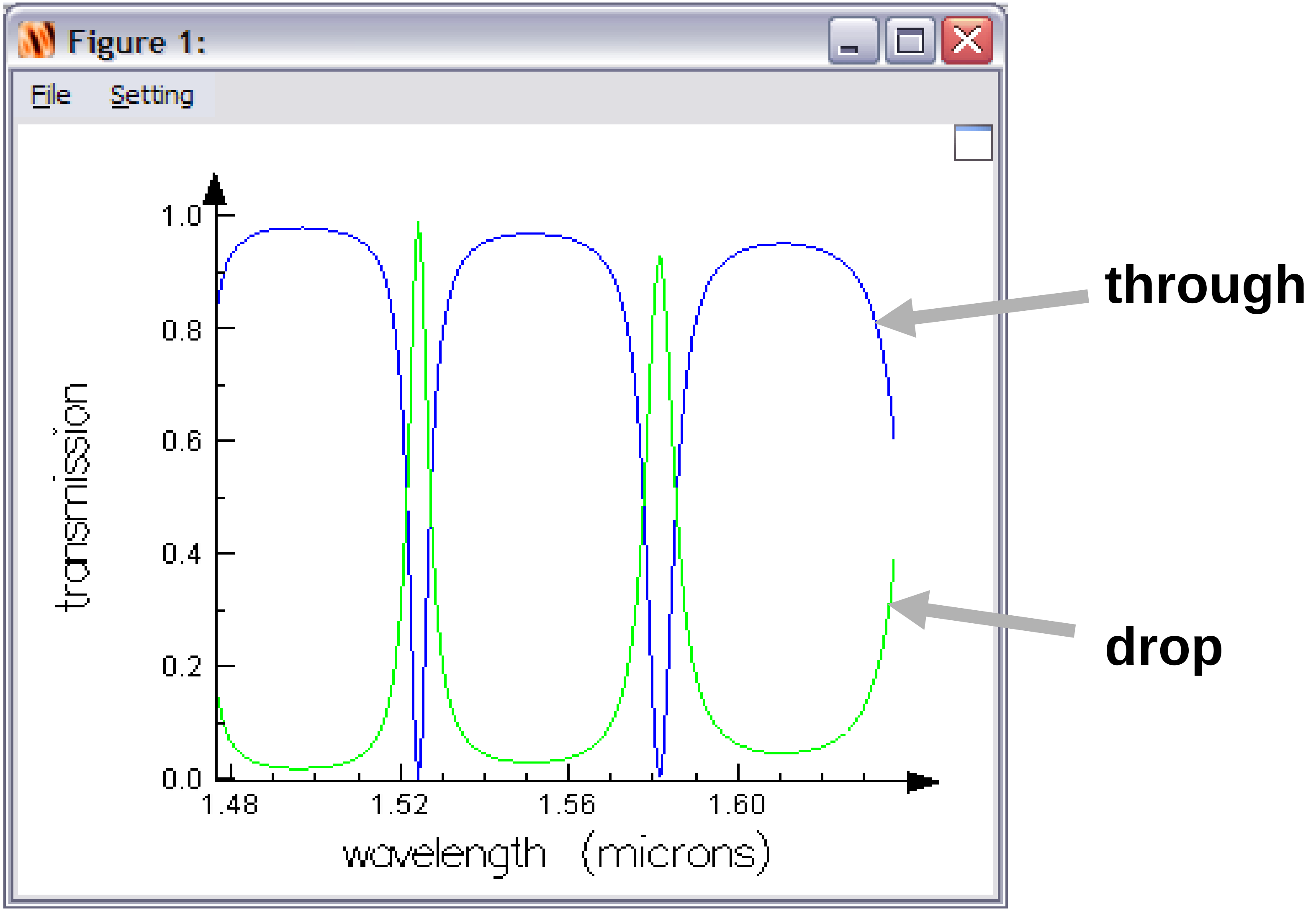
Example, ring resonator



Example: waveguide ring resonator



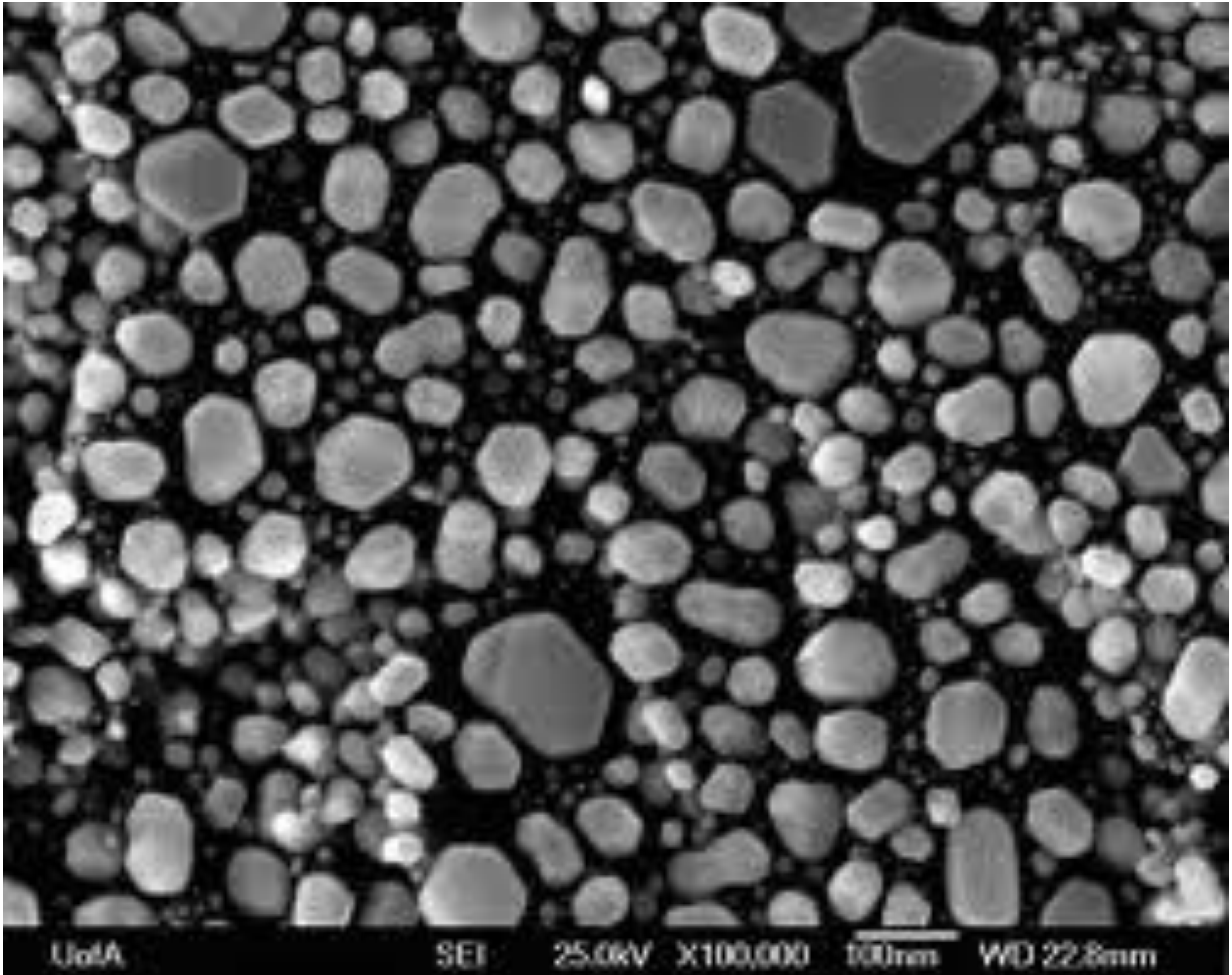
Example: waveguide ring resonator



Install FDTD Solutions

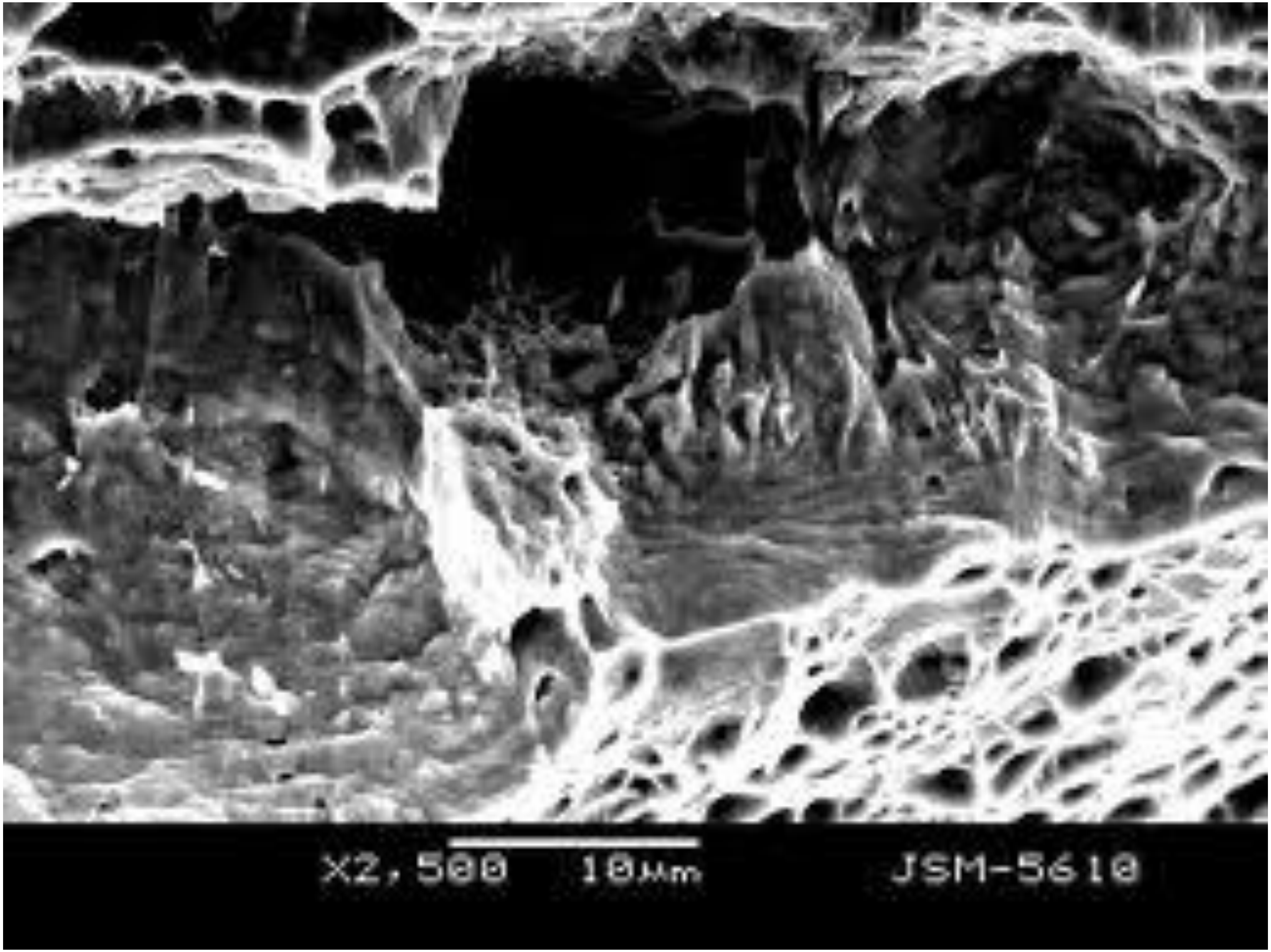
- We will now take a quick break and install FDTD Solutions on your computers.
- A portable license will be used.
- You will need a product CD and Hardware Key.

Function of import image



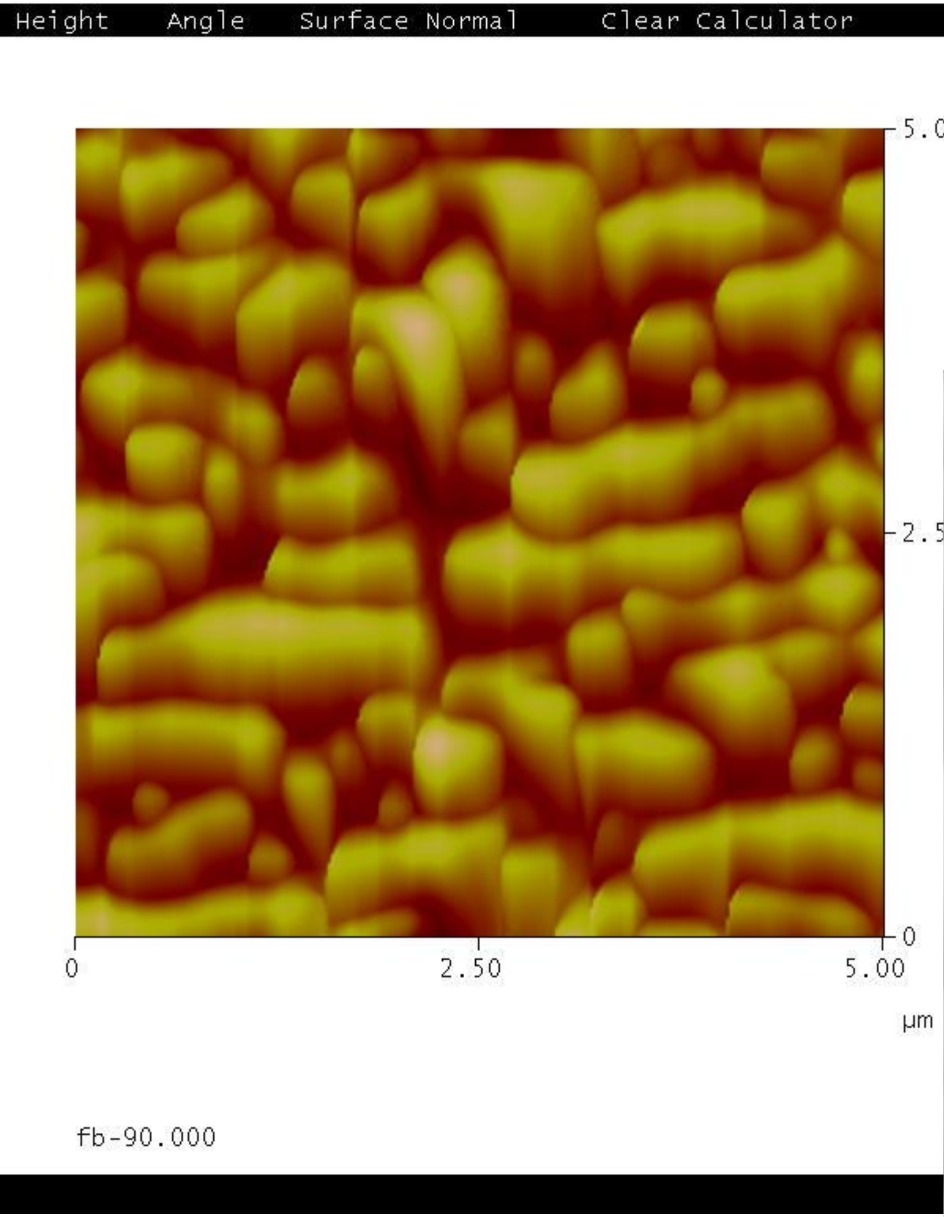
Top view SEM image

Function of import image

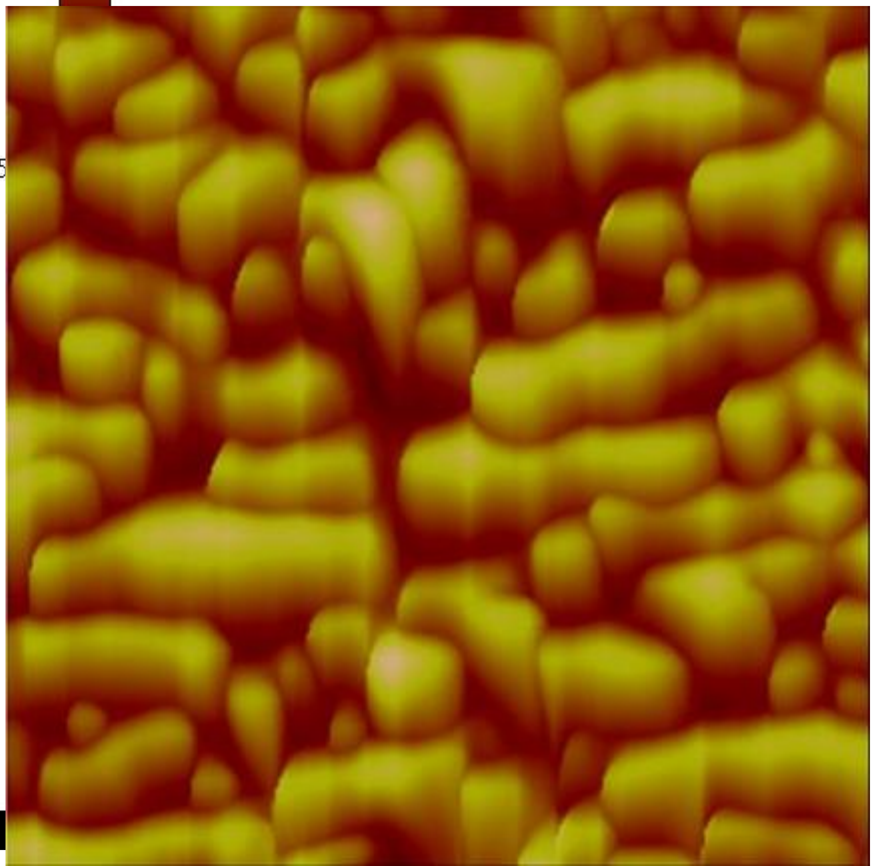


Side view SEM image

Function of import image



AFM image



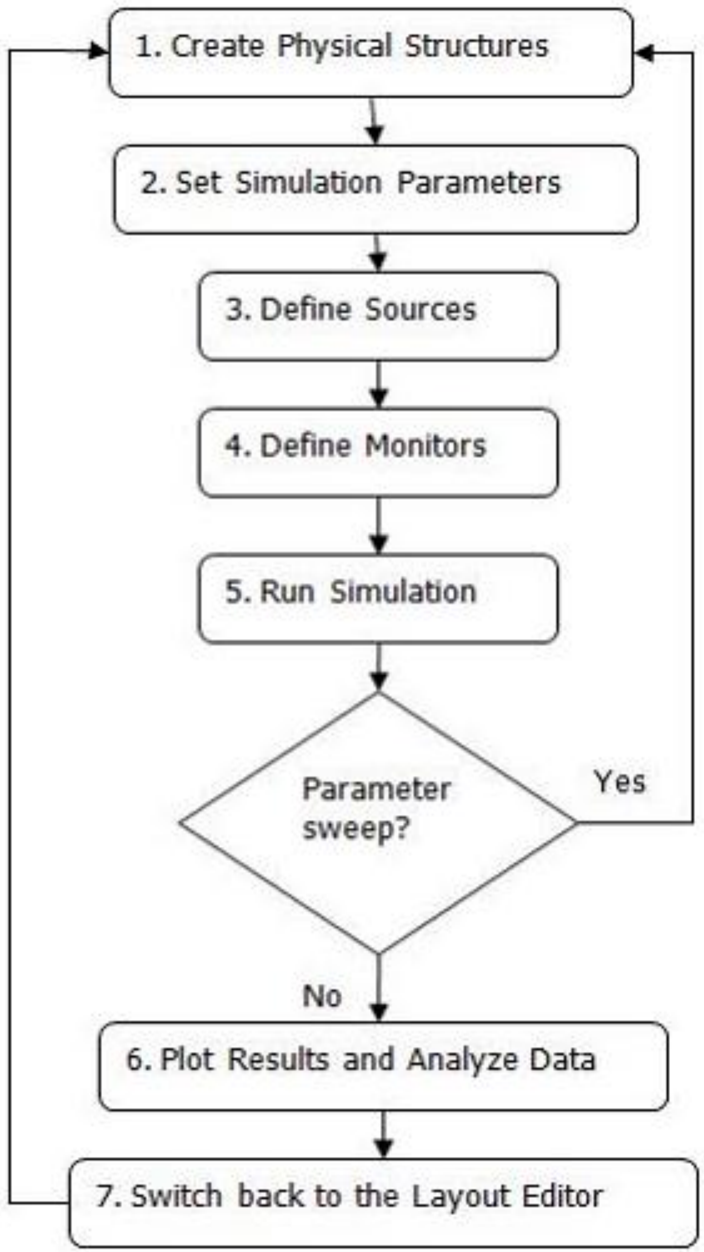
FDTD Solution onsite demonstration

FDTD *Solutions* **7.5**

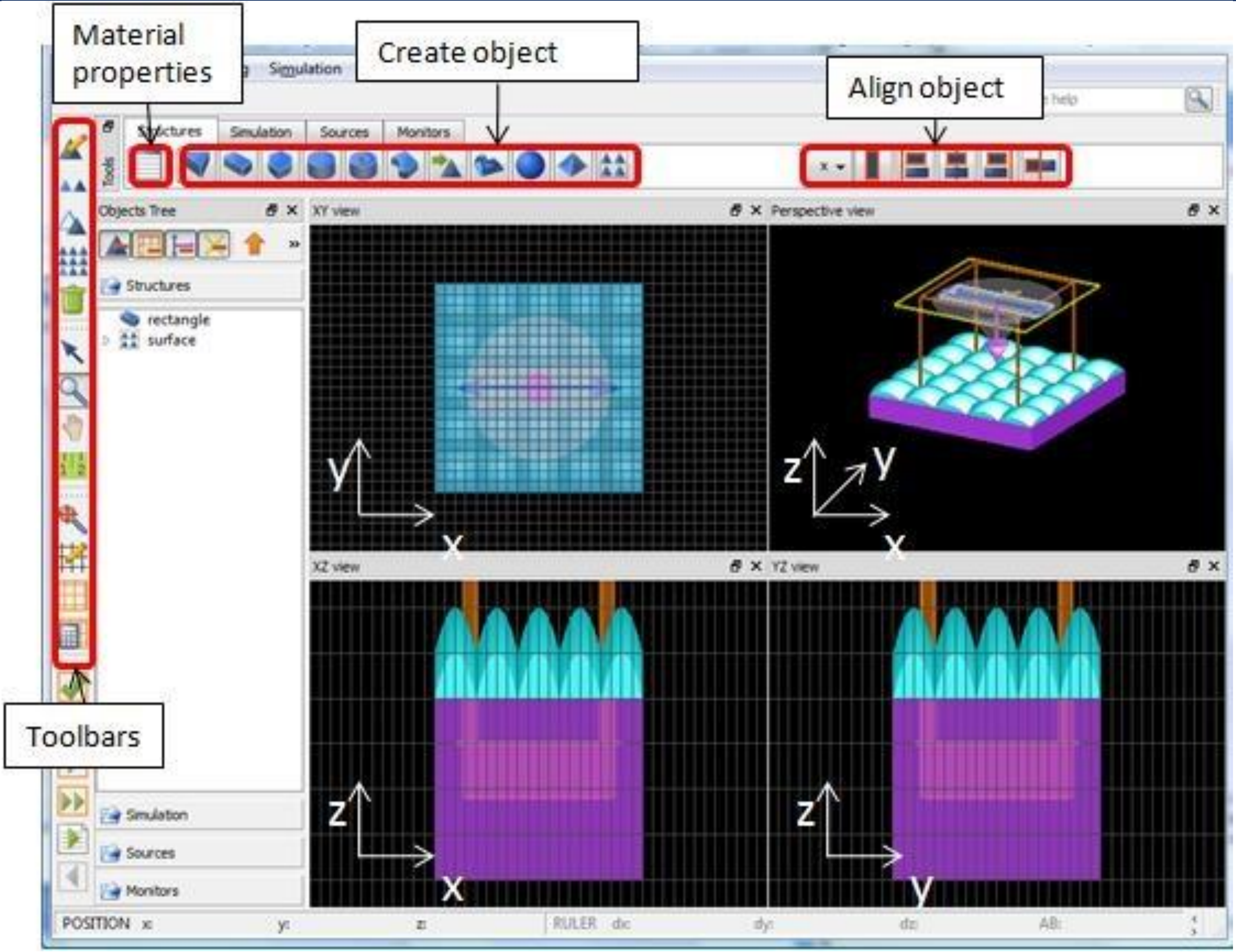
Tea Break

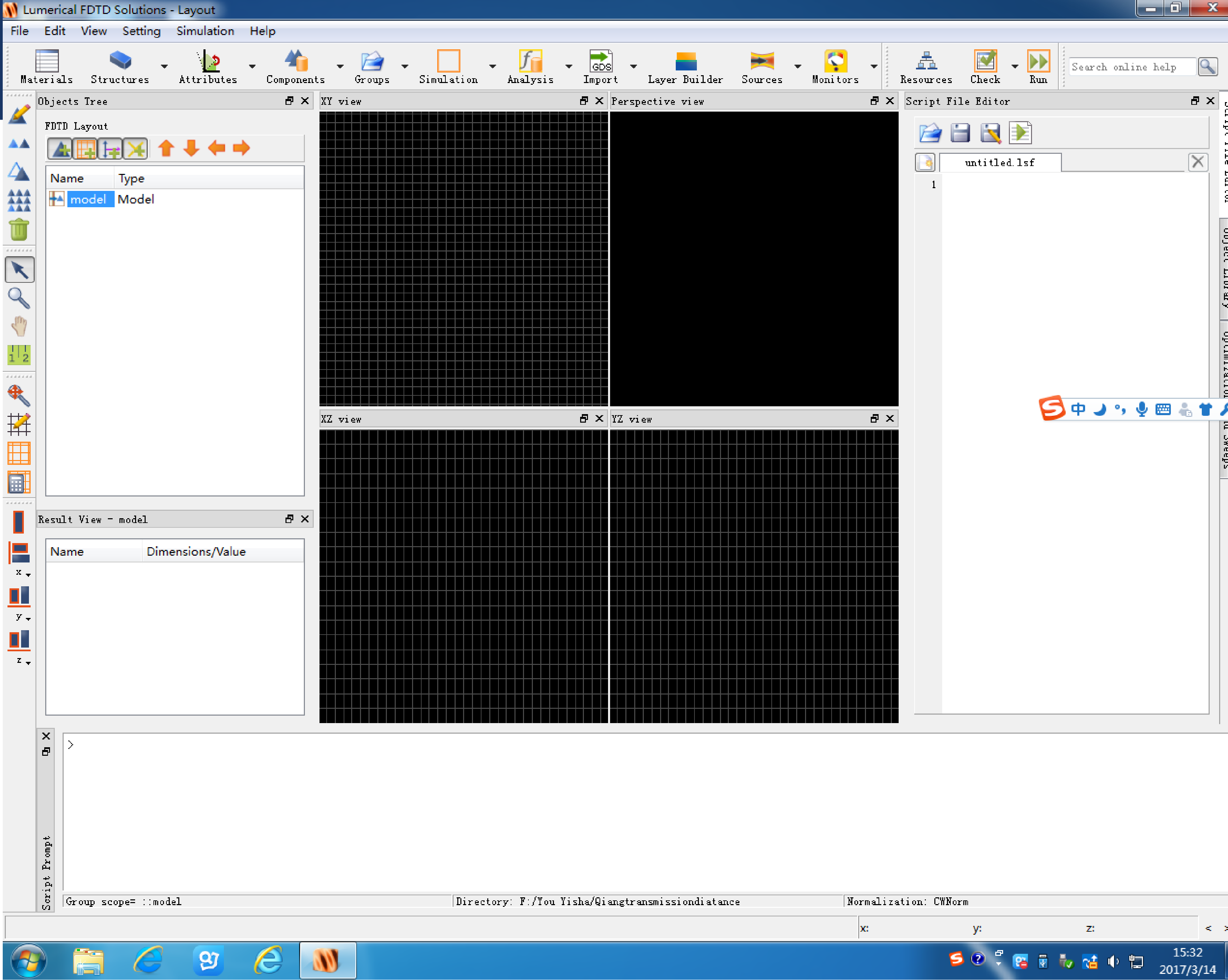
FDTD Solutions Features and Workflow

- Starting FDTD Solutions
- Basic program layout
- **Structures**
- **Simulation region**
- **Sources**
- **Monitors**
- **Analysis**
- Script commands

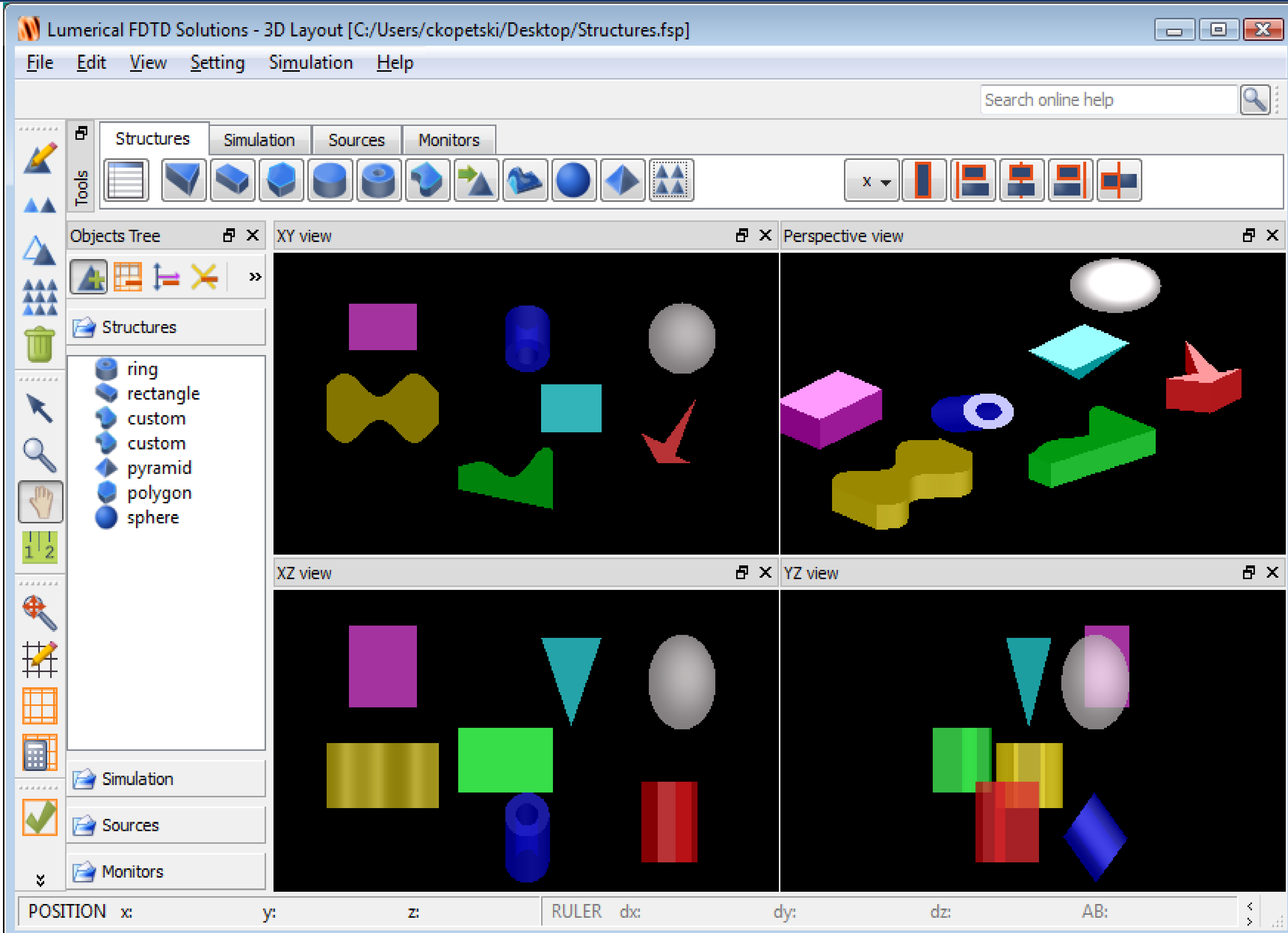


Features – General layout

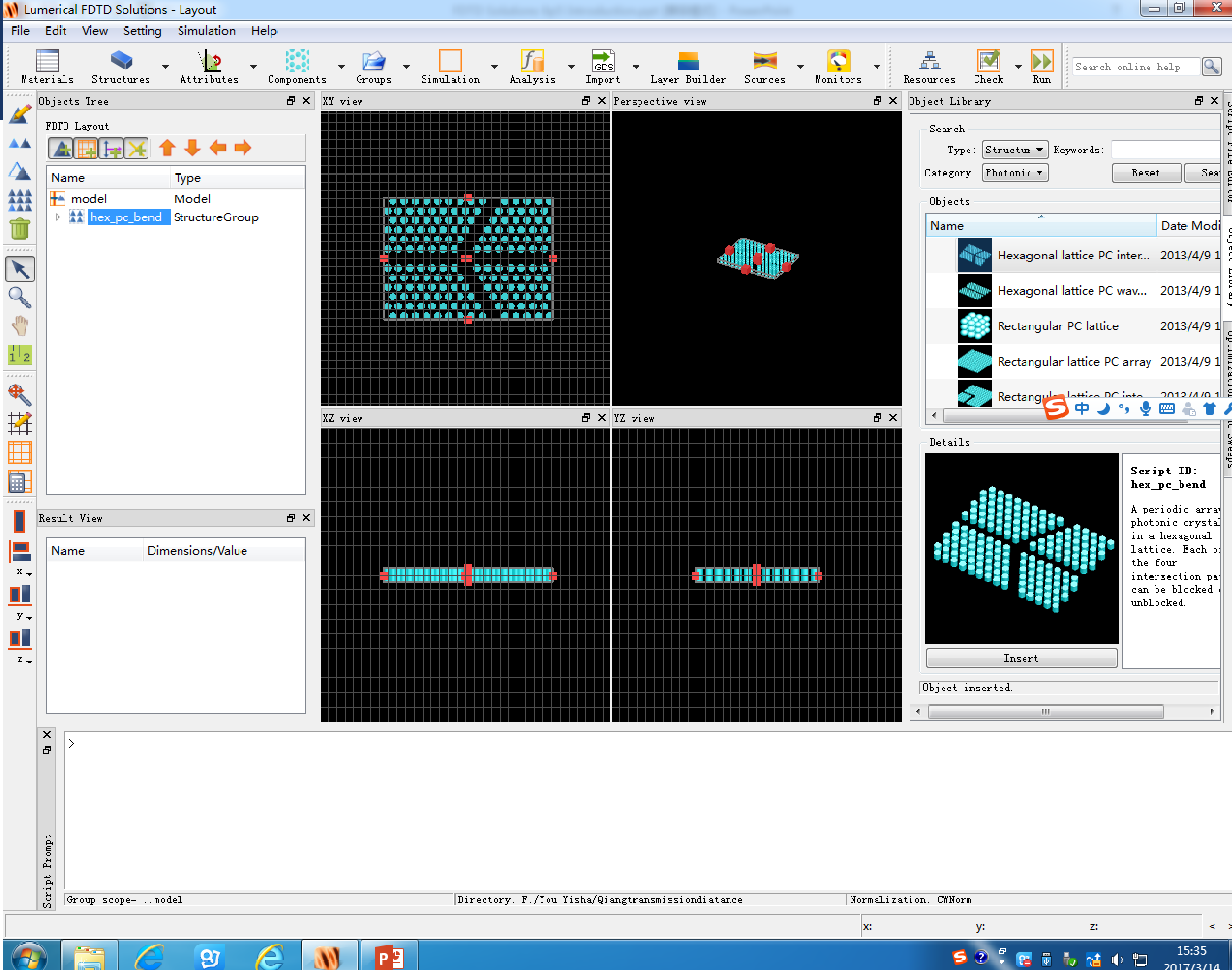



Lumerical FDTD Solutions - Layout
File Edit View Setting Simulation Help
Materials
Structures
Attributes
Components
Groups
Simulation
Analysis
Import
Layer Builder
Sources
Monitors
Resources
Check
Run
Search online help
Objects Tree
FDTD Layout
Name Type
model Model
XY view
Perspective view
XZ view
YZ view
Script File Editor
untitled.lsf
Object Library
Optimization and Sweeps
Result View - model
Name Dimensions/Value
Script Prompt
Group scope= ::model
Directory: F:/You Yisha/Qiangtransmissiondiatance
Normalization: CWNorm
15:32
2017/3/14

Structures

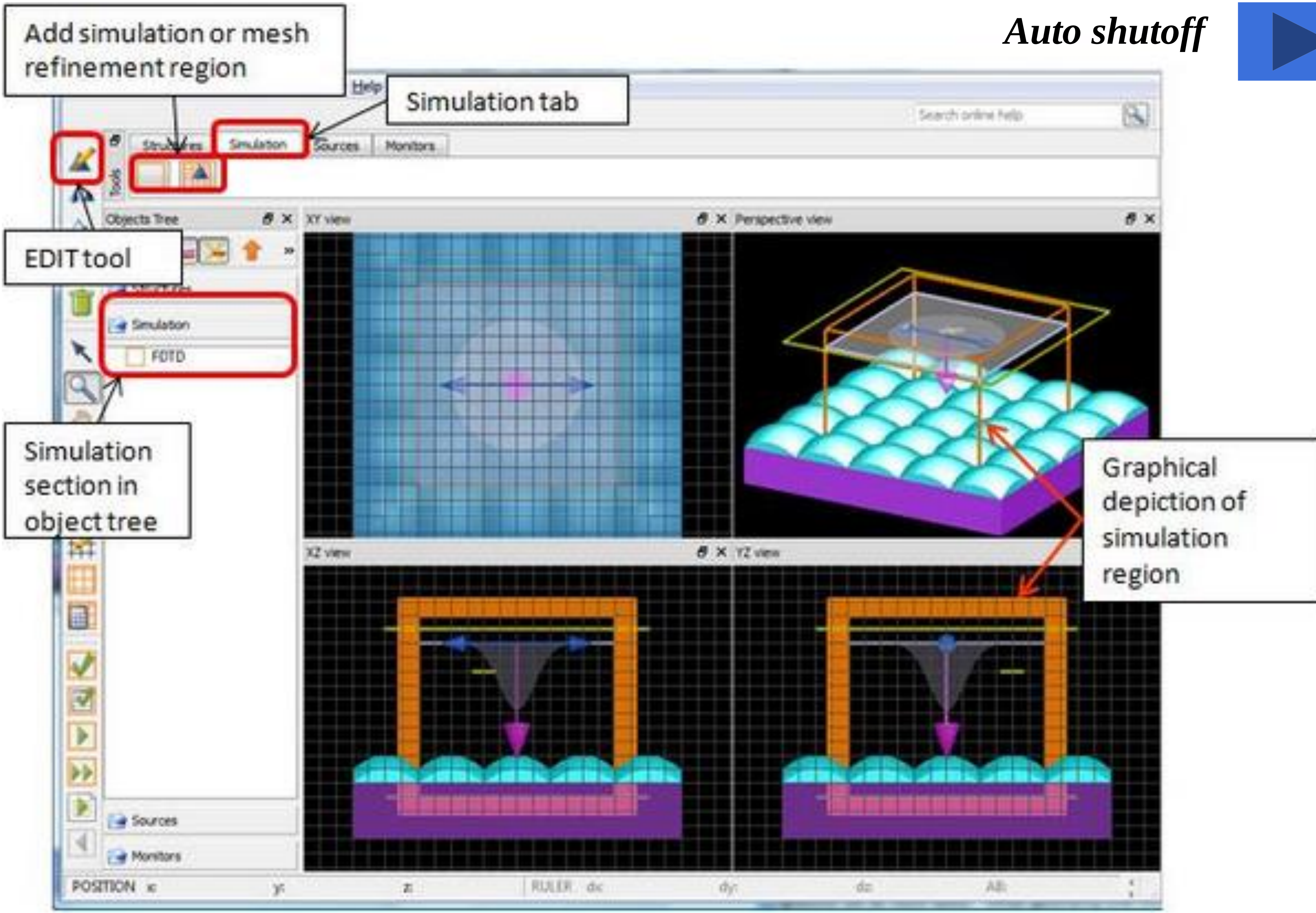


Lumerical FDTD Solutions - 3D Layout [C:/Users/ckopetski/Desktop/Structures.fsp]
File
Edit
View
Setting
Simulation
Help
Search online help
Tools
Structures
Simulation
Sources
Monitors
Objects Tree
Structures
ring
rectangle
custom
custom
pyramid
polygon
sphere
Simulation
Sources
Monitors
XY view
Perspective view
XZ view
YZ view
POSITION x:
y:
z:
RULER dx:
dy:
dz:
AB:


Lumerical FDTD Solutions - Layout
File Edit View Setting Simulation Help
Materials Structures Attributes Components Groups Simulation Analysis Import Layer Builder Sources Monitors Resources Check Run
Objects Tree
FDTD Layout
Name Type
model Model
hex_pc_bend StructureGroup
XY view
Perspective view
XZ view
YZ view
Object Library
Search
Type: Structu Keywords:
Category: Photonic Reset
Objects
Name Date Modi
Hexagonal lattice PC inter... 2013/4/9
Hexagonal lattice PC wav... 2013/4/9
Rectangular PC lattice 2013/4/9
Rectangular lattice PC array 2013/4/9
Details
Script ID: hex_pc_bend
A periodic array photonic crystal in a hexagonal lattice. Each of the four intersection pa can be blocked unblocked.
Insert
Object inserted.
Result View
Name Dimensions/Value
Script Prompt
Group scope= ::model
Directory: F:/You Yisha/Qiangtransmissiondiatance
Normalization: CWNorm
15:35
2017/3/14

Simulation

Auto shutoff



Boundary conditions

PEC (Perfect Electrical Conductor) : 电场分量在垂直于边界处连续，而平行于边界处为零；而磁场则与之相反。

PML (Perfect Matching Condition) : 消除在数值仿真过程中散射场对计算结果的影响。此时，介质中的电导率和磁导率满足下式：

$$\frac{\sigma}{\varepsilon_0} = \frac{\sigma^*}{\mu_0}$$

Periodic boundary condition

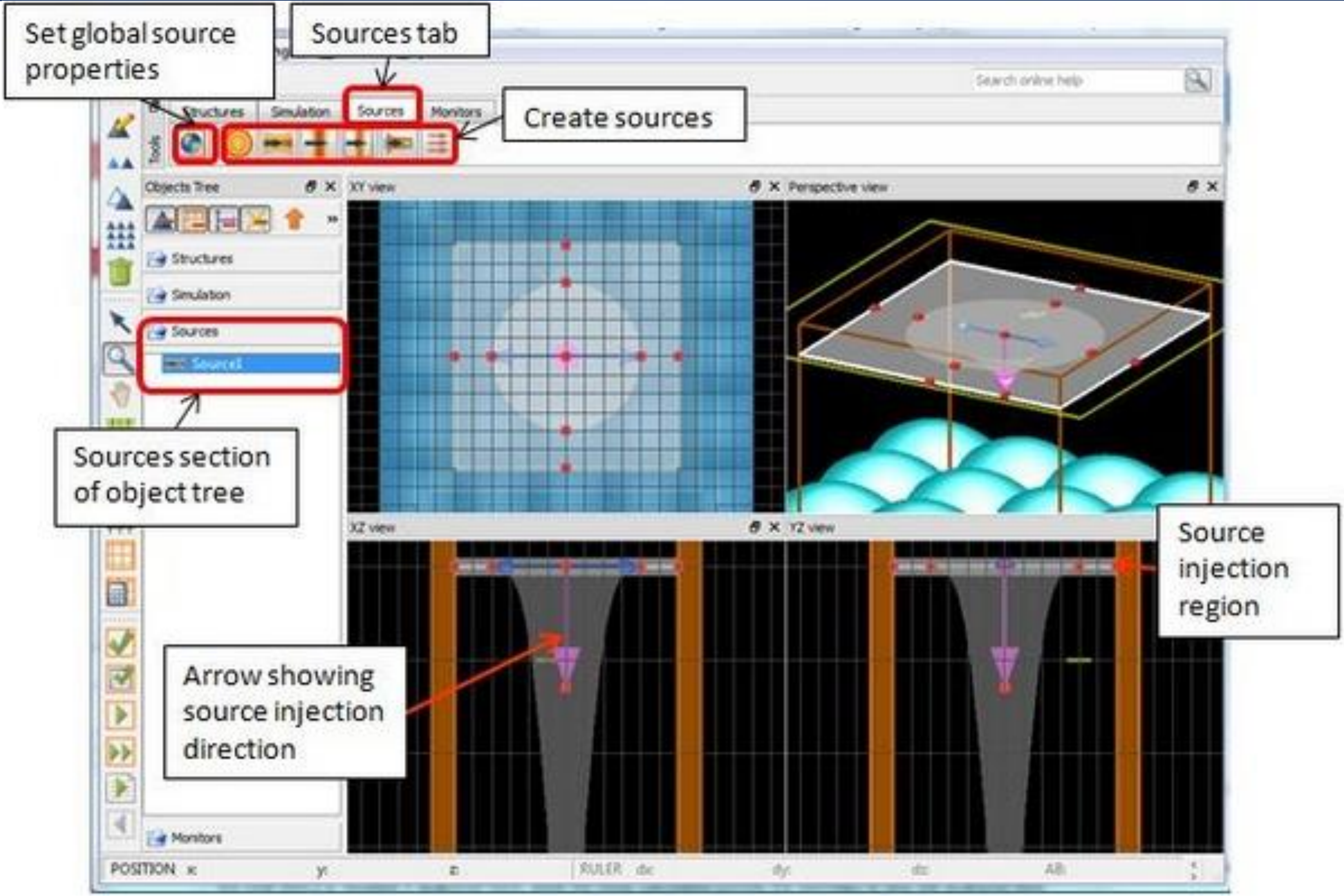
Symmetric

Anti-symmetric

Bloch Boundary： 平面波斜入射到周期结构中。

Metal boundary： 用于诊断仿真运算发散的原因。

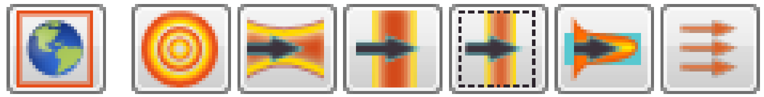
Sources


Set global source properties
Sources tab
Create sources
Sources section of object tree
Source injection region
Arrow showing source injection direction

Sources

FDTD Solutions has a variety of sources available:

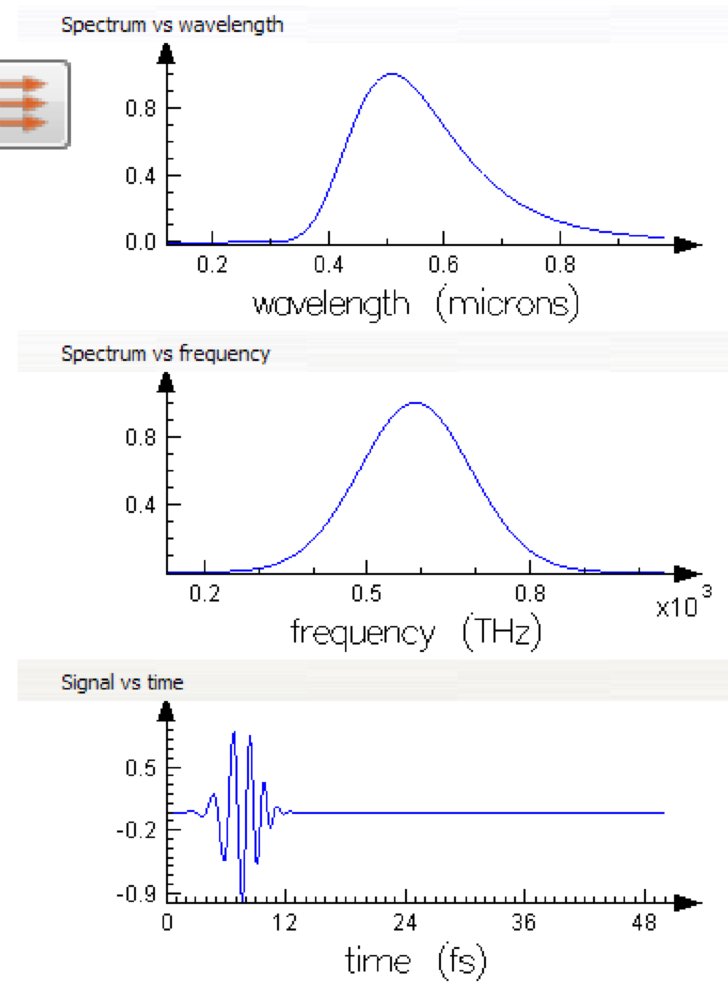
Basic Sources



- Dipole
- Gaussian beam
- Plane wave
- Mode

Advanced sources

- Total field/scattered field
- Large NA source
- ASAP (with aberration)
- User-defined
- Circular/elliptical,radial polarization



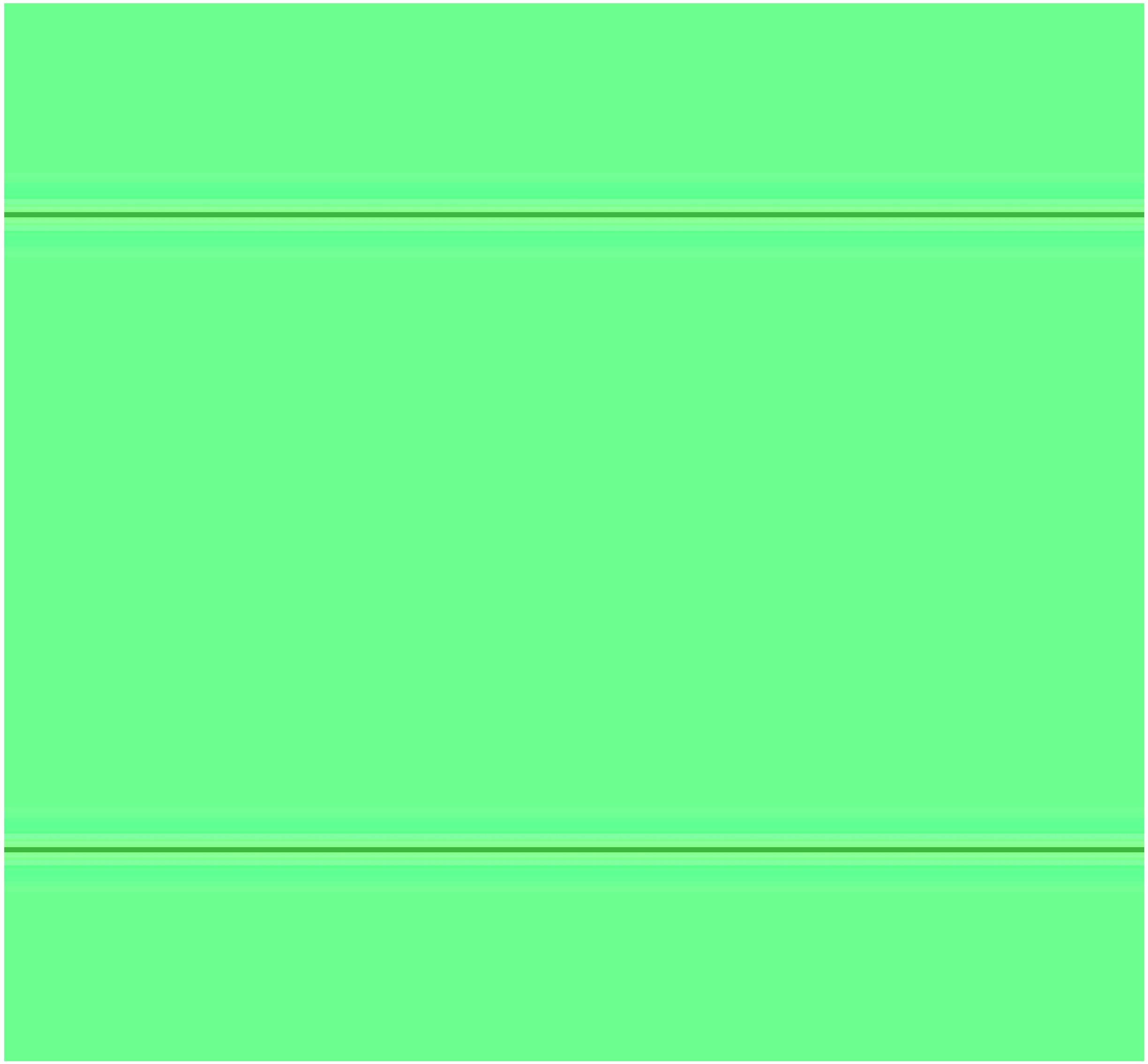
Dipole

TM

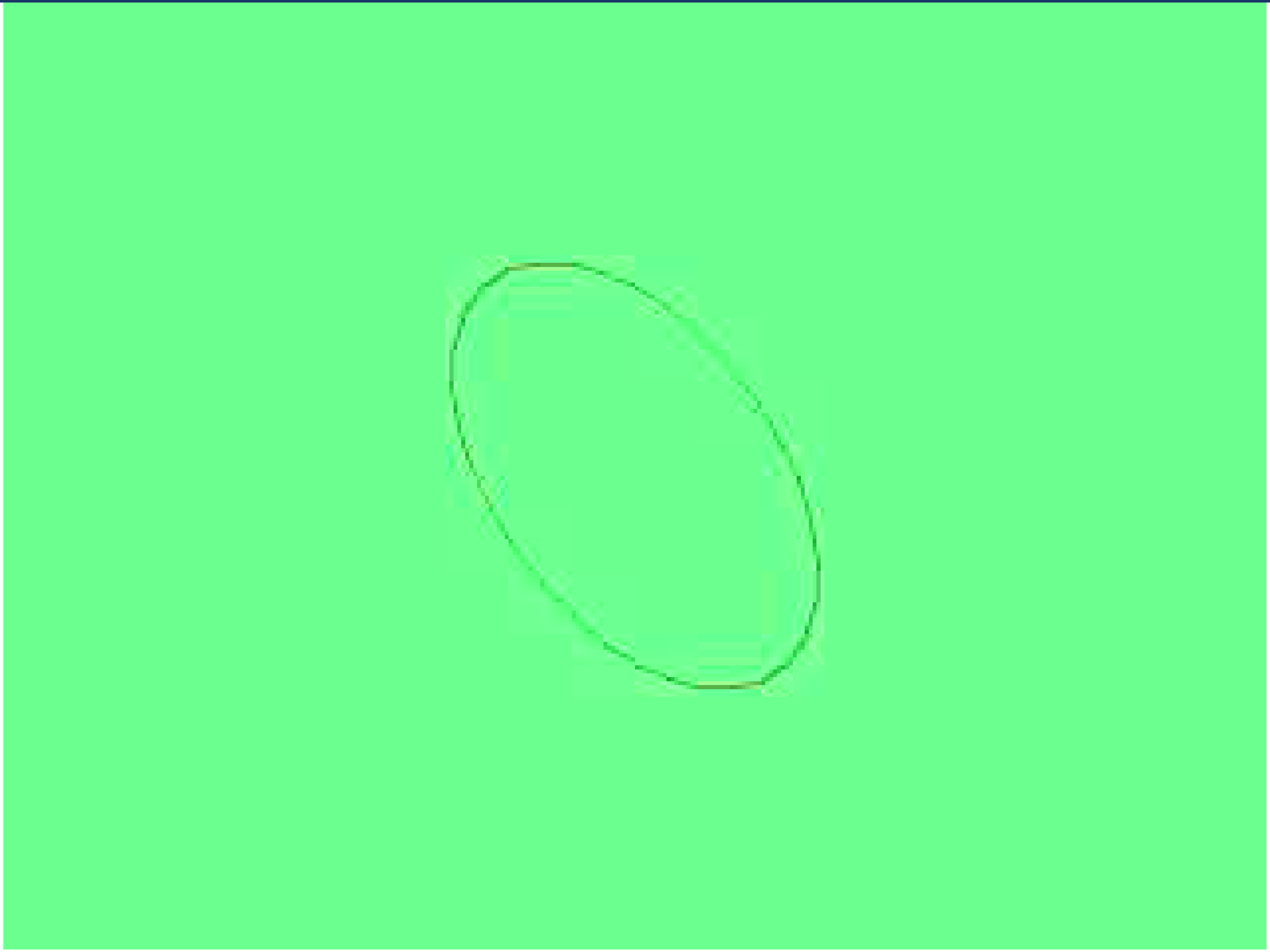
TE

Gaussian and plane wave

Mode source

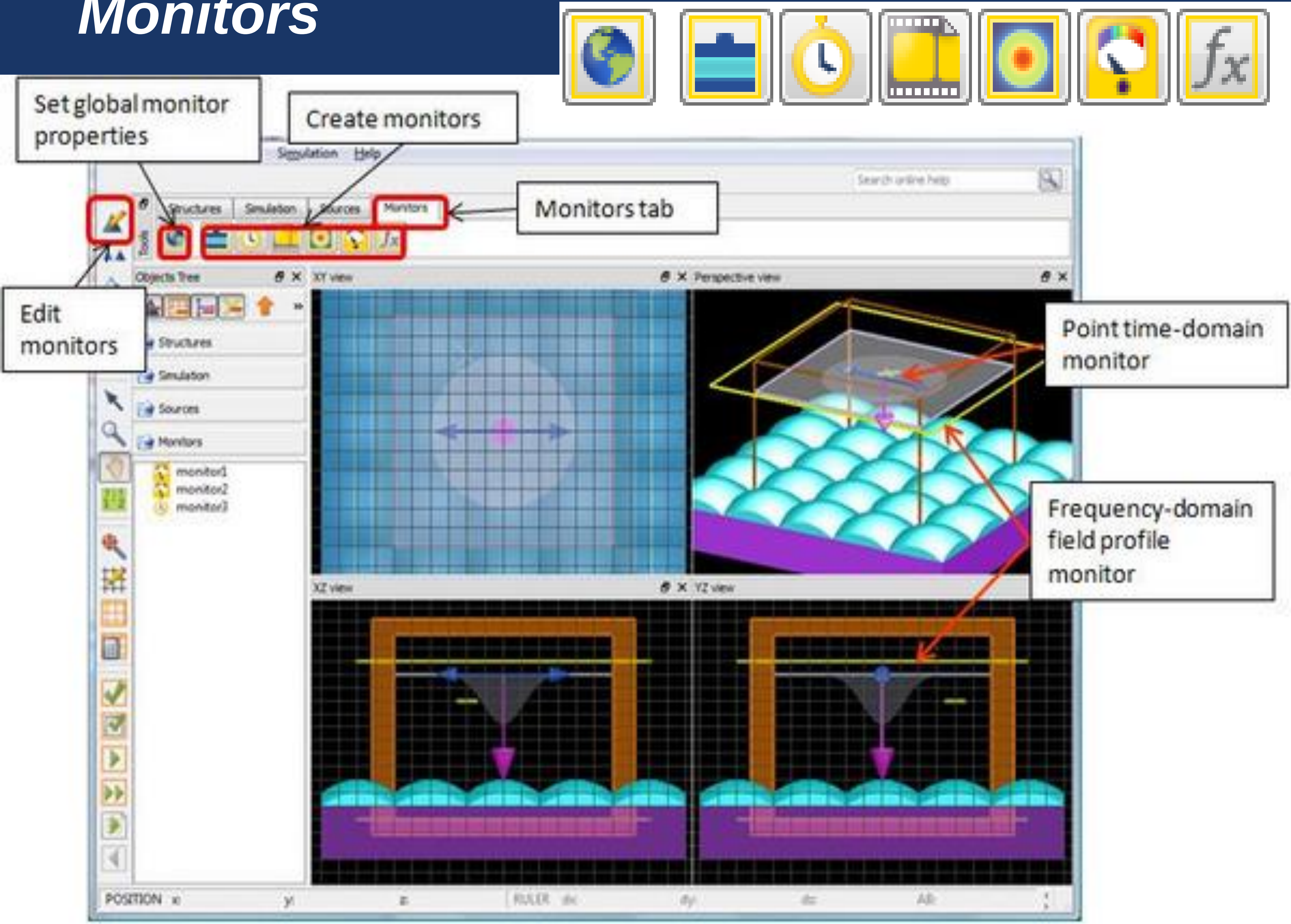


Total-Field Scattered-Field (TFSF)



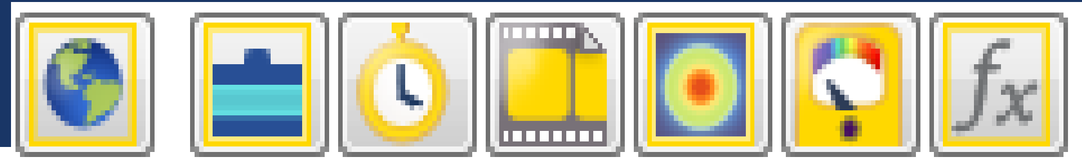
是计算纳米金属颗粒的小光谱专用光源

Monitors



Set global monitor properties
Create monitors
Monitors tab
Edit monitors
Point time-domain monitor
Frequency-domain field profile monitor

Monitors

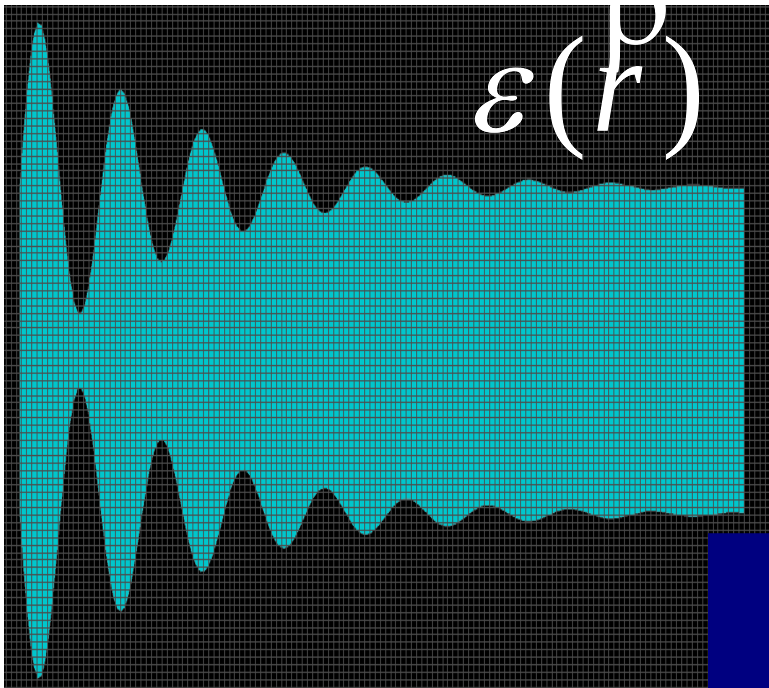


FDTD Solutions has several monitors

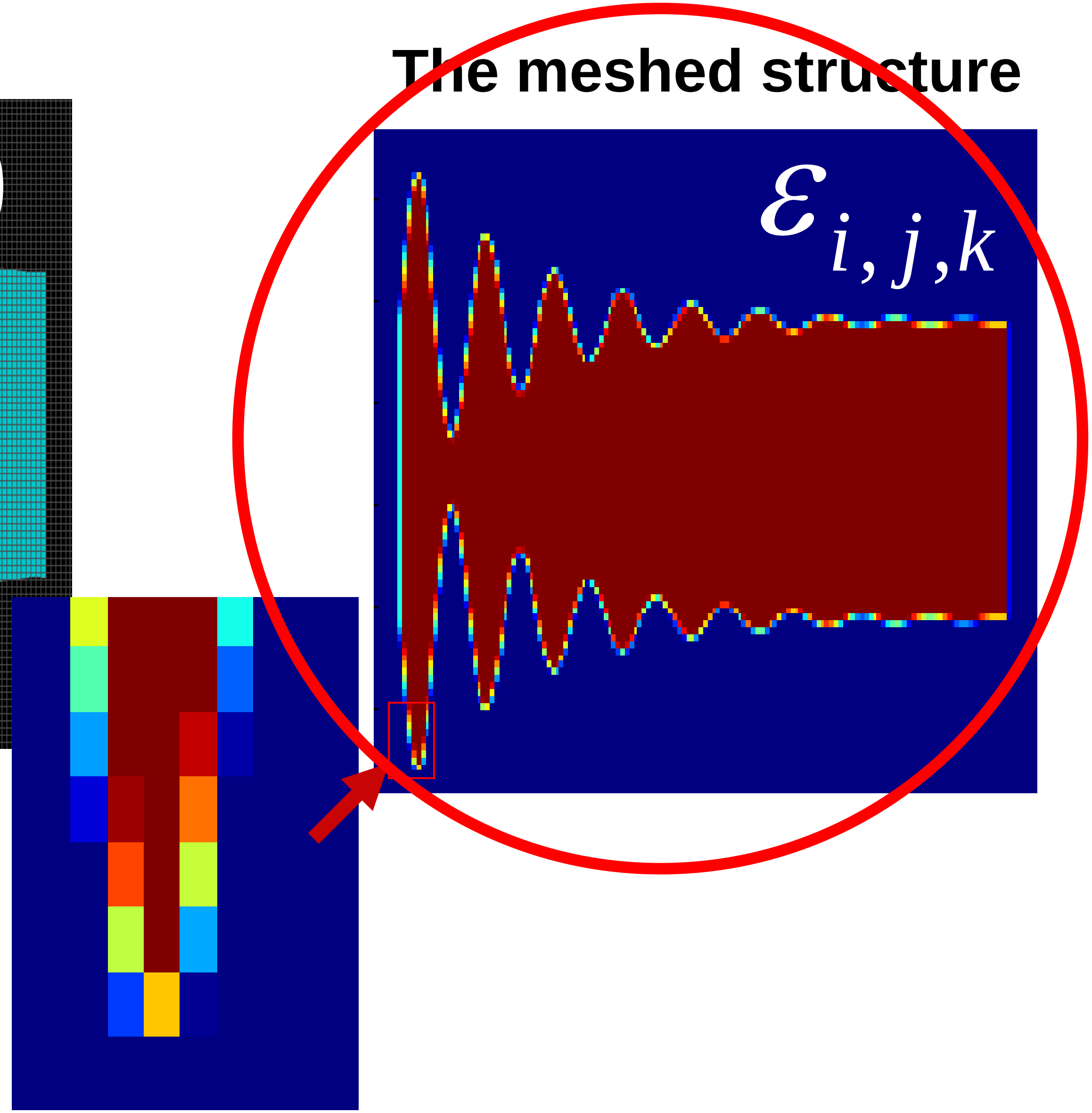
- **Index** monitors to record material properties
- **Movie** monitors to create mpg movie files
- **Time** monitors to record electromagnetic fields as a function of time
- **Frequency** monitors to perform Fourier transforms during the simulation
  - : **Profile** monitors
  - : **Power** monitors (generate accurate values)

Index monitors

The true structure



The meshed structure

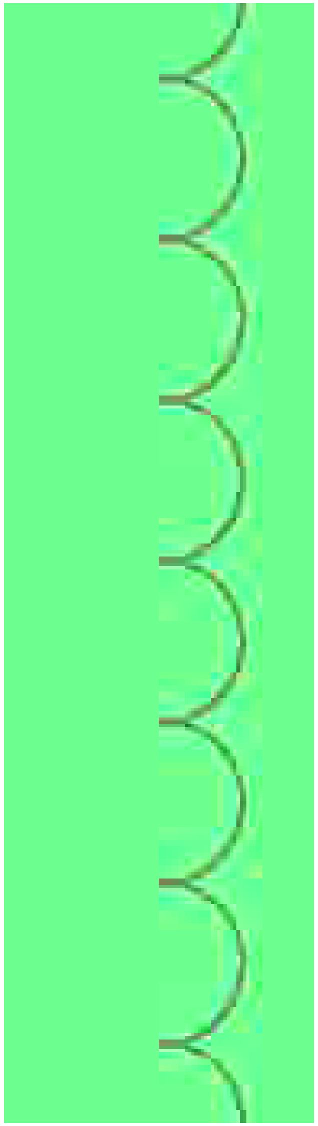


1. 检查材料的设定是否正确；
2. 显示复杂拐点处的平均网格精度。

Movie Monitors

Use movie monitors for

- visual aids in presentations!
- observe dynamic light interaction with the structure
- to develop intuition for what the simulation is doing
- to make sure the simulation is doing qualitatively what you want



Time Monitors

Time monitors record the electromagnetic fields as a function of time，E(t) and H(t).

- Normally we only record the data at one point.
- Sometimes we record data at a plane or over a volume at a small number of points in time.
- We can use time monitors to (目的)
  - Ensure the simulation has run long enough.
  - Look for resonant frequencies (**spectrum**) by doing a fast Fourier transforms (FFT) of a time signal
    - Find modes of resonant cavities
    - Band structure calculations (slab-based photonic crystals)

Frequency monitors

Commonly used for most designers/researchers!

Frequency monitors are used to **perform Fourier transforms** while the simulation is running.

Functions:

- **Transfer** from the transient-state time domain to the steady-state frequency/ wavelength domain.
- Obtain data at many wavelengths from **a single simulation**!
- **Each vectorial component (E** and **H)** is treated separately.
- **Wavelength range** must be specified in advance.

Frequency monitors

- Quantitative monitors used in simulations allow us to calculate:

  : transmission

  : reflection

  : absorption

  : scattering

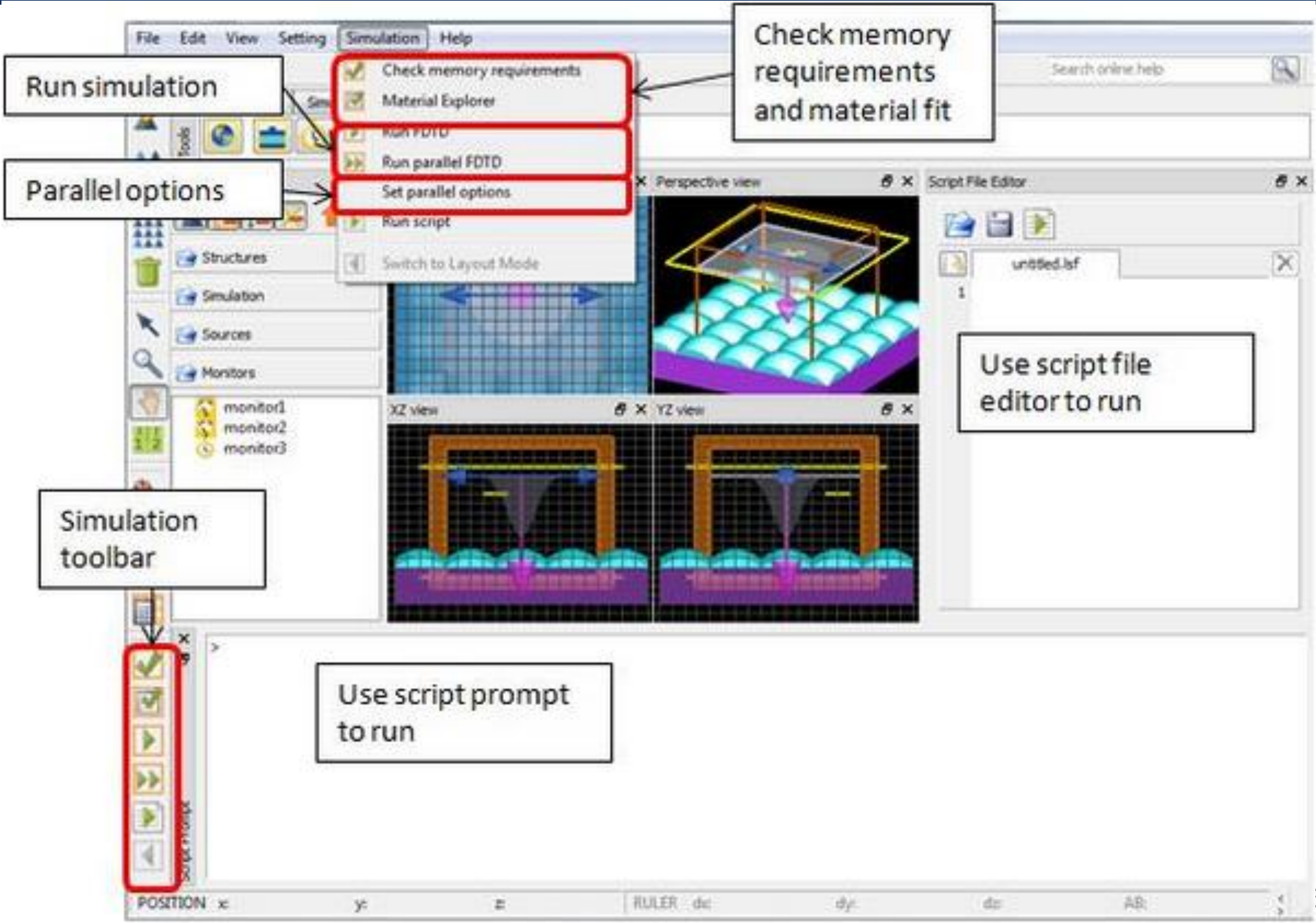
  : spatial field profiles

  : far field projections

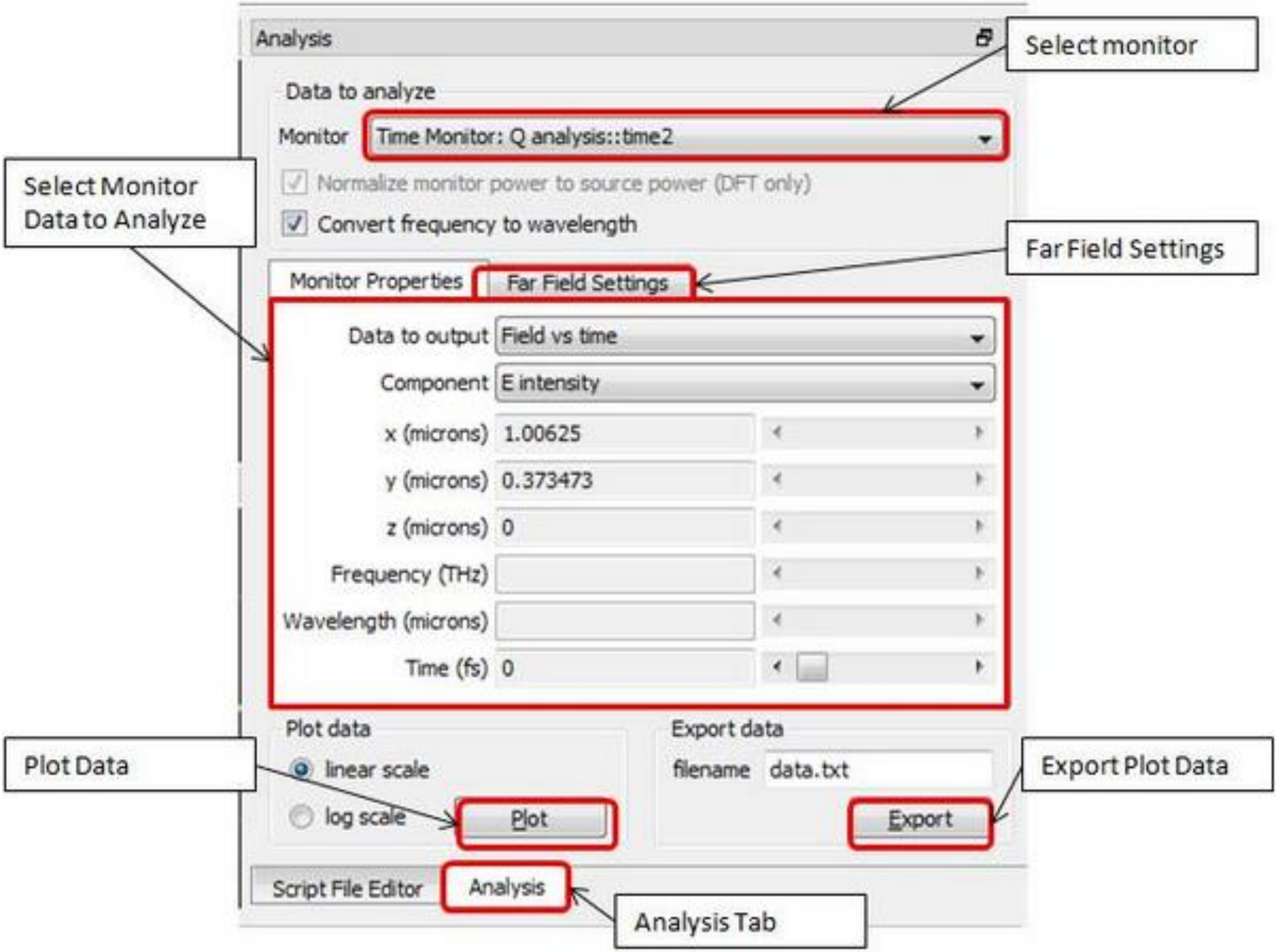
  : local (near) field enhancements

  : light extraction enhancement

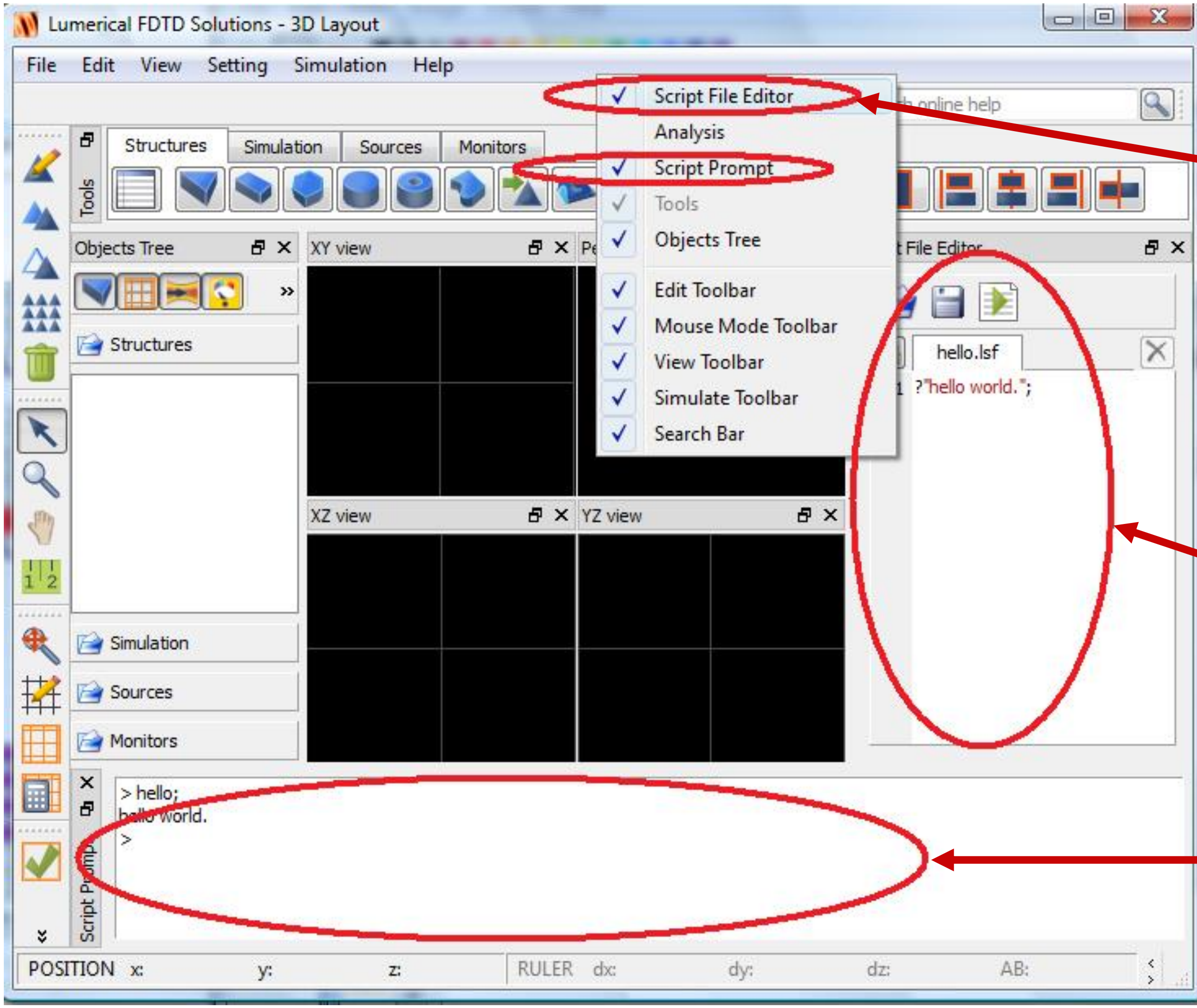
Run simulation



Basic Analysis



Advanced analysis with scripting



Right click on menu bar (or use View menu)

Script file editor

Script prompt

Basic Scripting

TOPICS

- The script window
- Simple mathematics
- Interacting with FDTD Solutions
- Script files

Basic Scripting

Simple Mathematics: plot some simple functions

```
> x=linspace(-10,10,500);
> y=sin(x);
> plot(x,y,”x”,”y”,”sin(x)”);

> y=exp(-x^2/9)*sin(10*x);
> plot(x,y,”x”,”y”,”exp(-x^2/9)*sin(10*x)”);

> ?size(x);
```

Interacting with FDTD Solutions

- Script commands can add or modify simulation objects
  - : addplane; will add a plane wave source
- Script commands can get simulation data
  - : getdata("monitor", "E_x"); will get the x component of the Electric field from a monitor
- Multiple script commands can be combined in script files. These files can be run by typing their name at the script prompt.
- You can use the up and down arrows to avoid retyping commands!

Script files

Open the example file scripting 0.lsf 

- Try running this script file
- Try pasting lines from this script file into your script prompt
- Try modifying this script file to add a rectangle and set the “x span” to 4 microns

FDTD Solutions Workflow Example

1. Create Physical Structures
2. Set Simulation Parameters
3. Define Sources
4. Define Monitors
5. Run Simulation
6. Analyze Results
7. Repeat if necessary

We will go through these steps in

- □ **A simple example**
- □ **The Getting Started examples**
- □ **A more advanced example**

Simple example

We want to

- Calculate the transmission through a 50 nm thick slab of Si on glass from 400 to 800nm
- Etch 200nm lines in the Si and repeat the measurement

If you get stuck, finished example files are in

- Simple example\simple_example.fsp
- Simple example\simple_example.lsf

Simple example

- Physical structures:
  - Create a New 2D simulation from defaults
  - Set the drawing grid to 25 nm
  - Create structures (use stacking feature)

- Simulation area:
  - Boundary conditions (Periodic in x, PML in y)
  - Dimensions (“x span” = 400nm, “y span” = 1 micron)
  - Mesh accuracy 2

Simple example

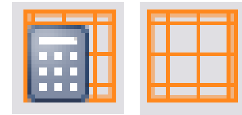
- Sources
  - Plane wave source, from glass side to air
  - Wavelength 400 to 800nm

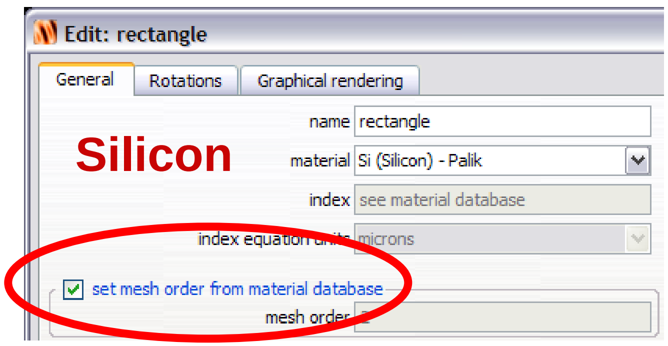
- Monitors
  - Movie monitor name movie
  - Index monitor over the entire structure name index
  - Time monitor in Si layer name time1
  - Transmission/Reflection monitors (100 frequency points each)
    - Name them "R" and "T" name T name R
  - Full profile over entire structure (3 frequency points)

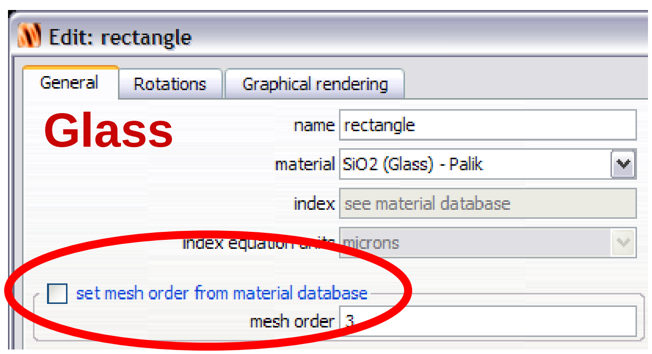
name full_profile

Simple example

- Recalculate and look at the FDTD mesh
  - Do we need a mesh override region?
- What happens at the interface?
  - Which material is used here?
- For precise control
  - Set mesh order correctly

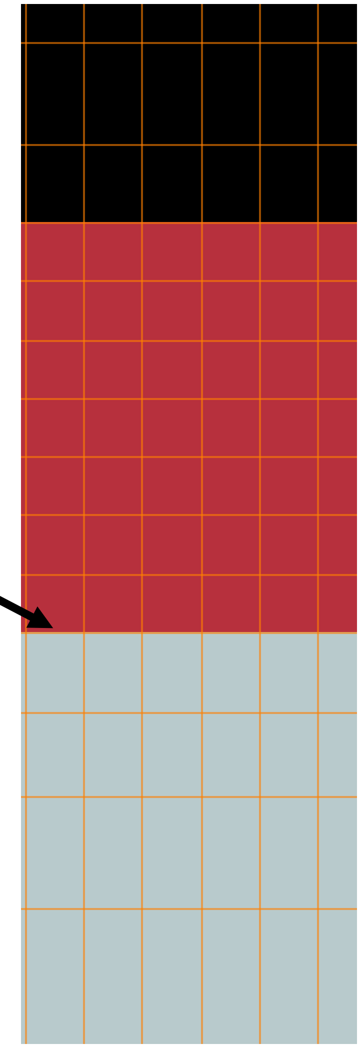






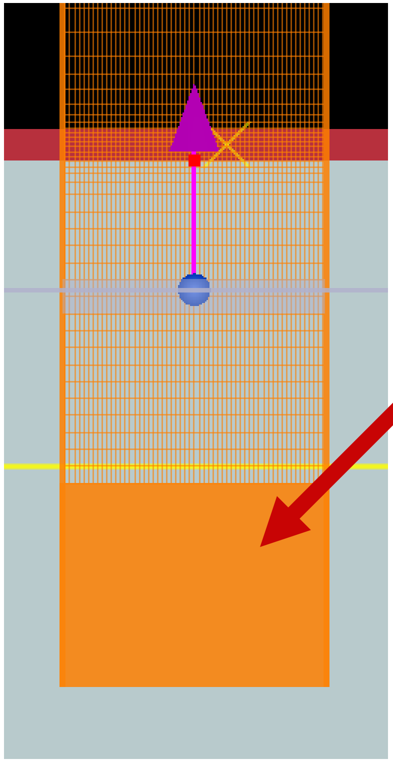
- Set Silicon mesh order to 2
- Set Glass mesh order to 3

The interface point will be Silicon!



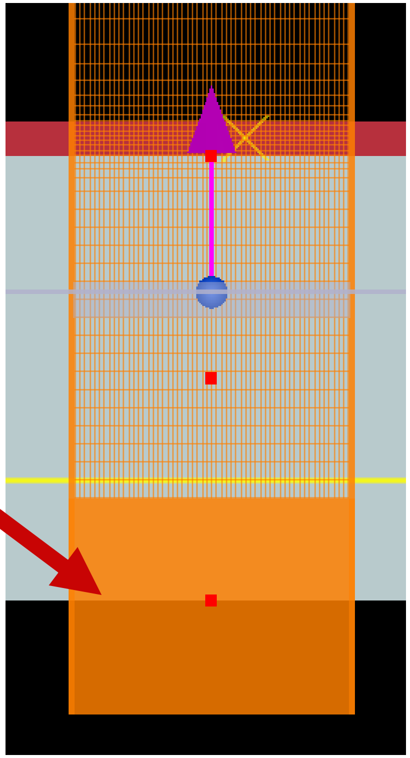
Simple example

- Be careful to extend structure through the PML boundary condition
  : Why? **Side-edges reflection issue.**

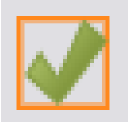
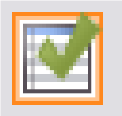


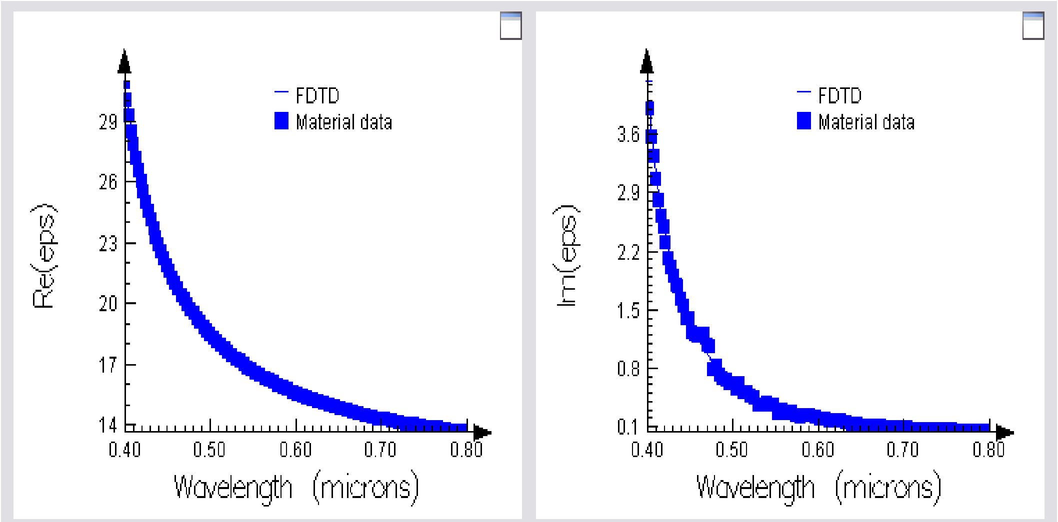
Correct

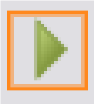
Incorrect



Simple example

- Check memory requirements! 
- Check material fits 



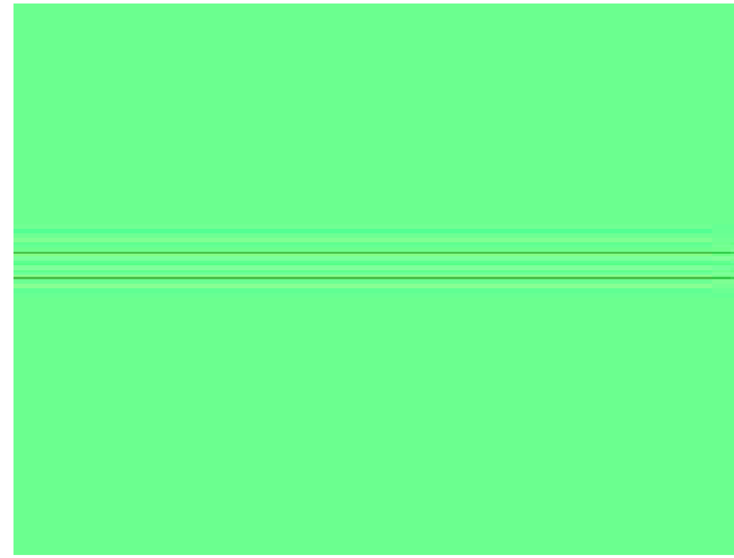
- Save simulation file under name **simple_example.fsp**
- Run simulation 
  - Note when the simulation “auto-shutoff” occurs
    - Can we reduce the maximum simulation time for the next simulation?

    : Can!

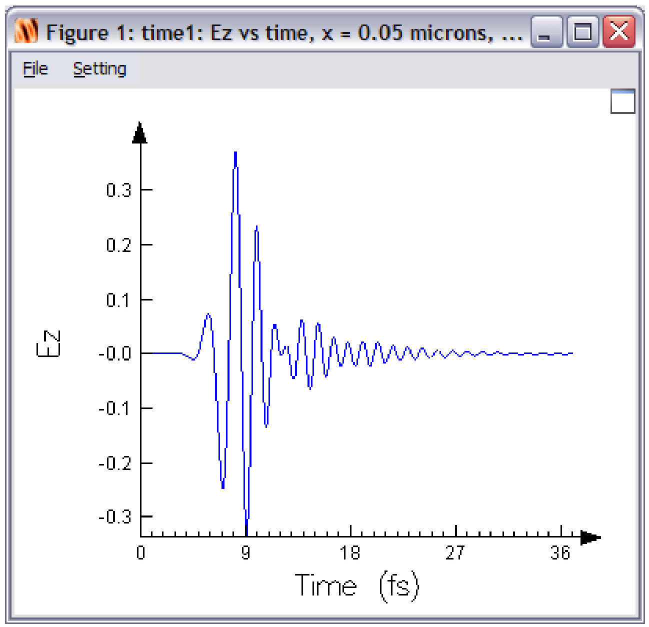
Simple example

- Analyze results

  : Run the movie: movie.mpg



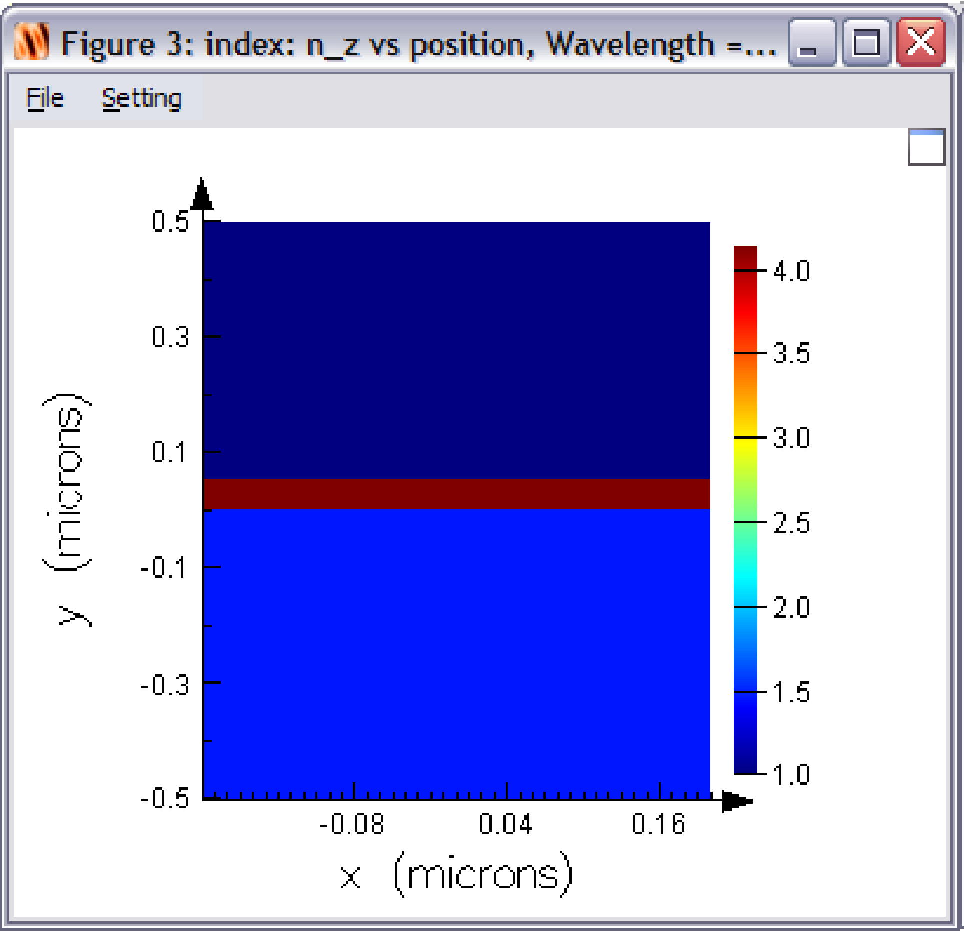
  : Plot Ez vs time

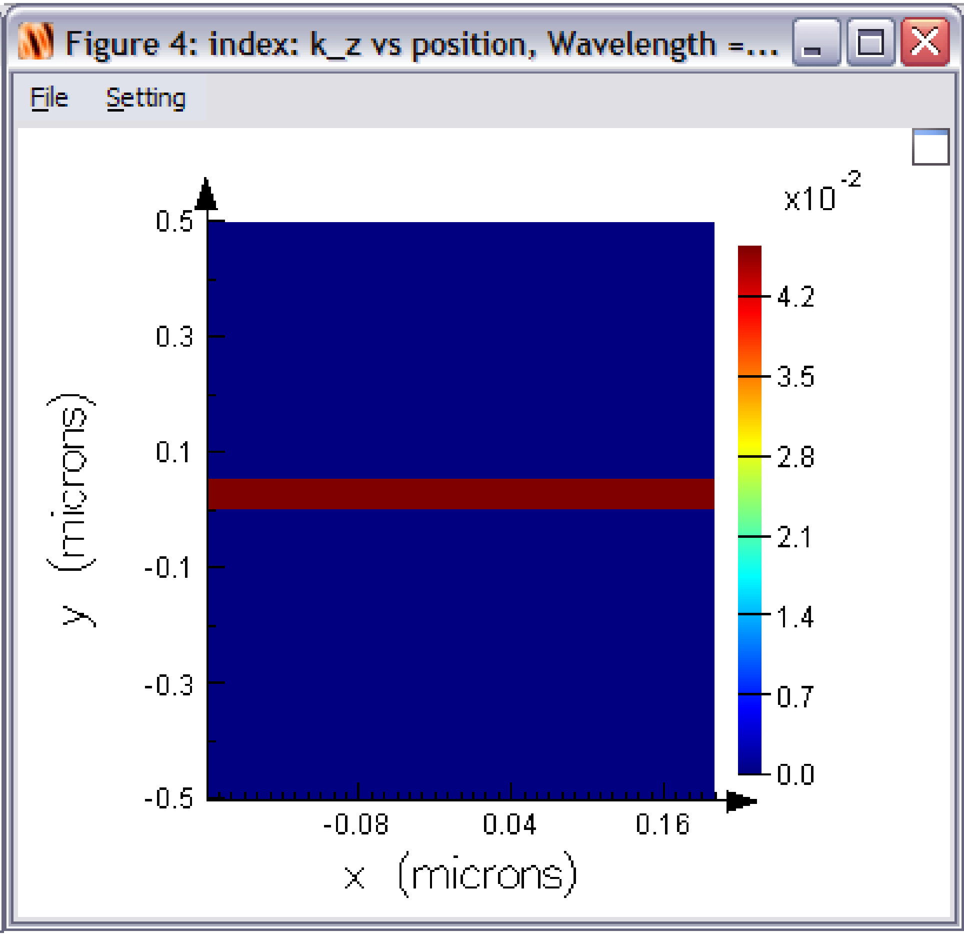


  : Did the auto-shutoff work?

Simple example

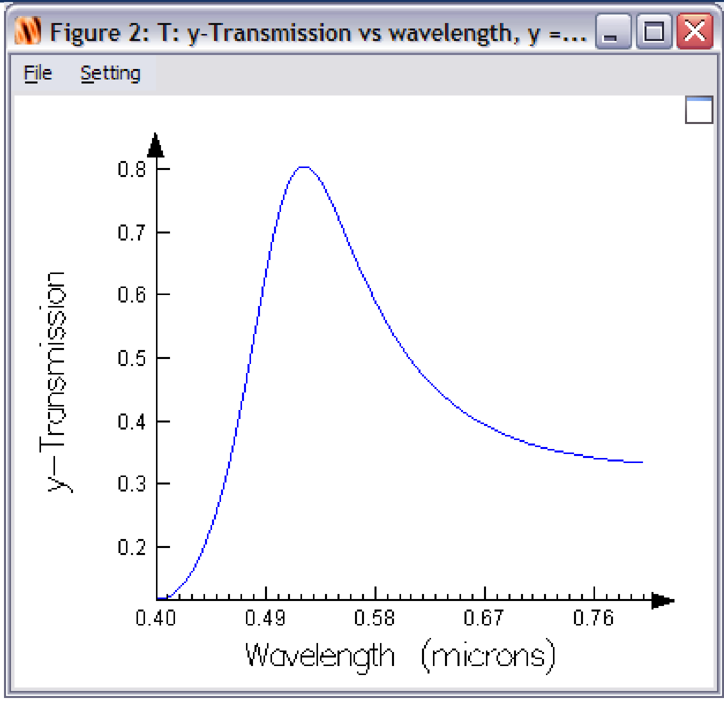
- Analyze results
  - Image ***n*** and ***k***. Is the structure correct?

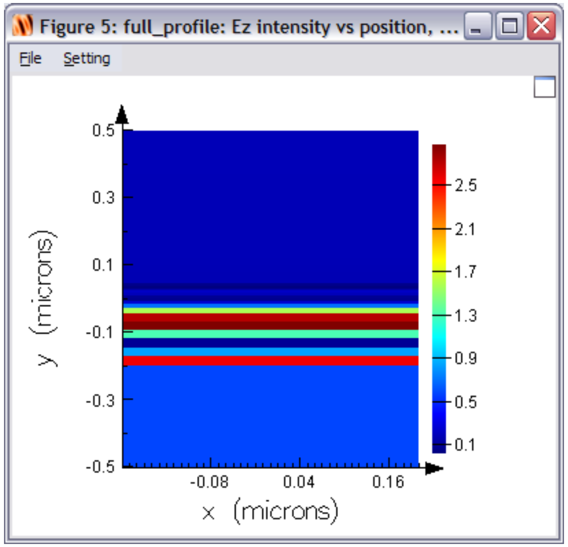


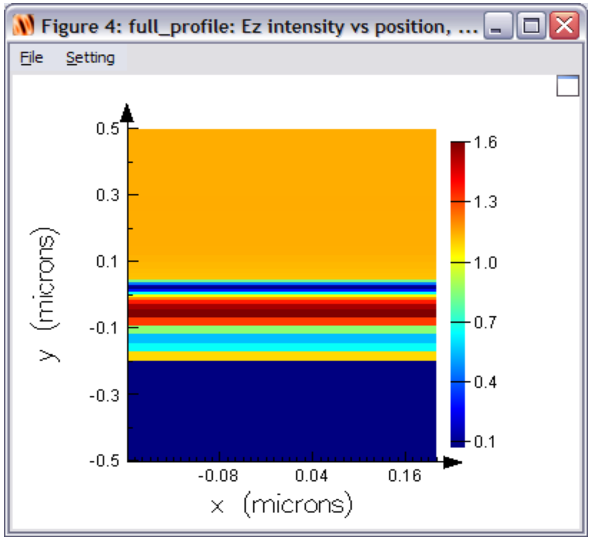


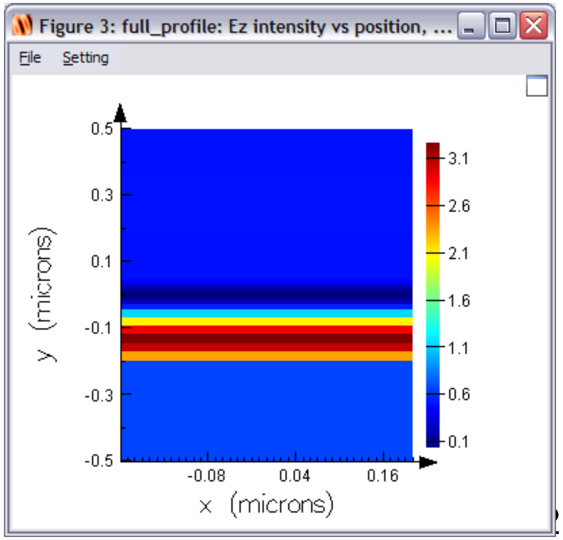
Simple example

- **Analyze results**
  - Plot transmission vs wavelength
  - Image $|E_z|^2$ at 3 different wavelengths





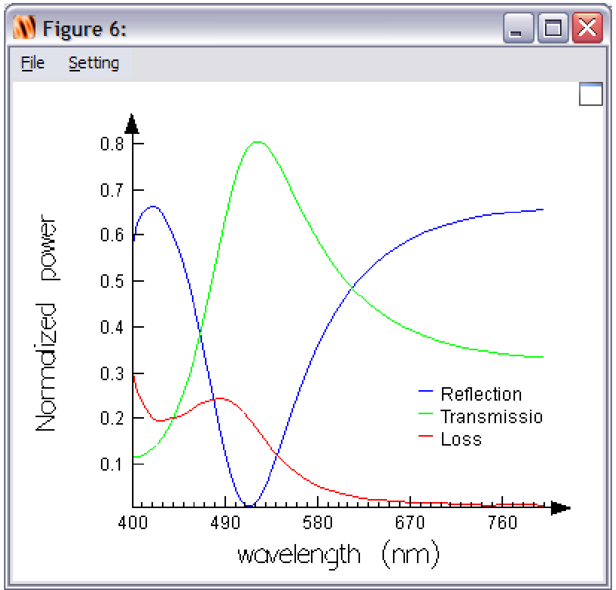




Simple example

- Analyze results
  - Create a script file with the following lines
    - f = getdata("T","f");
    - T = transmission("T");
    - R = -transmission("R");
    - L = 1-(R+T);
    - plot(c/f*1e9,R,T,L,"wavelength (nm)","Normalized power");
    - legend("Reflection","Transmission","Loss");
  - Try to move the legend to the position shown here (Setting menu)

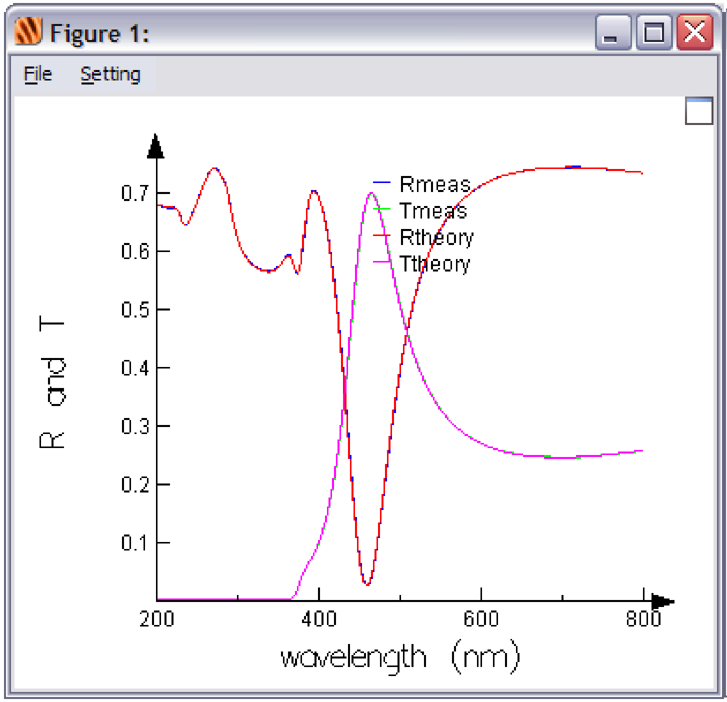
Question: why is there a negative sign here?



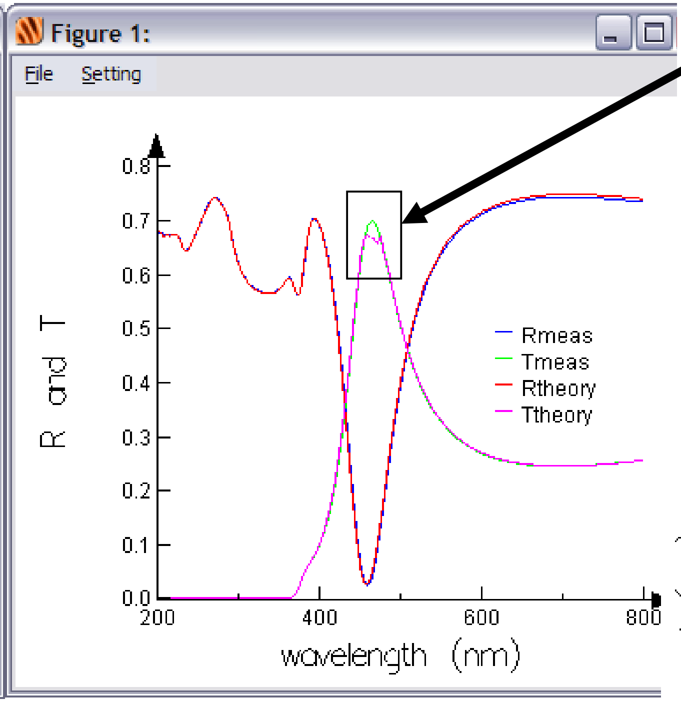
Simple example: accuracy

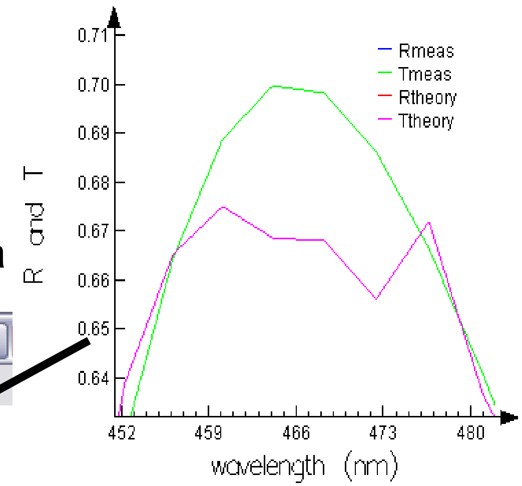
- Is this accurate?
  - Here is a 50 nm slab of Si in air, 200-800nm

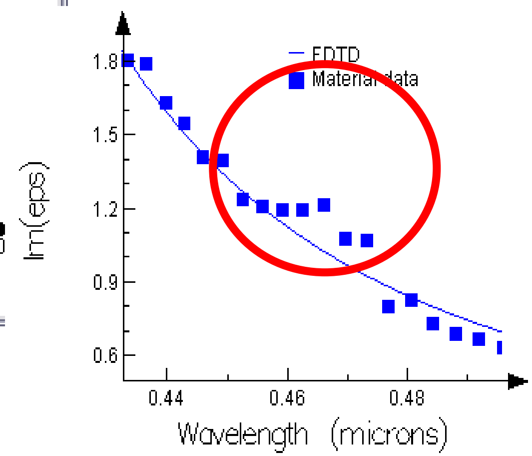
Theory based on FDTD material model



Theory based on Palik's Si data



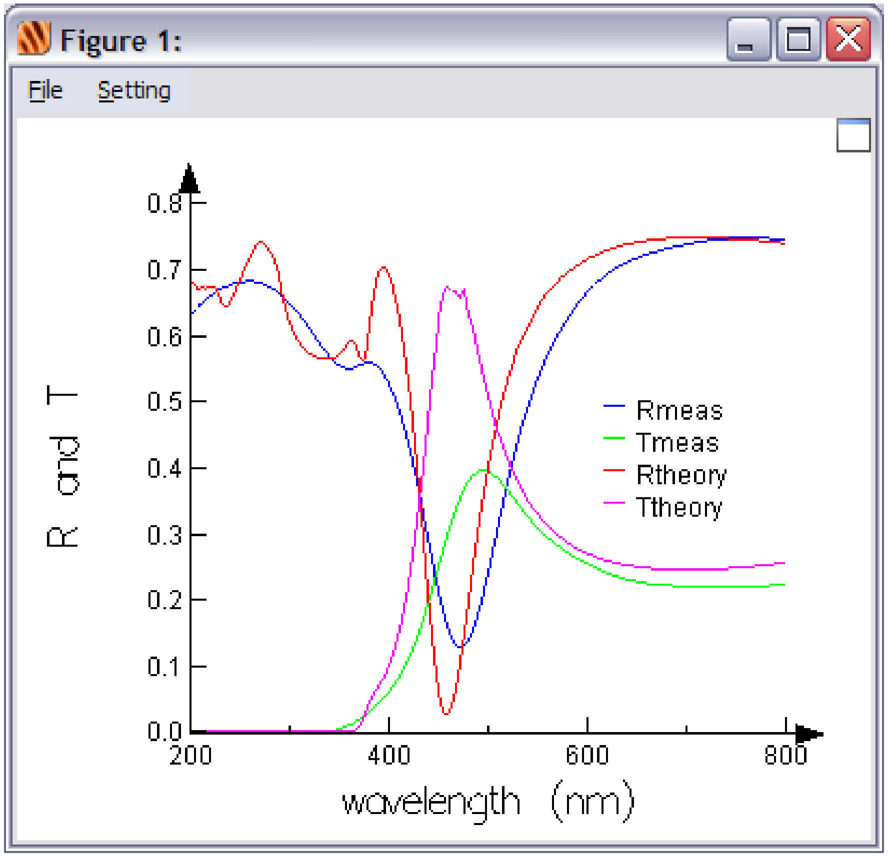




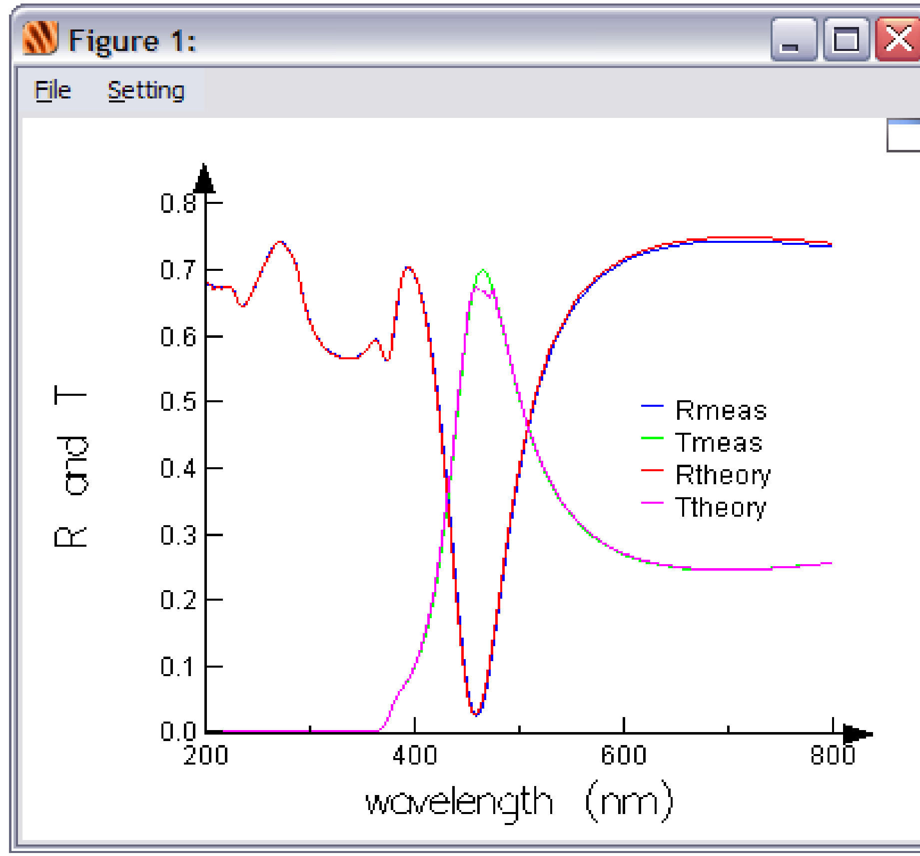
Simple example: accuracy

- Compare Lorentz model with multi-coefficient model

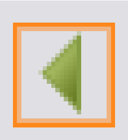
Lorentz model



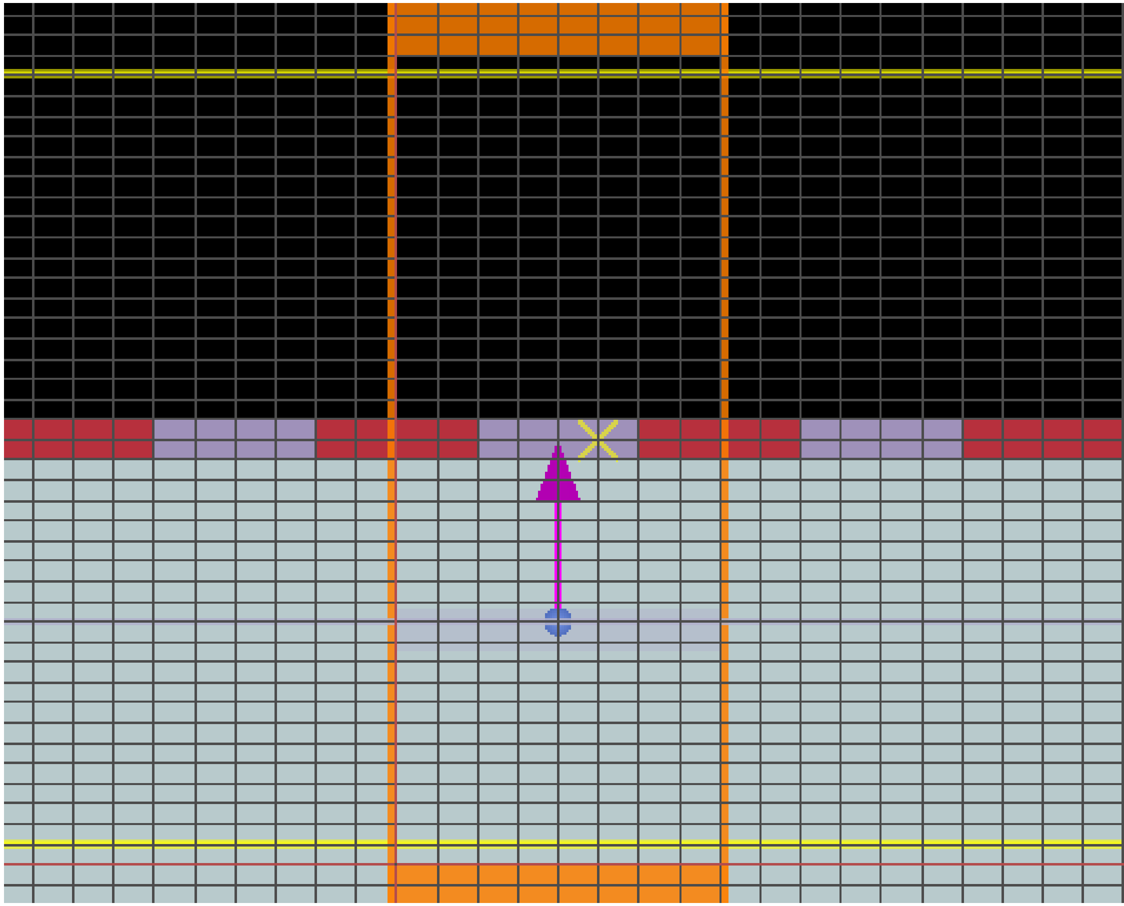
Lumerical's multi-coefficient model



Simple example

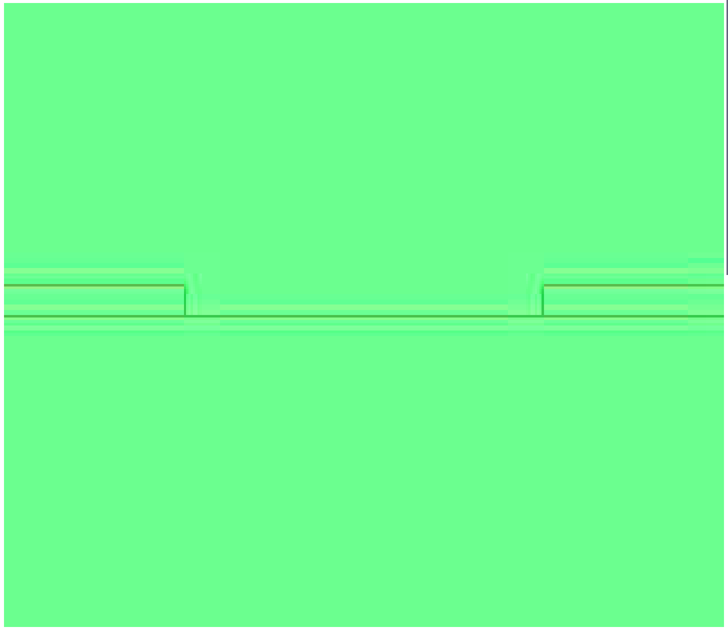
- **Switch back to Layout mode** 
- **Add etched lines (200nm wide, 400 nm period)**

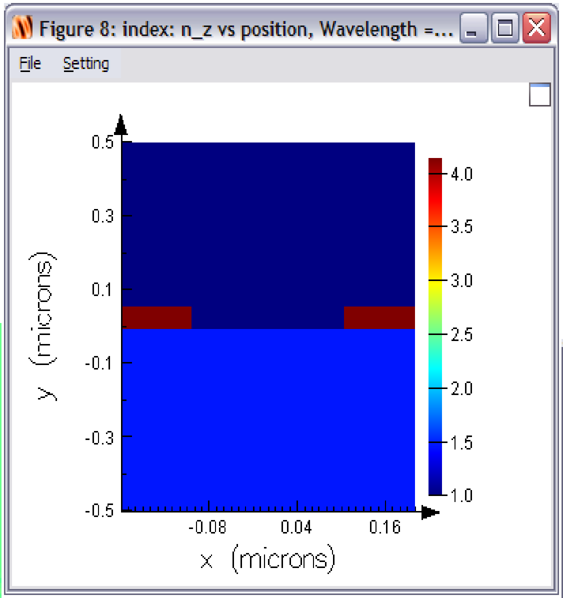
  - Adjust the drawing grid OR
  - Use the array feature

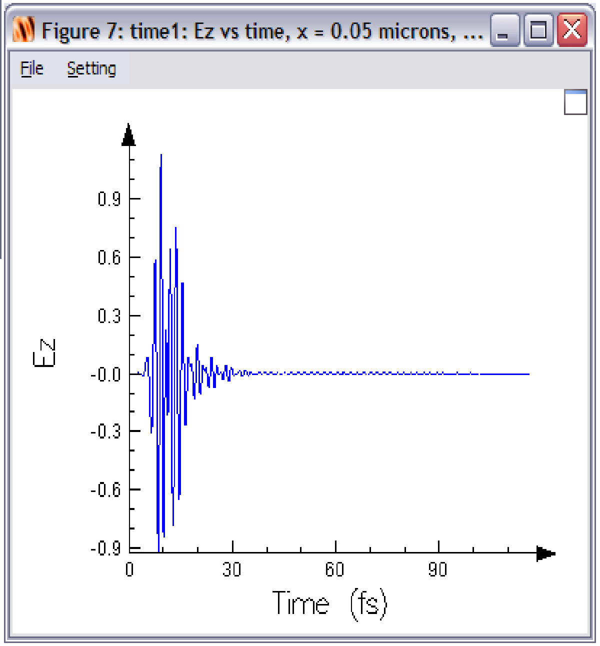


Simple example

- Run the simulation
  - Did the simulation run longer or shorter than before?
- Analyze the results
  - Index monitor
  - movie
  - Ez vs time

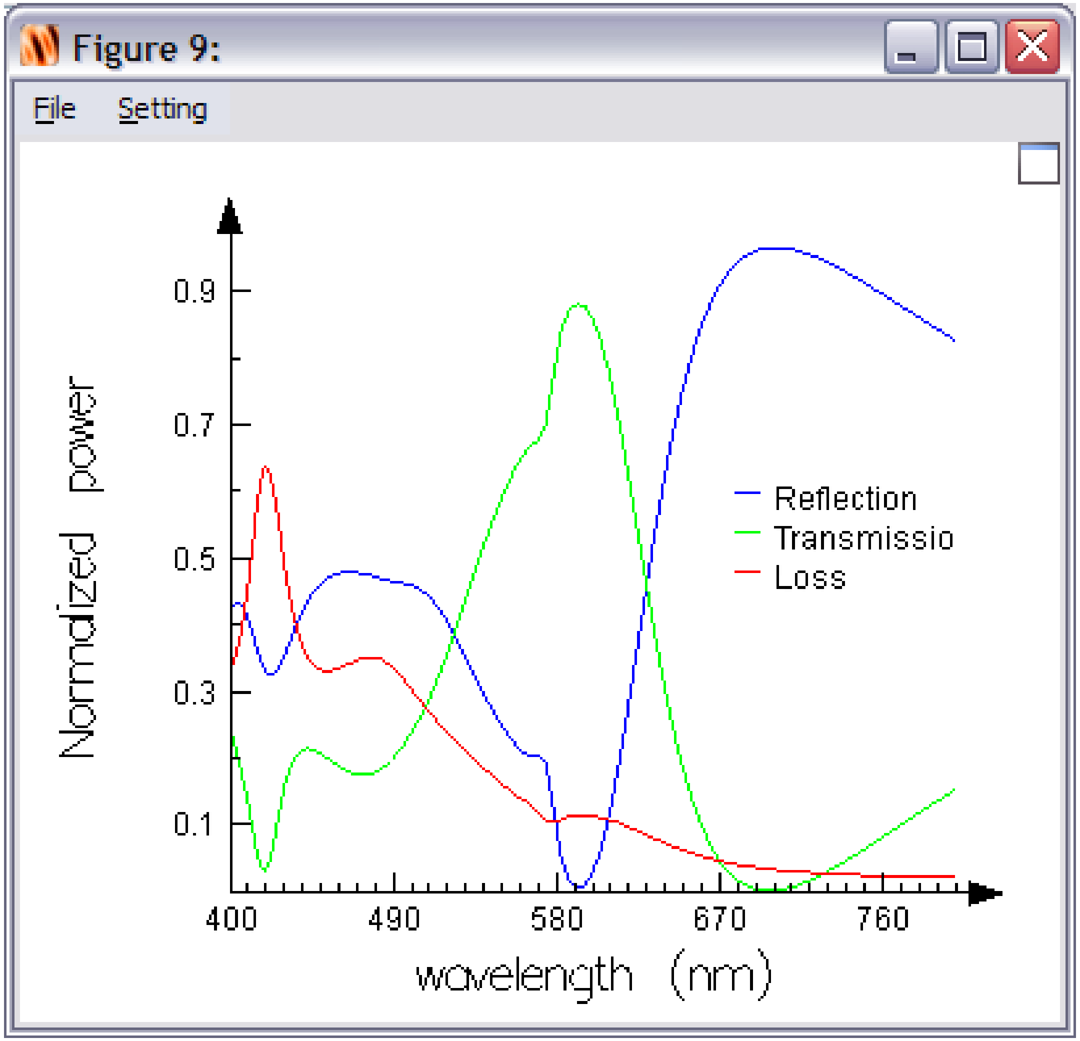






Simple example

- **Analyze results**
  : Rerun the script file



Getting Started Examples

- DVD surface analysis (3D)
- Silver nano-wire (2D)
- Photonic crystal cavity (3D)
- Ring resonator (2D)

- Examples files are included with every installation
- Detailed instruction are provided in the Getting Started Guide
  - : http://www.lumerical.com/fdtd_online_help/ (online)
  - : FDTD Solutions - Help Menu - **Getting Started** (PDF)

Applications Library

Home > Product Center > FDTD Solutions > FDTD Solutions Applications Library

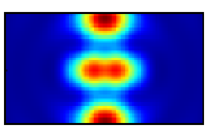
Applications of FDTD Solutions to microscale optics and nanophotonics

FDTD Solutions addresses a wide variety of applications involving the scattering, diffraction, and propagation of optical radiation. FDTD Solutions is useful for many engineering problems of interest, including:

CMOS Image Sensor Pixel

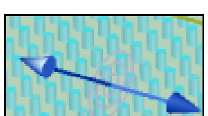
As CMOS pixel sizes decrease to reduce costs of digitial camera systems, there is a corresponding reduction in signal to noise and an increase in pixel cross-talk. Learn more ⇒

DVD Surface Design



Sub-wavelength features within a thin gold film within a DVD encodes information. Learn how to optmize this surface with FDTD Solutions to optimally store information. Learn more ⇒

LED/OLED Light Extraction Efficiency



Sub-wavelength texturing of LEDs increase light extraction efficiency, but accurate simulation tools like FDTD Solutions are needed to optimize microstructured LEDs. Learn more ⇒

DUV Lithography Simulation

FDTD Solutions

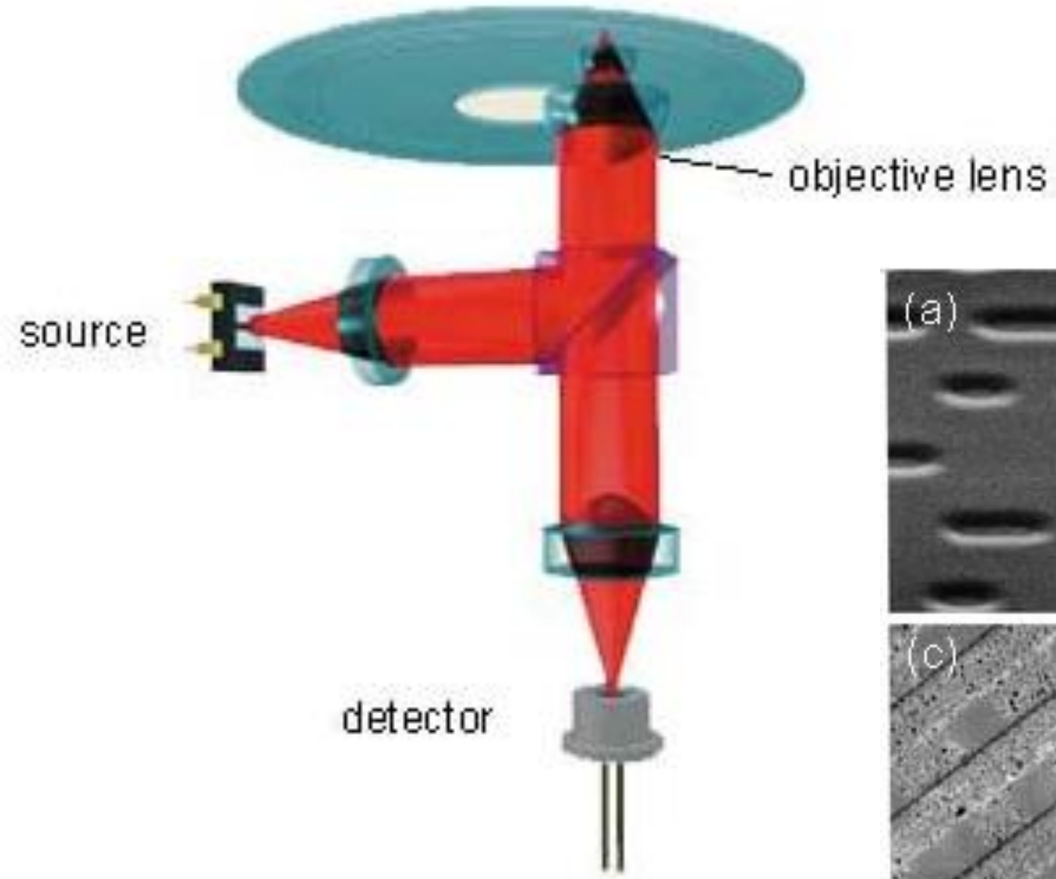
FDTD Solutions Applications Library

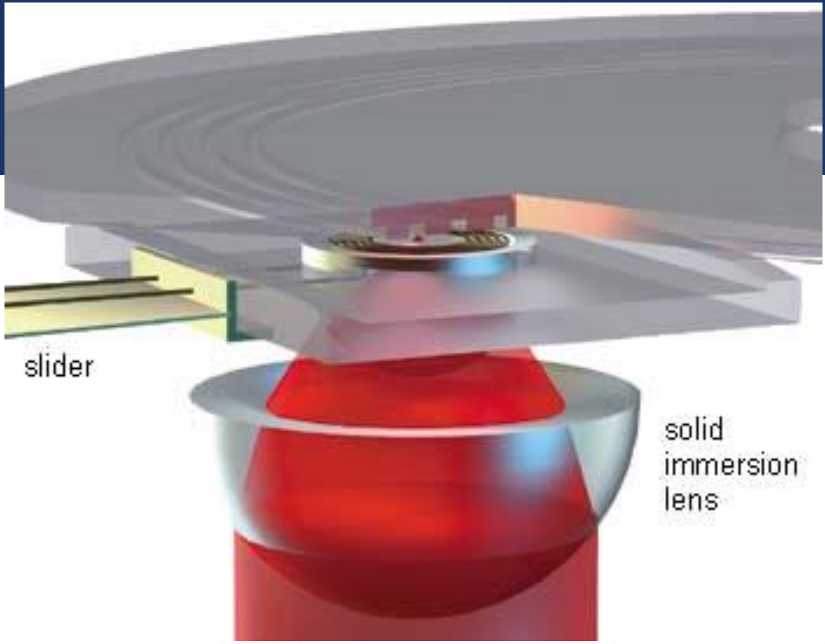
- CMOS Image Sensor Pixel
- DUV Lithography Simulation
- DVD Surface Analysis
- LED Light Extraction
- Nanoparticle Scattering
- Nanowire Grid Polarizers
- Photonic Crystal Cavity
- Photonic Crystal VCSEL
- SPR Nanolithography
- Thin Film Solar Cells
- Waveguide Microcavity

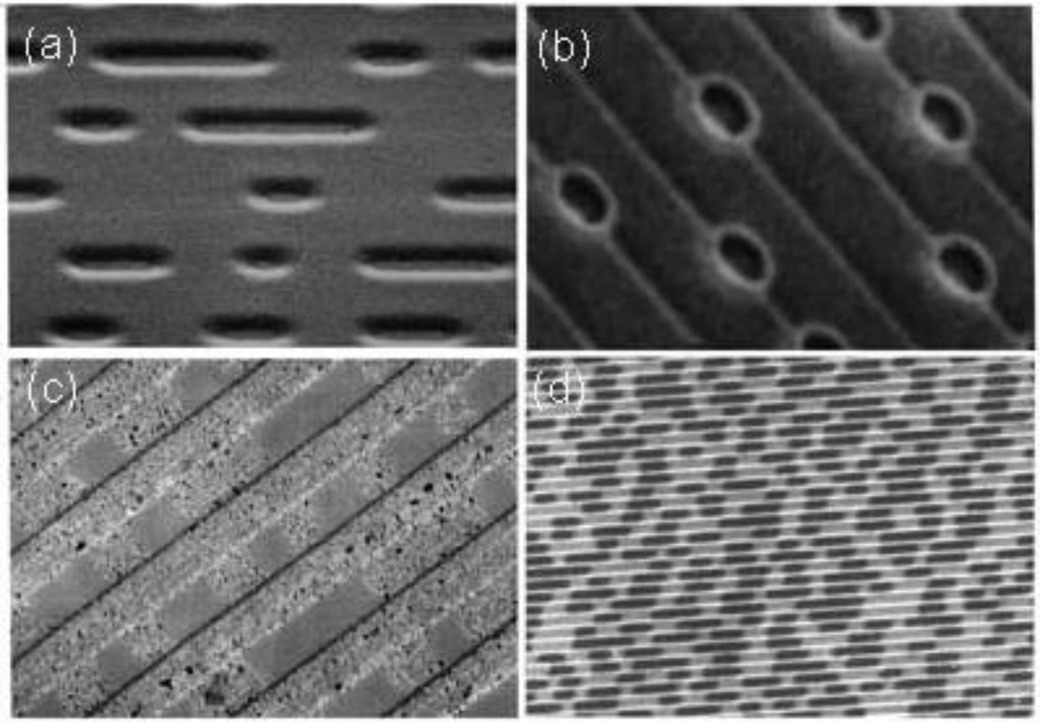
Supported Systems

DVD surface analysis

Optical reading/writing head

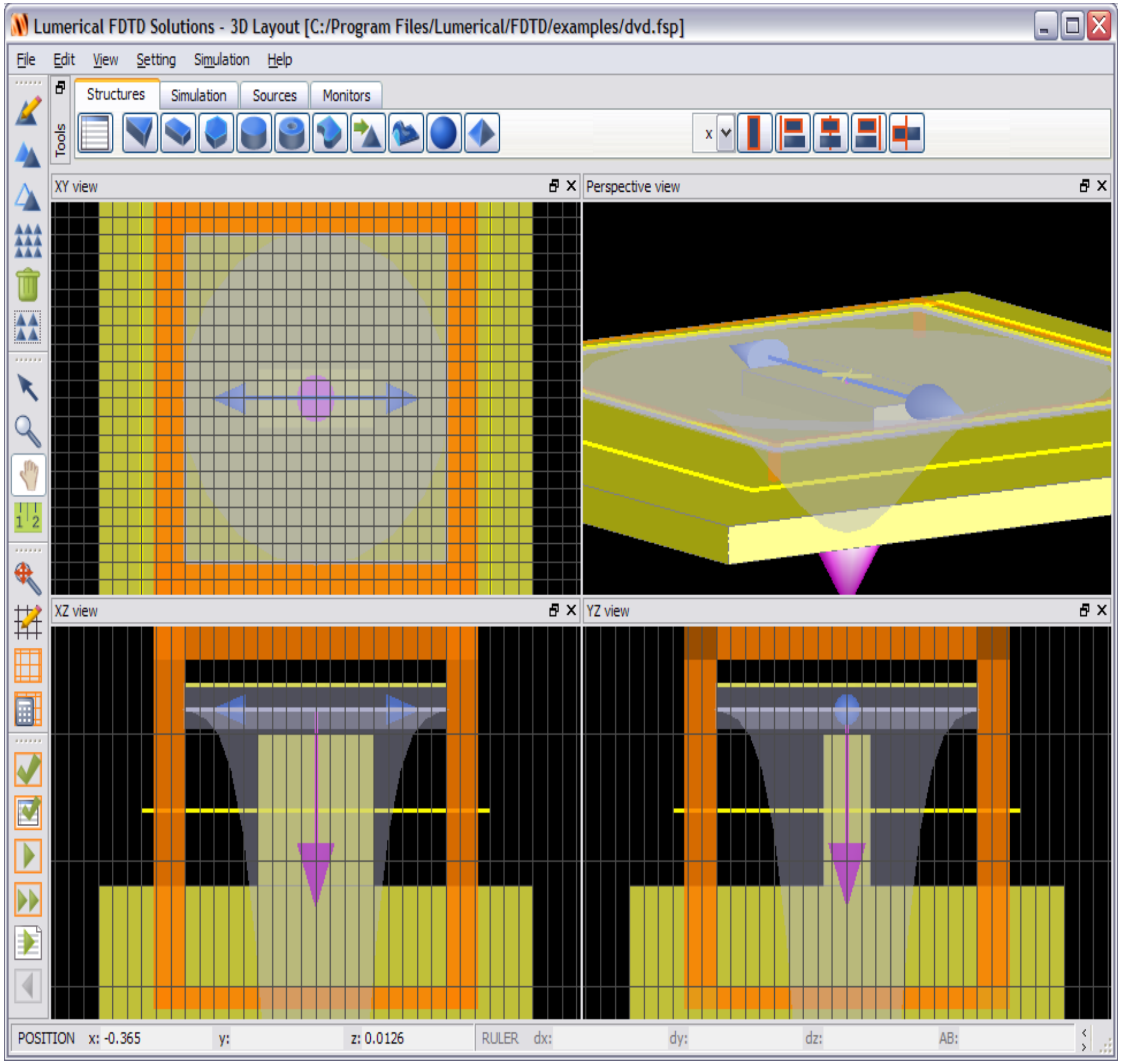






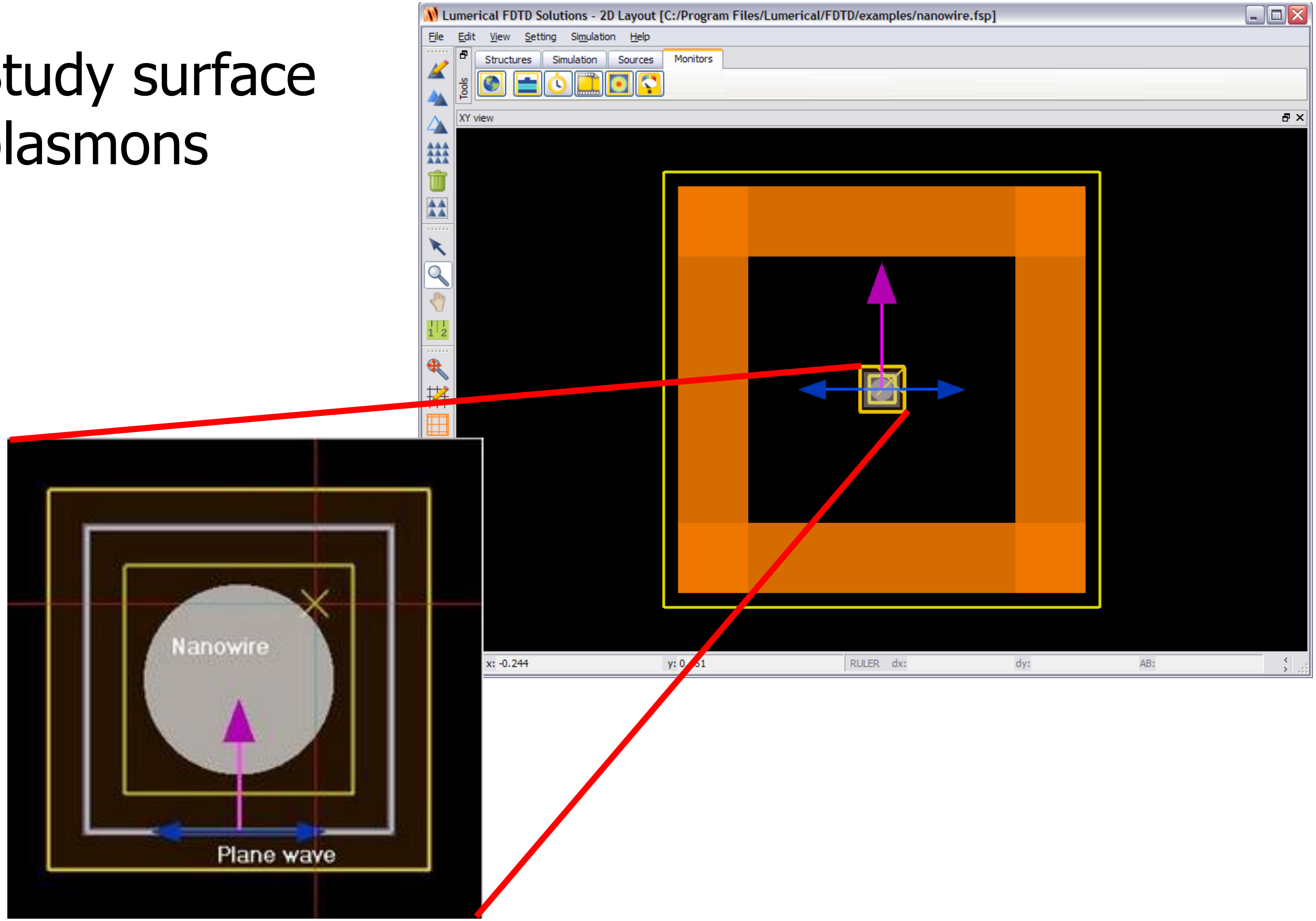
DVD surface analysis

- **Investigate reflections of a focused beam from DVD surface features**



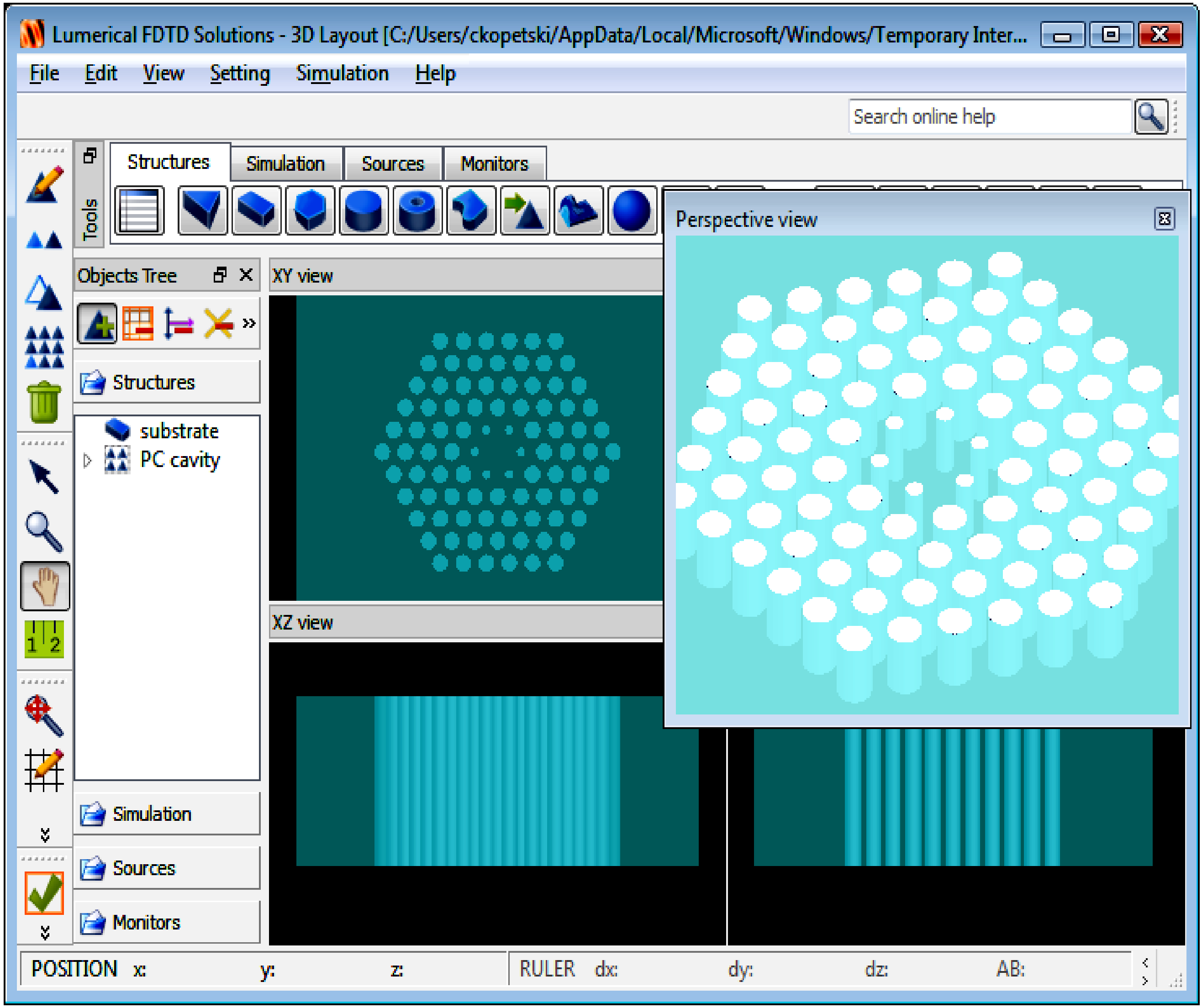
Silver nano-wire

- Study surface plasmons

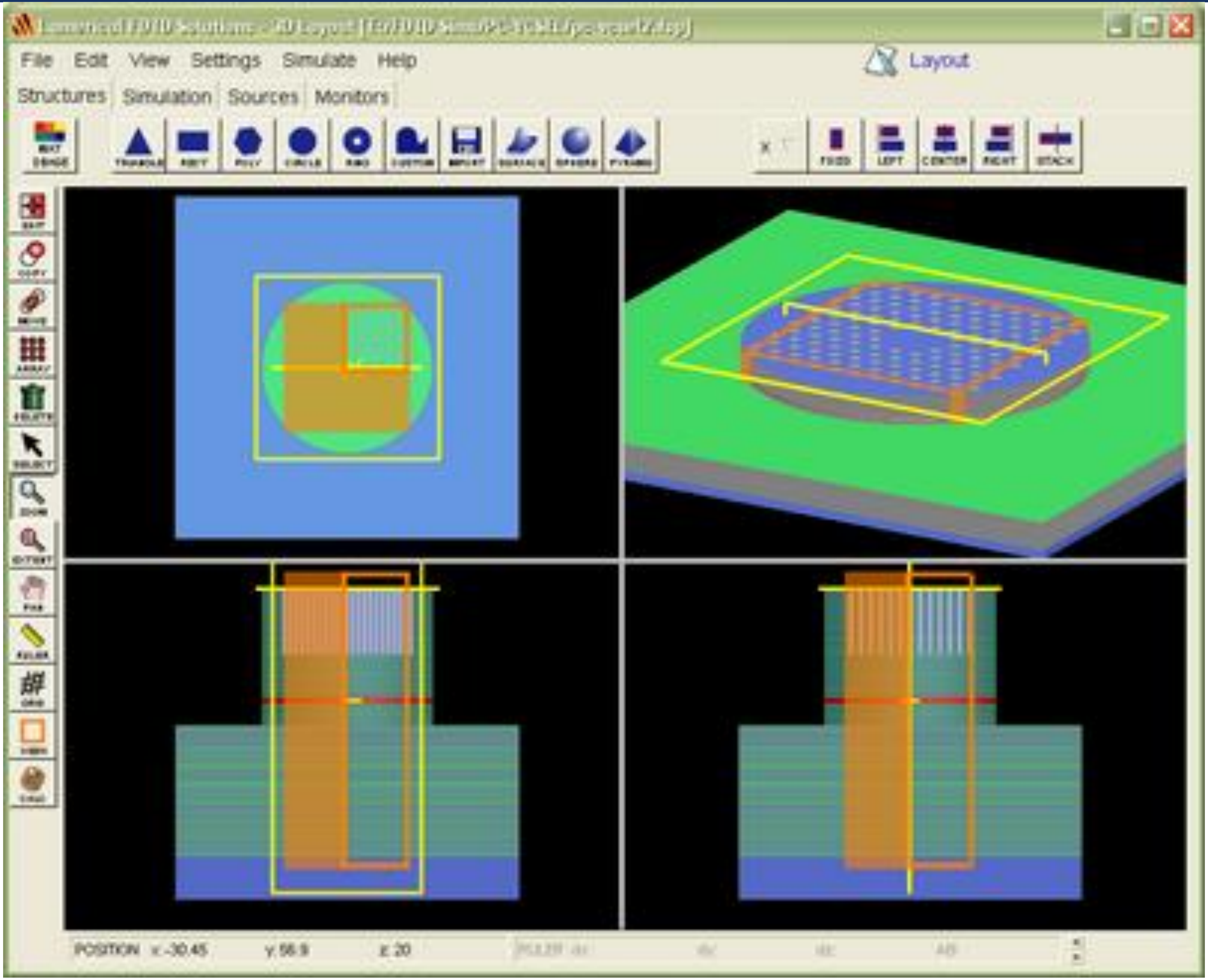


Photonic crystal cavity

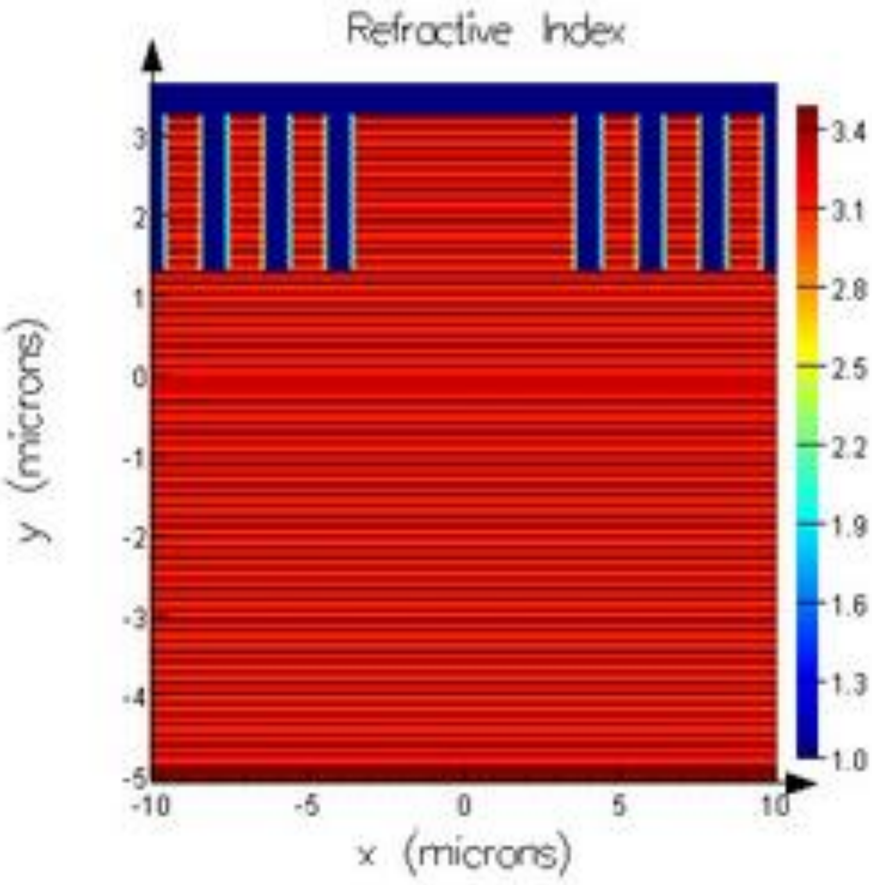
- Determine resonant frequencies of PC cavity

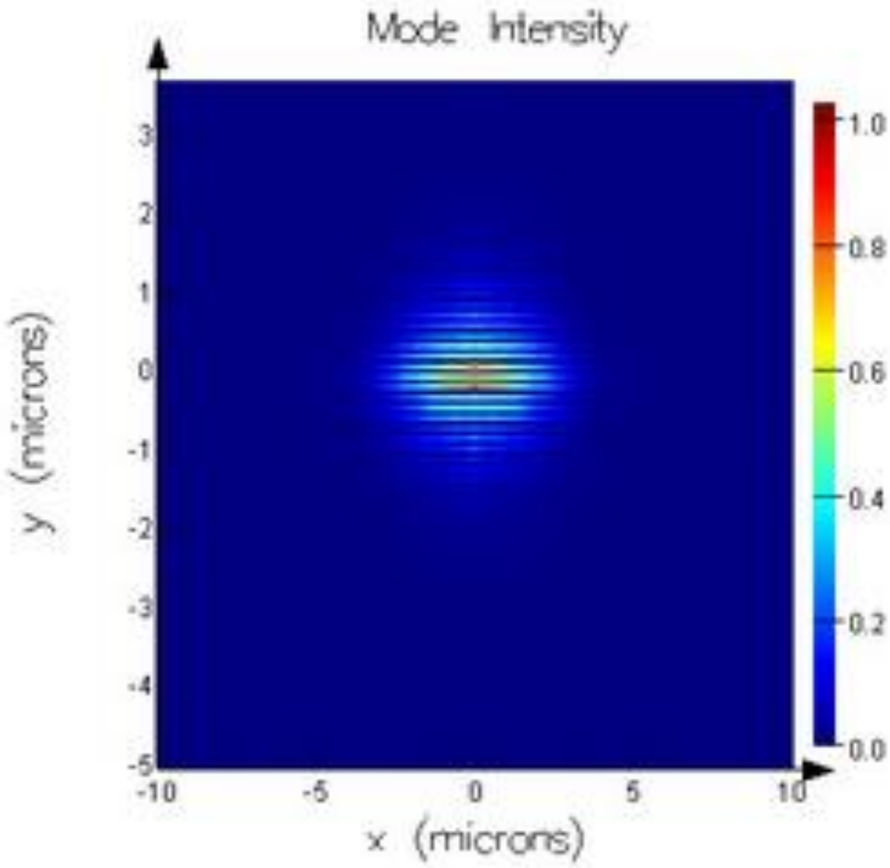


Integration of Photonic Crystal and VCSEL



Integration of Photonic Crystal and VCSEL

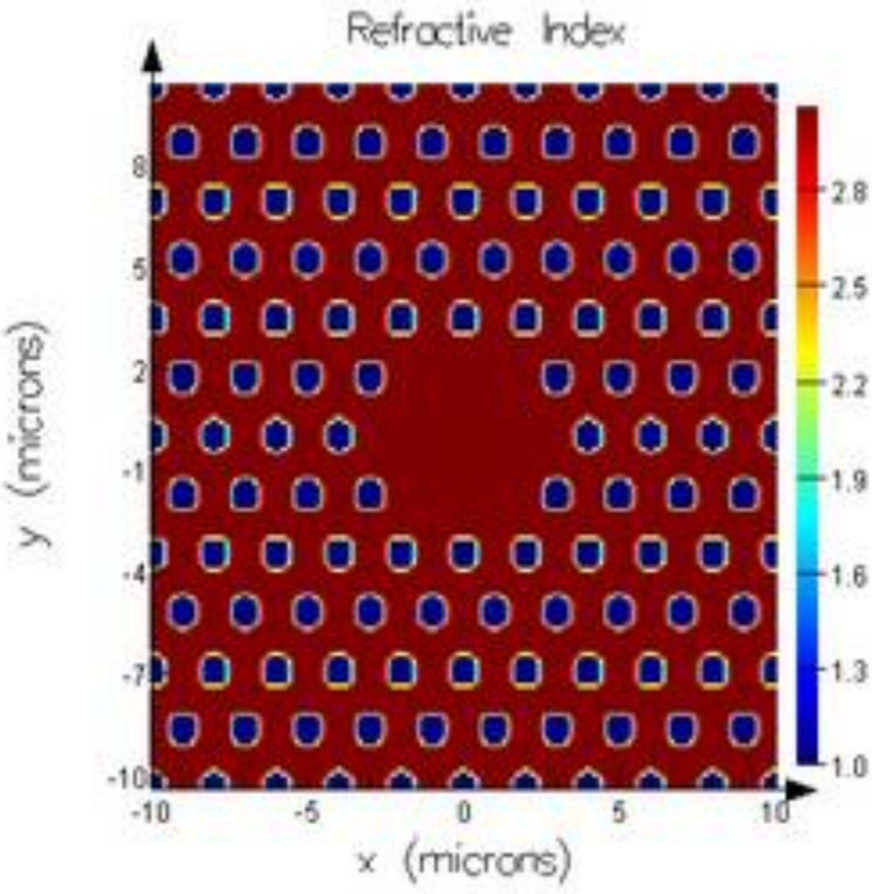




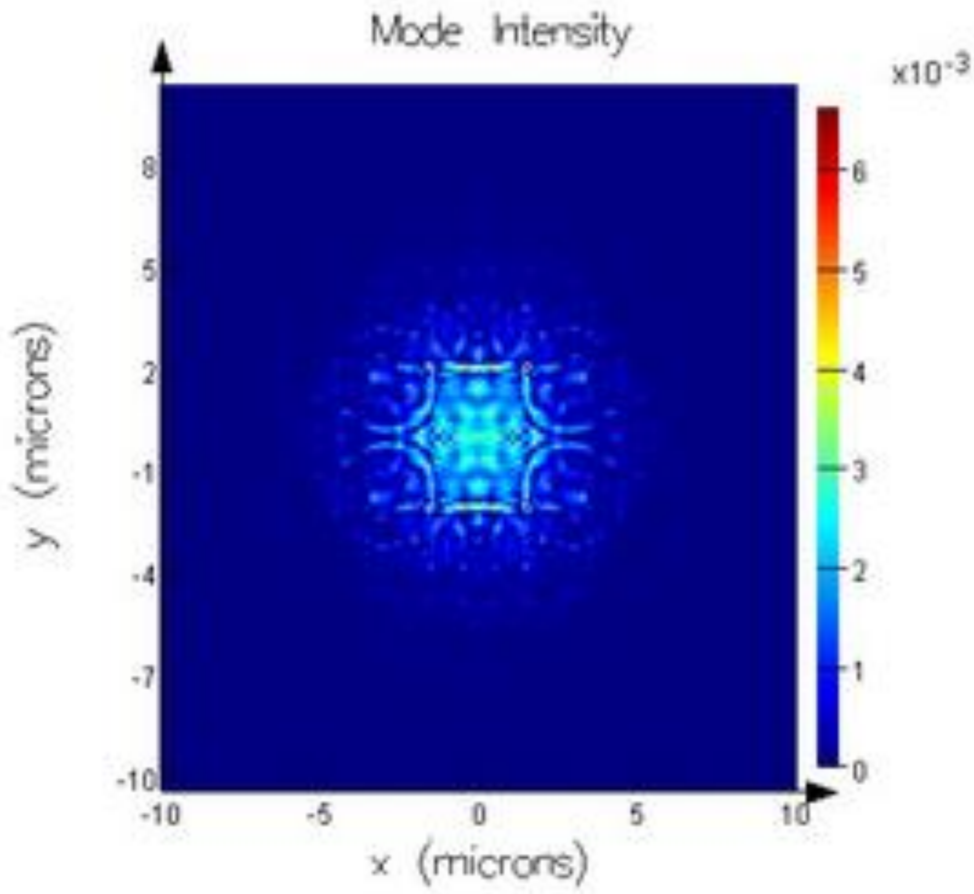
Cross-sectional refractive index distribution of VCSEL

Cross-section of intensity profile of PC-VCSEL cavity mode

Integration of Photonic Crystal and VCSEL

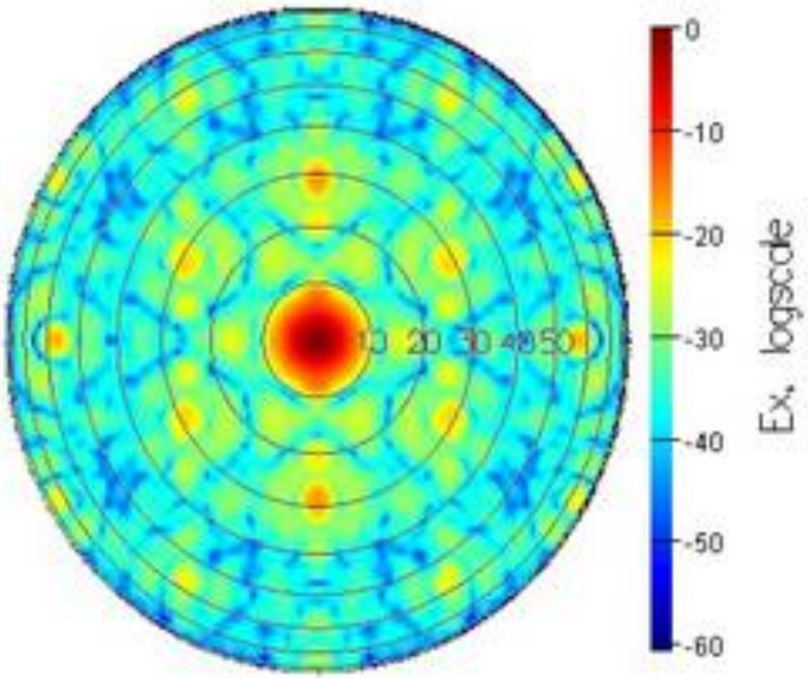


Planar refractive index distribution of PC-VCSEL

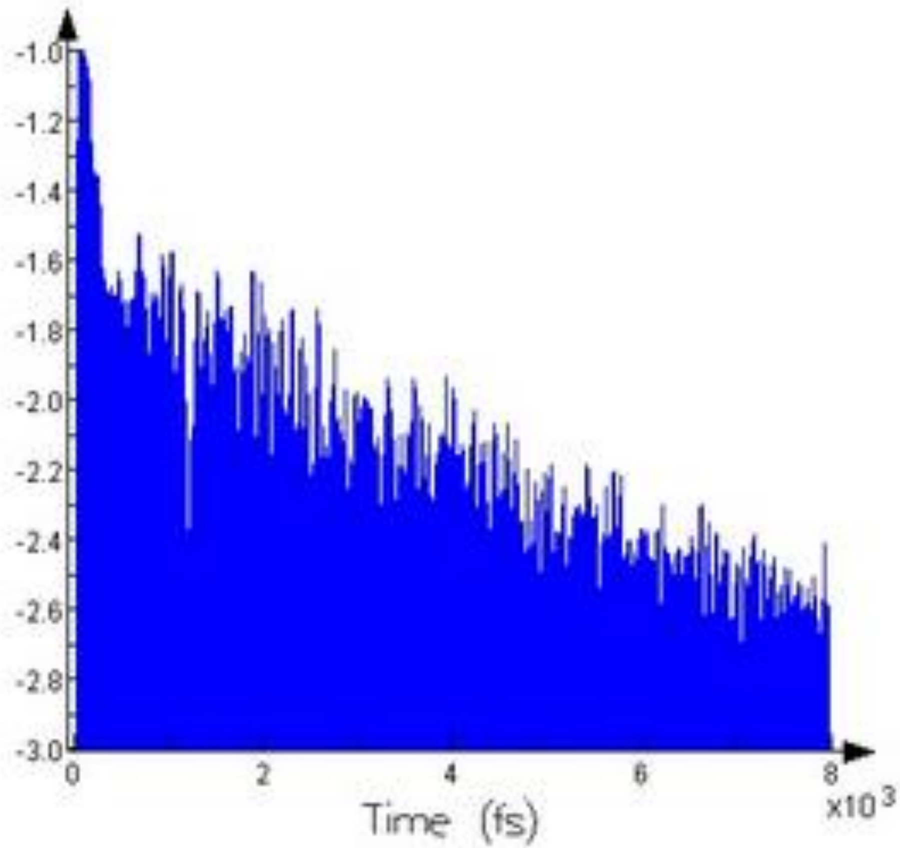


Planar intensity profile at surface of PC-VCSEL

Integration of Photonic Crystal and VCSEL



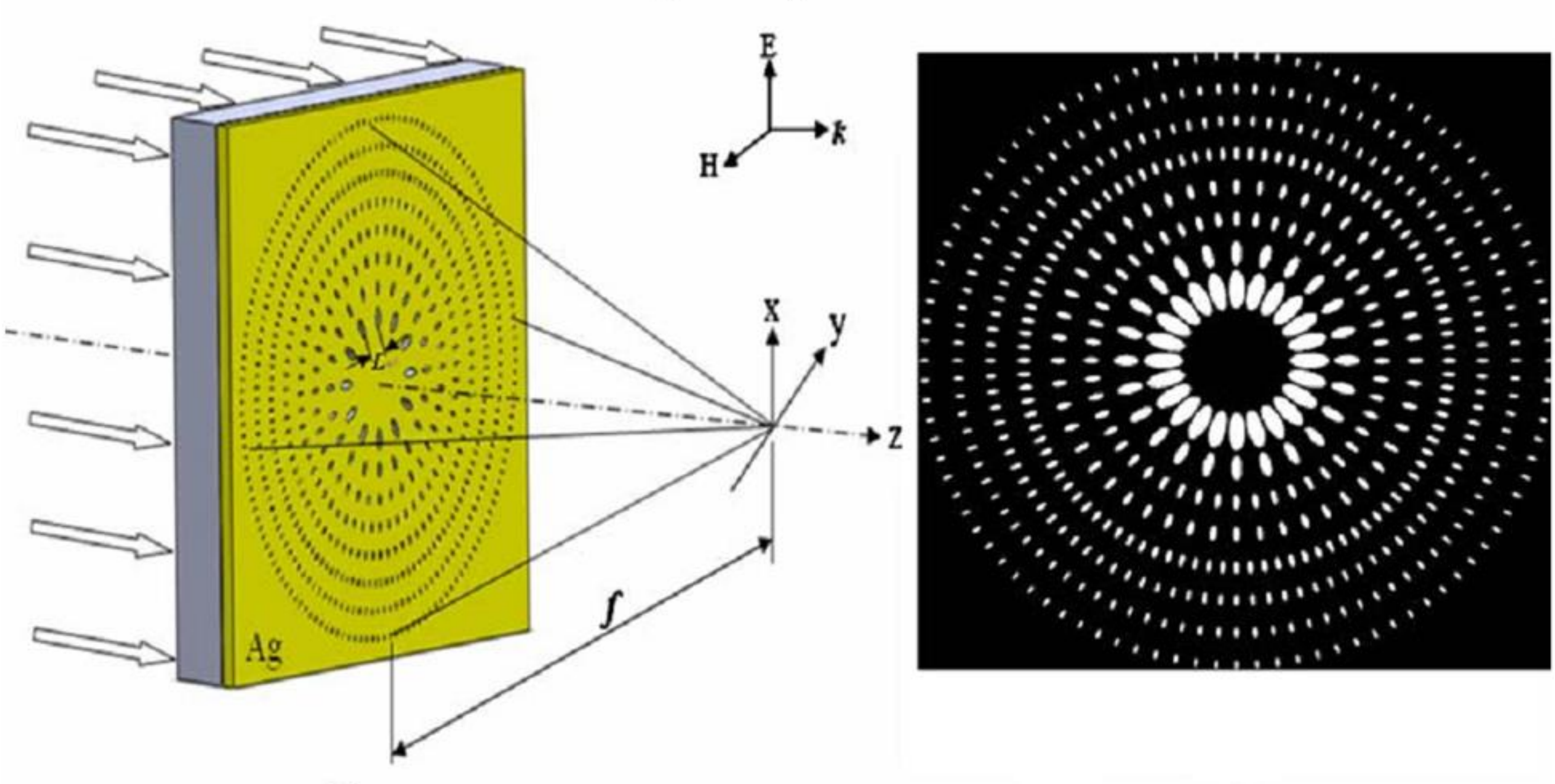
Far-field intensity distribution for PC-VCSEL cavity mode (plot scale in dB).



Time signal showing decay of PC VCSEL cavity mode. The linear slope of the amplitude (plot on a log scale) determines the Q-factor.

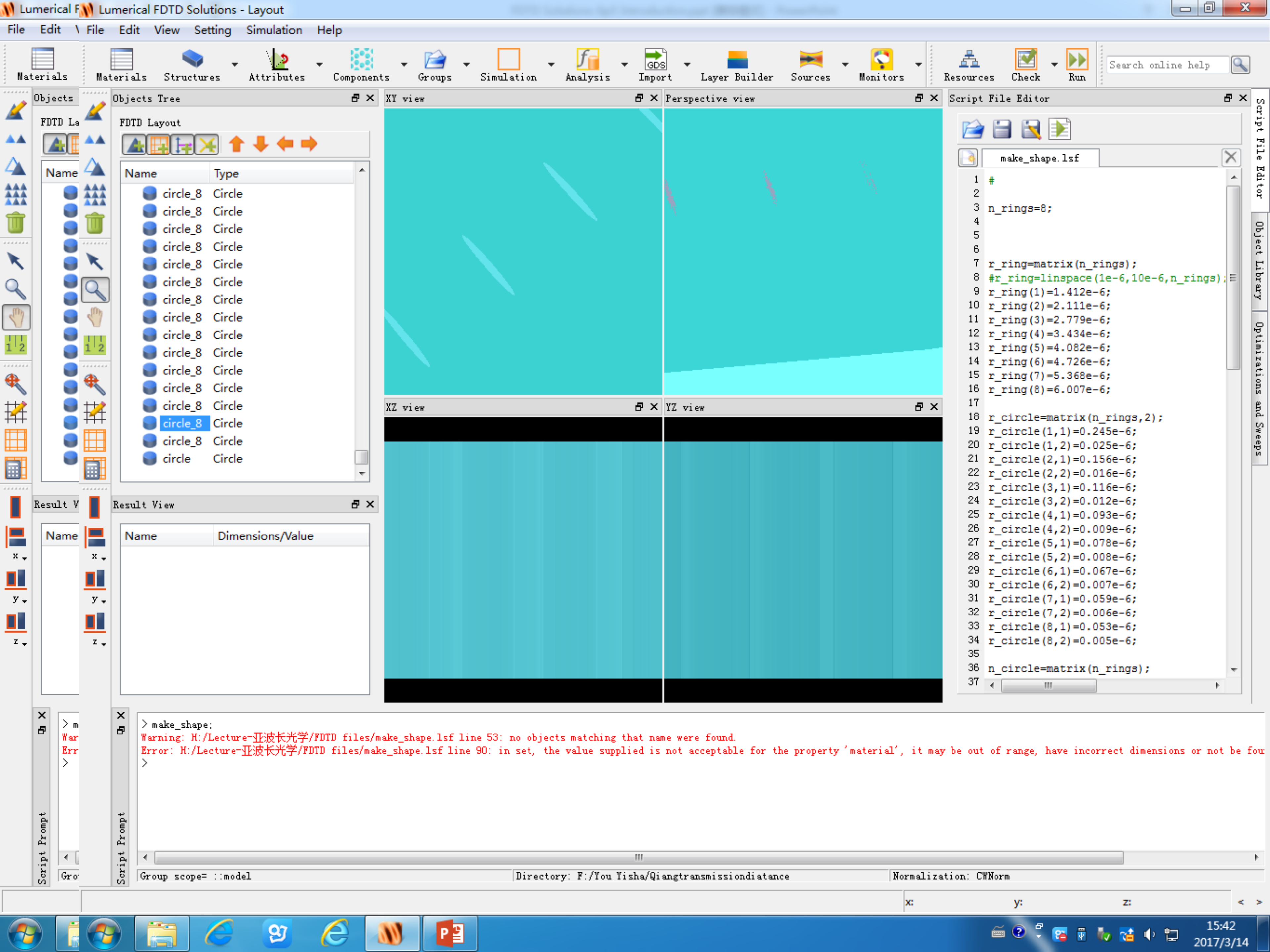
Scripting: Editor and prompt

Structure creation using script



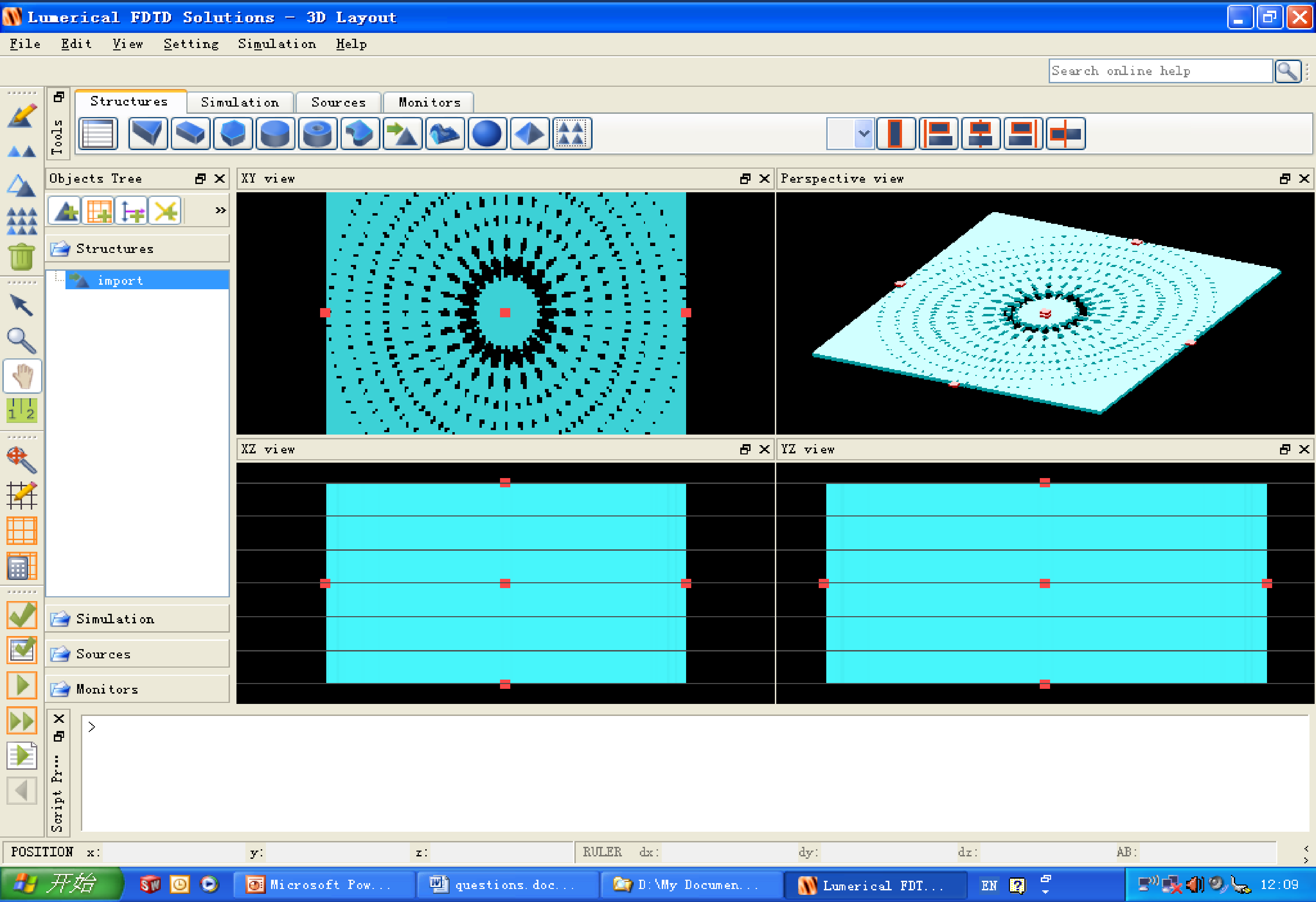
(a) (b)

Zhenkui Shi, **Yongqi Fu**, et. al., Polarization effect on focusing of a plasmonic lens structured with radialized and chirped elliptical nanopinholes. ***Plasmonnics*** 5(2), (2010). (in press)



Lumerical FDTD Solutions - Layout
File Edit View Setting Simulation Help
Materials Structures Attributes Components Groups Simulation Analysis Import Layer Builder Sources Monitors Resources Check Run
Search online help
Objects Tree
FDTD Layout
Name Type
circle_8 Circle
circle_8 Circle
circle_8 Circle
circle_8 Circle
circle_8 Circle
circle_8 Circle
circle_8 Circle
circle_8 Circle
circle_8 Circle
circle_8 Circle
circle_8 Circle
circle_8 Circle
circle_8 Circle
circle_8 Circle
circle_8 Circle
circle Circle
Result View
Name Dimensions/Value
XY view
Perspective view
XZ view
YZ view
Script File Editor
make_shape.lsf
#
n_rings=8;
r_ring=matrix(n_rings);
#r_ring=linspace(1e-6,10e-6,n_rings);
r_ring(1)=1.412e-6;
r_ring(2)=2.111e-6;
r_ring(3)=2.779e-6;
r_ring(4)=3.434e-6;
r_ring(5)=4.082e-6;
r_ring(6)=4.726e-6;
r_ring(7)=5.368e-6;
r_ring(8)=6.007e-6;
r_circle=matrix(n_rings,2);
r_circle(1,1)=0.245e-6;
r_circle(1,2)=0.025e-6;
r_circle(2,1)=0.156e-6;
r_circle(2,2)=0.016e-6;
r_circle(3,1)=0.116e-6;
r_circle(3,2)=0.012e-6;
r_circle(4,1)=0.093e-6;
r_circle(4,2)=0.009e-6;
r_circle(5,1)=0.078e-6;
r_circle(5,2)=0.008e-6;
r_circle(6,1)=0.067e-6;
r_circle(6,2)=0.007e-6;
r_circle(7,1)=0.059e-6;
r_circle(7,2)=0.006e-6;
r_circle(8,1)=0.053e-6;
r_circle(8,2)=0.005e-6;
n_circle=matrix(n_rings);
Script File Editor
Object Library
Optimizations and Sweeps
> make_shape;
Warning: H:/Lecture-亚波长光学/FDTD files/make_shape.lsf line 53: no objects matching that name were found.
Error: H:/Lecture-亚波长光学/FDTD files/make_shape.lsf line 90: in set, the value supplied is not acceptable for the property 'material', it may be out of range, have incorrect dimensions or not be fou
Script Prompt
Group scope= ::model
Directory: F:/You Yisha/Qiangtransmissiondiatance
Normalization: CWNorm
15:42
2017/3/14

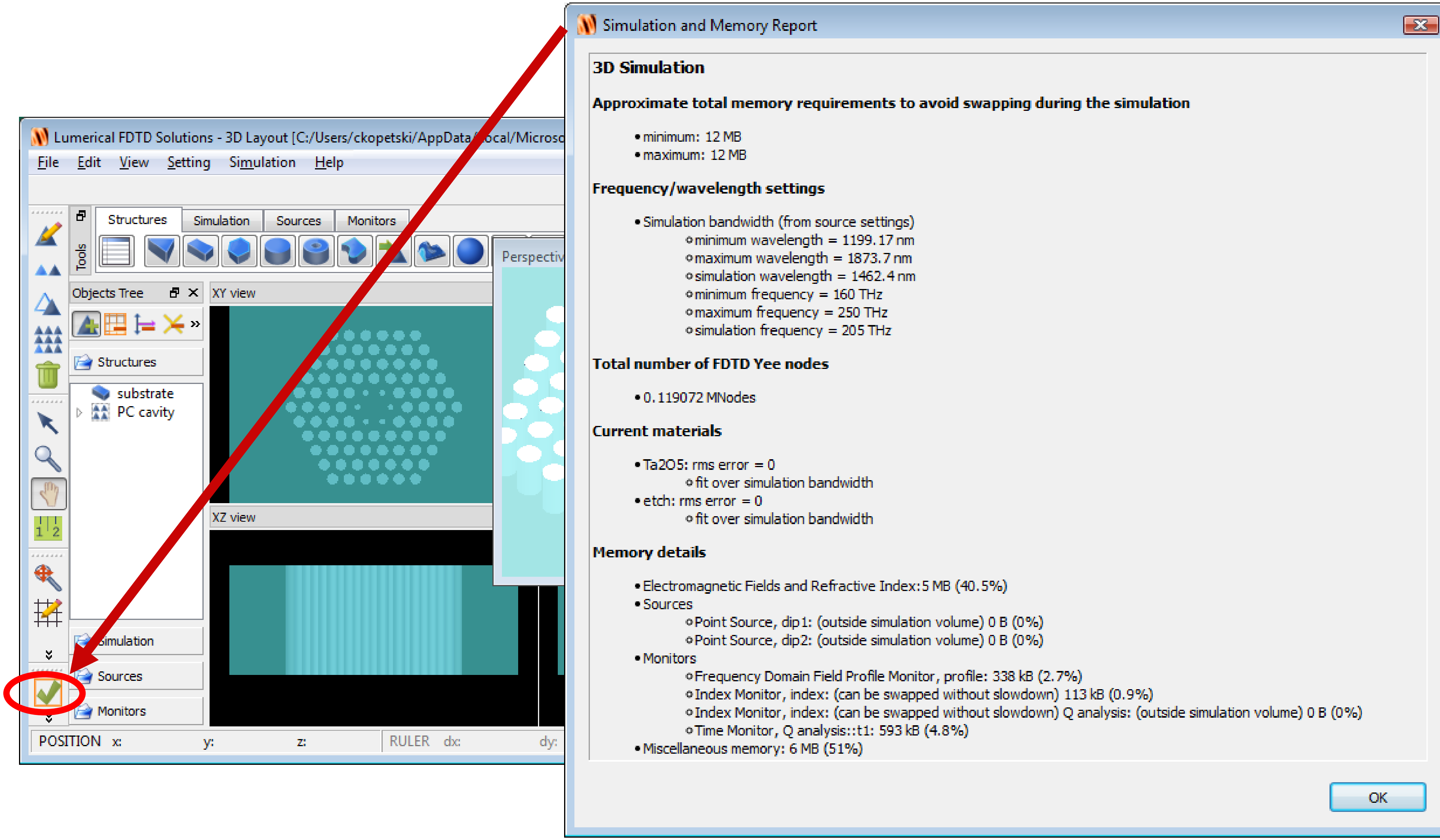
Comparison to the bitmap import method



Review and Tips

- **Review workflow**
  - Frequently asked questions
  - Tips for reducing computational requirements (time and memory)

Computational Resource Requirements



FDTD Solutions: Optimizing Resources

What are some tricks for speeding up FDTD Solutions, and reducing the memory requirements?

- Avoid simulating homogeneous regions with no structure
  - Use far field projections instead
- Use symmetry where possible
  - Gain factors of 2, 4 or 8
- Use periodicity where possible
  - Gain factors of 100s or 1000s
- Enlarge virtual memory of your computer
- Use a coarse mesh (use a refined mesh for final simulations)
  - Start with "mesh accuracy" of 1 instead of 2
    - gives 8 times faster simulation
    - 5 times less memory
    - within 10-20% accuracy in general
  - User mesh accuracy of 2-4 for final simulation
  - Use mesh override regions for local regions of fine mesh

Where to find help and examples

- **Online help** at www.lumerical.com/fdtd_online_help
  - New features summary
  - Installation manual
  - Getting started
  - Reference guide
  - Script function reference
  - User guide
  - Application help

- Application summaries
  - www.lumerical.com/fdtd_applications

Getting help

- Technical Support
  - **Email**: gsun.support@lumerical.com 孙桂林
  - **Online help**: www.lumerical.com/fdtd_online_help
    - Many examples, user guide, full text search, getting started, reference guide, installation manuals
  - Phone: +1-604-733-9006 and press 2 for support

- Sales information: sales@lumerical.com

- Find an authorized sales representative for your region: www.lumerical.com and select **Contact Us**

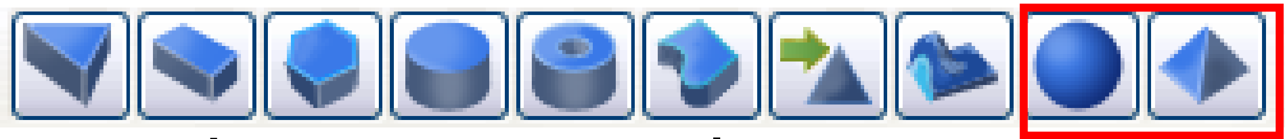
For Your Attention

Thank You

Appendix

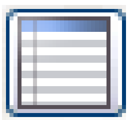
FAQ 1. Creating Physical Structures

- What are the basic primitives used in 2D? In 3D?



3D only

- How do I set material properties?



- How can I easily create layer structures?

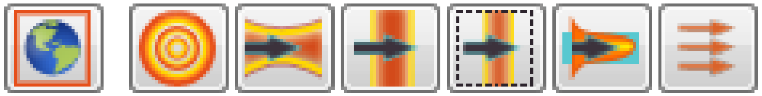
- Can structures be rotated?
  - : **Yes**
- Can I import from a file or image?
  - : **Yes**

FAQ 2. Setting Simulation Parameters

- What mesh size should I use?
  - "mesh accuracy" of 1 or 2 for initial setup (faster)
  - Use "mesh accuracy" of 2-4 for final simulations
  - "mesh accuracy" 5-8 is almost never necessary
    - Use mesh overrides instead for most applications
- How long a simulation time should I use?
  - At least long enough for pulse to propagate throughout simulation volume.
  - Start with longer simulations times and let the "auto-shutoff" feature find out when you can stop the simulation
  - Check with point time monitors
- What boundary conditions should I use?
  - PML allows light to exit simulation region
  - Symmetric/anti-symmetric, periodic, Bloch boundary conditions can save memory and time.

FAQ 3. Using Sources

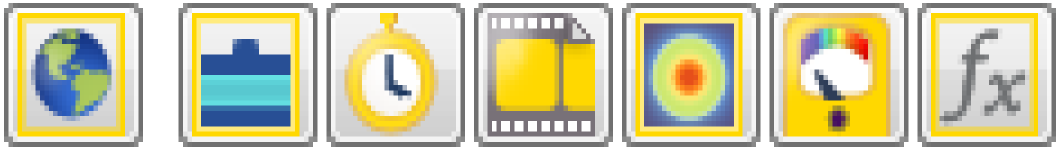
- What sources can I use in FDTD Solutions?



- How do I set the pulse length in time?
  - FDTD Solutions does this automatically when you set wavelength or frequency of interest.
- How can I set a broadband source?
  - Define a range of frequencies and FDTD Solutions creates one for you automatically.
- Can I create my own source spectrum?
  - yes

FAQ 4. Using Monitors

- What monitors can I use in FDTD Solutions?



- When do I choose a power monitor instead of a profile monitor?
  - Power and profile monitors are almost identical and can collect all the same data
  - Power monitors are optimized for the best accuracy when calculating power flow
    - they “snap” to the nearest Yee cell
  - Profile monitors are optimized to preserve perfect field symmetry
    - they can interpolate fields to any location inside the Yee cell

FAQ 5. Running Simulation

- How do I check the memory requirements?
  - On the Simulate menu, left panel 
- How do I reduce memory requirements?
  - Minimize simulation volume using symmetry
  - Decrease the "mesh accuracy" if possible
    - Increases dx, dy and dz
  - Down sample monitors spatially
  - Record fewer frequency points in frequency monitors
  - Record only the necessary field components