lumerical
illuminating the way

FDTD *Solutions*

Introductory Training

Outline

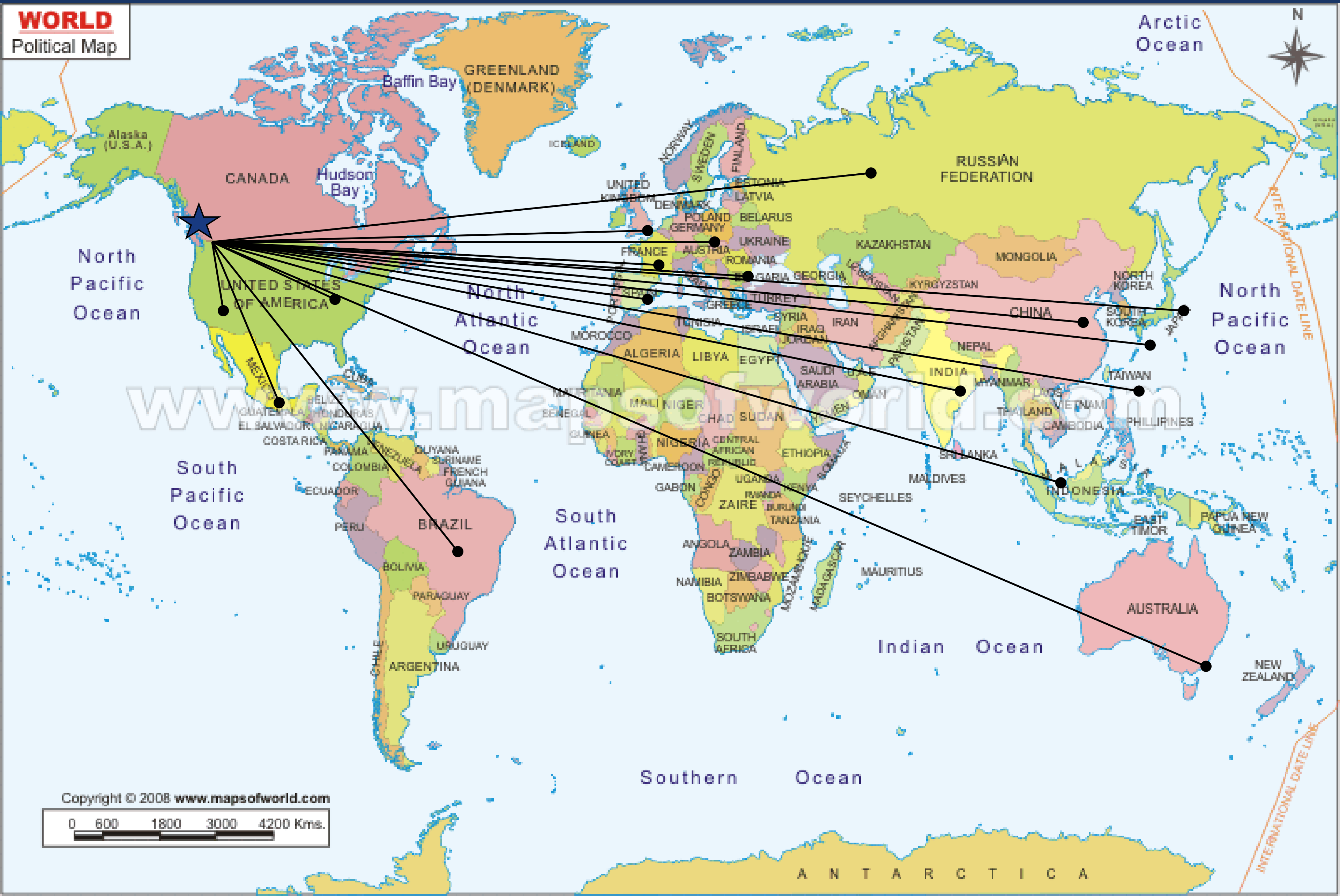
- Introduction: history background, application areas
- Overview of FDTD method
- Install FDTD Solutions
- Features of FDTD Solutions

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

Goals

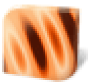
- **Understand the types of problems that require FDTD Solutions.**
- **Learn the fundamentals of the FDTD algorithm**
- **Learn the basic features of FDTD Solutions**
- **Gain initial experience using FDTD Solutions**

Introduction: History and Background



Introduction: History and Background

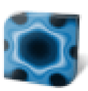
Optical Design Products



FDTD Solutions

Single- and multi-processor finite-difference time-domain (FDTD) optical design software. Advanced material modeling, non-uniform mesh support, and robust parallel processing make this industry's most capable optical simulator.

Product information
Applications library
30-day trial download
(registration required)



MODE Solutions

Accurate and flexible mode solver technology for the design and analysis of guided-wave optical devices. Its intuitive user interface allows component designers to quickly prototype new device concepts.

Product information
Applications library
30-day trial download
(registration required)

Lumerical empowers designers with best-in-class optical design software and support services to develop next generation micro/nanoscale photonic technologies.

Customer Successes

"As devices shrink, choosing the appropriate design technique is crucial. Lumerical delivers easy-to-use design software for microscale optical components.
K.Y. Kim, Samsung

"FDTD Solutions is a powerful optical simulation package that offers efficient parallel computation, an intuitive user interface, and a versatile scripting environment.
Y. T., Olympus

"[Lumerical's] technical support is second to none.
E. Chow, Agilent

"Lumerical provides extremely fast single and multi-processor software to speed your design efforts.
H. Greiner, Philips

"The ease with which new design concepts can be tested using Lumerical's software is a refreshing change from the usual.
S. Bidnyk, Enablence

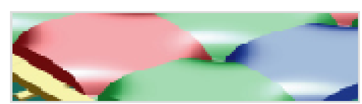
Technology Trends

FDTD Solutions 500%+ faster via Intel's Nehalem

Relatively inexpensive computing systems, like the the Xeon 5500 series HPC workstation tested, offer tremendous 6-fold speed improvements over processors only 12-18 months older.

FDTD Solutions leverages new multi-core processors

Recent benchmarks of FDTD Solutions on Intel's Core i7 processor demonstrate a 3 times performance improvement when running in parallel. Read what is in store for parallel computation on these new multi-core processors.



Overcoming the Multi-Wavelength Challenge

A single time-domain simulation delivers accurate broadband results, but only if the materials models are accurate over a wide wavelength range. Learn how multi-coefficient materials enable

FDTD Solutions Training

March 17 & 18th, 2010:
Taiwan

March 29 & 30th, 2010:
Wuerzburg, Germany

In the Literature

"FDTD-based optical simulations methodology for CMOS image sensors pixels architecture and process optimization"

"Design principles for particle plasmon enhanced solar cells"

Featured publication list

Lumerical News

February 22nd, 2010: Lumerical partners with the NNIN/C at Harvard University to boost US-based nanophotonics research. More

February 3rd, 2010: To benefit UK academic researchers, Lumerical Solutions has donated ten FDTD Solutions Engine licenses to ScotGrid, one of the largest grid computing sites in the United Kingdom. More

November 19th, 2009: Lumerical donates FDTD Engines to Compute/Calcul Canada, enabling

Internet

Introduction: History and Background

Contact details

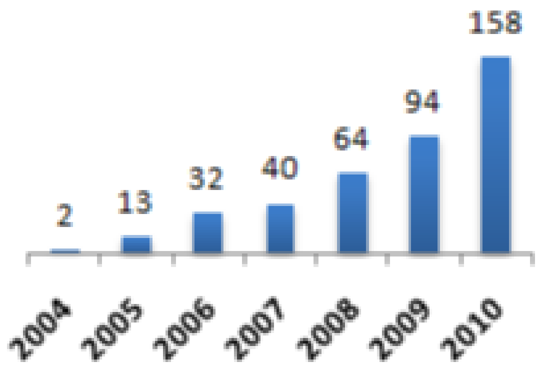
Privacy policy
Site map

Biophotonics
Imaging
Integrated Optical Devices, Cavities, and Lasers
Lighting and Display Applications
Metamaterials
Microstructured Optical Fiber Devices
Novel Applications
Photonic Crystal Devices
Photovoltaic Solar Cells
Surface Plasmon Devices

Can't find your paper?

Contact Technical support with the citation and we will add your paper to our list below.

Featured Publications



Biophotonics

K. Aslan, M. J. R. Previte, Y. Zhang and C. D. Geddes, "Microwave-accelerated surface plasmon-coupled directional luminescence 2: A platform technology for ultra fast and sensitive target DNA detection in whole blood," Journal of Immunological Methods 331, 103-113 (2008)

M. H. Chowdhury, S. K. Gray, J. Pond, C. D. Geddes, K. Aslan, and J. R. Lakowicz, "Computational study of fluorescence scattering by silver nanoparticles," J. Opt. Soc. Am. B 24, 2259-2267 (2007) http://www.opticsinfobase.org/abstract.cfm?URI=josab-24-9-2259

M. H. Chowdhury, J. Pond, S. K. Gray and J. R. Lakowicz, "Systematic Computational Study of the Effect of Silver Nanoparticle Dimers on the Coupled Emission from Nearby Fluorophores", J. Phys. Chem. C., 112(30), 11236-11249 (2008). http://pubs.acs.org/cgi-bin/abstract.cgi/jpccck/2008/112/i30/abs/jp802414k.html

Mustafa H. Chowdhury, Krishanu Ray, Stephen K. Gray, James Pond and Joseph R. Lakowicz, "Aluminum Nanoparticles as Substrates for Metal-Enhanced Fluorescence in the Ultraviolet for the Label-Free Detection of Biomolecules," Analytical Chemistry 2009 81 (4), 1397-1403

S. Mandal and D. Erickson, "Nanoscale optofluidic sensor arrays," Opt. Express 16, 1623-1631 (2008) http://www.opticsinfobase.org/abstract.cfm?URI=oe-16-3-1623

Total SCI papers:

(2003-2010)

~300

Internet

Introduction: History and Background

Our Products

FDTD Solutions: Single and multi-processor finite-difference time-domain optical design software.
Product Details | Trial Download

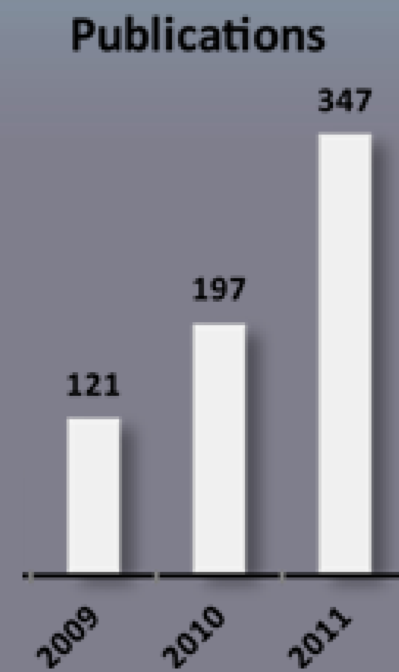
MODE Solutions: Waveguide eigenmode solver and omni-directional broadband propagator design software.
Product Details | Trial Download

INTERCONNECT: Optoelectronic and photonic integrated circuit (PIC) design software package.
Product Details | Trial Download

DEVICE: Powerful semiconductor TCAD device simulation software for silicon-based optoelectronic structures.
Product Details | Trial Download

Proven, Trusted Technology

Our products have been referenced in more than 1,000 scientific publications and patents. With references growing faster than 70% per year, the photonic research and design community is increasingly selecting Lumerical as their design software solution of choice.



Explore how our products can help you ⇒

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:

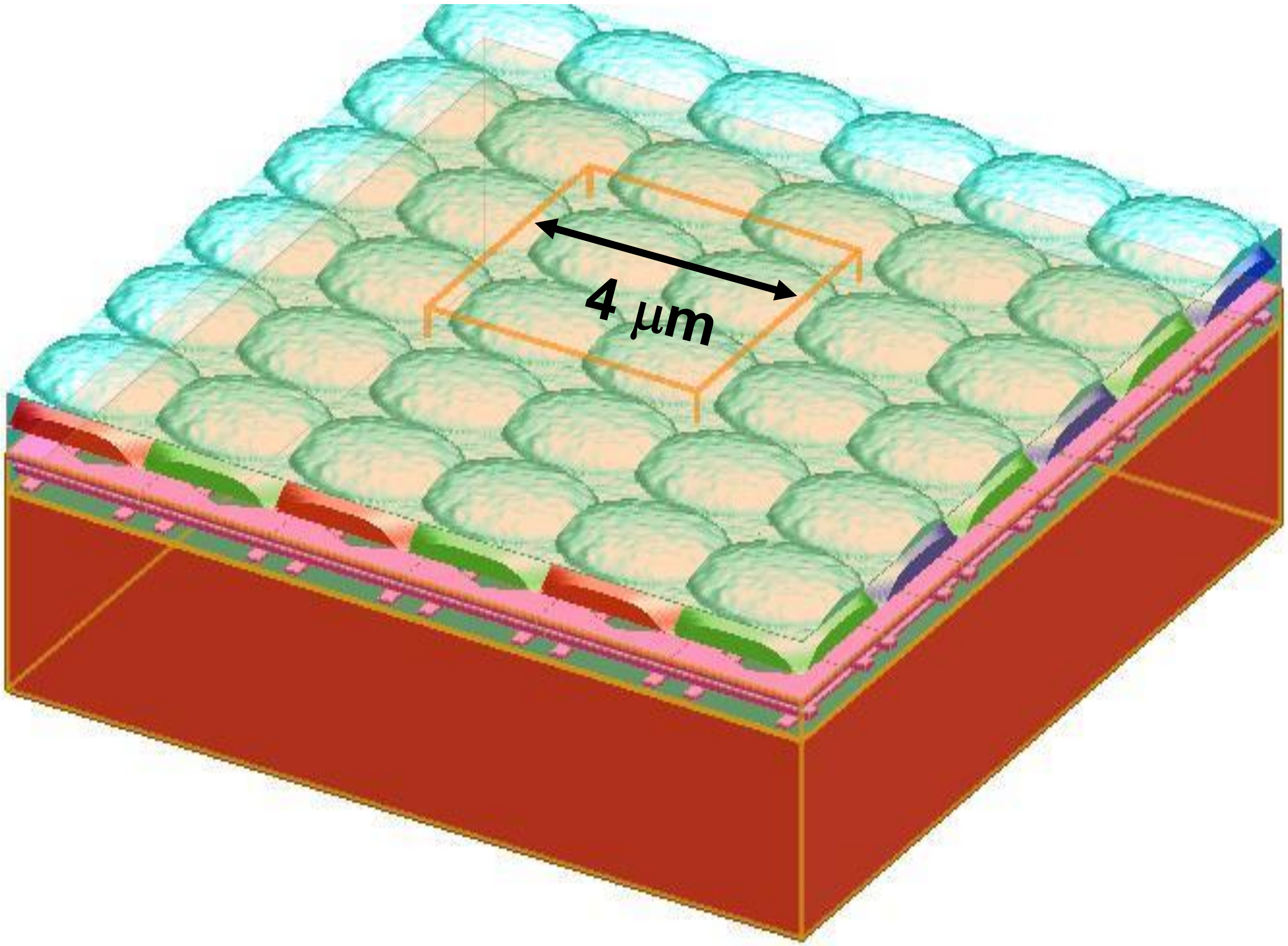
What features are common points among these applications?

(When do you need to use FDTD Solutions?)

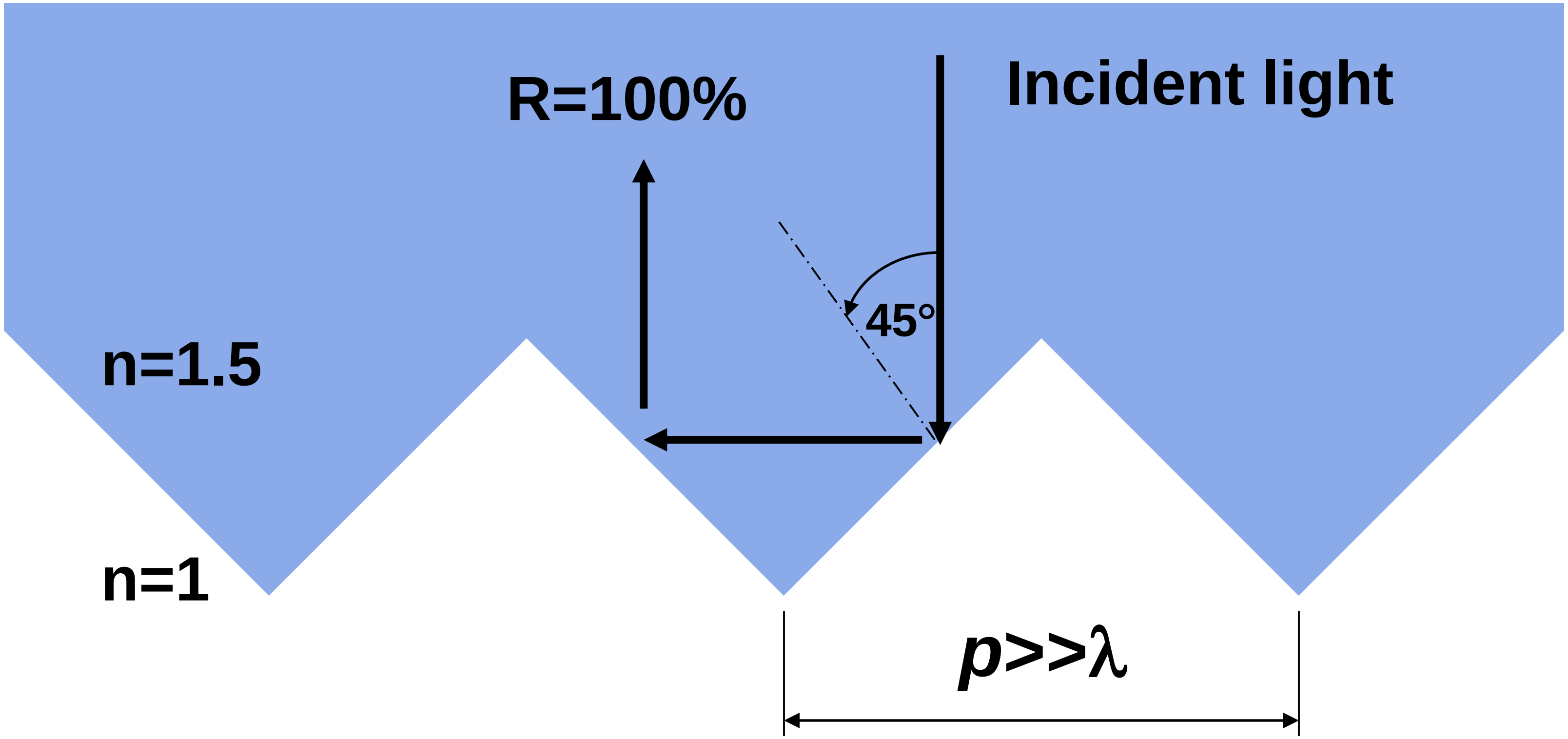
Answer: ???

Wave Optics vs. Ray tracing

Source λ = 0.55 μm



Wave Optics vs. Ray tracing

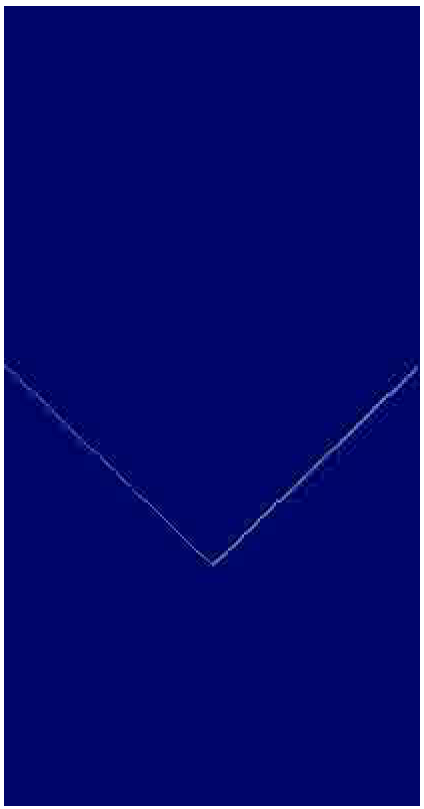


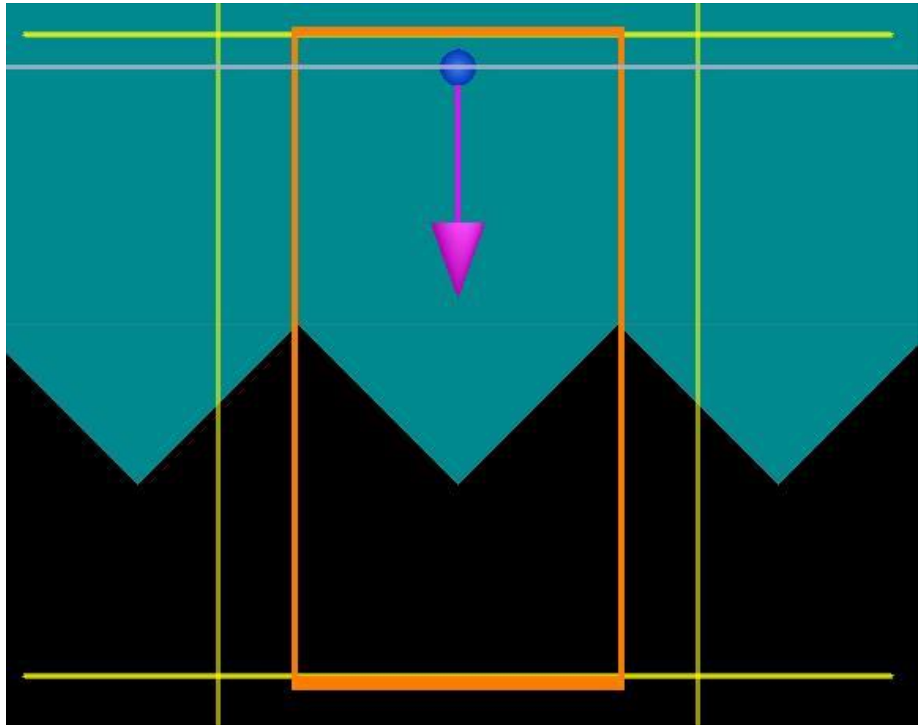
Snell's Law gives

θ_c: 41.8°

Wave Optics vs. Ray tracing

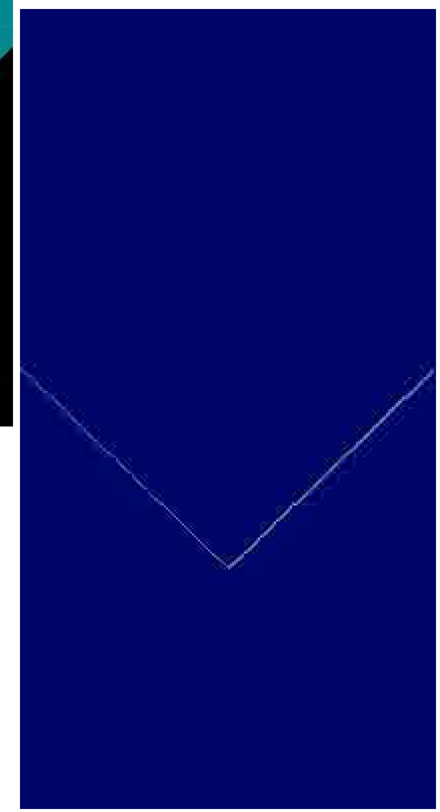
λ = 0.4 μm





20 μ m

λ = 4 μ m



Wave Optics vs. Ray tracing

Conclusion:

You need FDTD Solutions when feature sizes *p* are on the order of a wavelength $p \sim \lambda$, and $p < \lambda$.

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):	$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$	$\oint_C \mathrm{H} \cdot d\mathrm{l} = \int_S \mathrm{J} \cdot d\mathrm{A} + \frac{d}{dt} \int_S \mathrm{D} \cdot d\mathrm{A}$

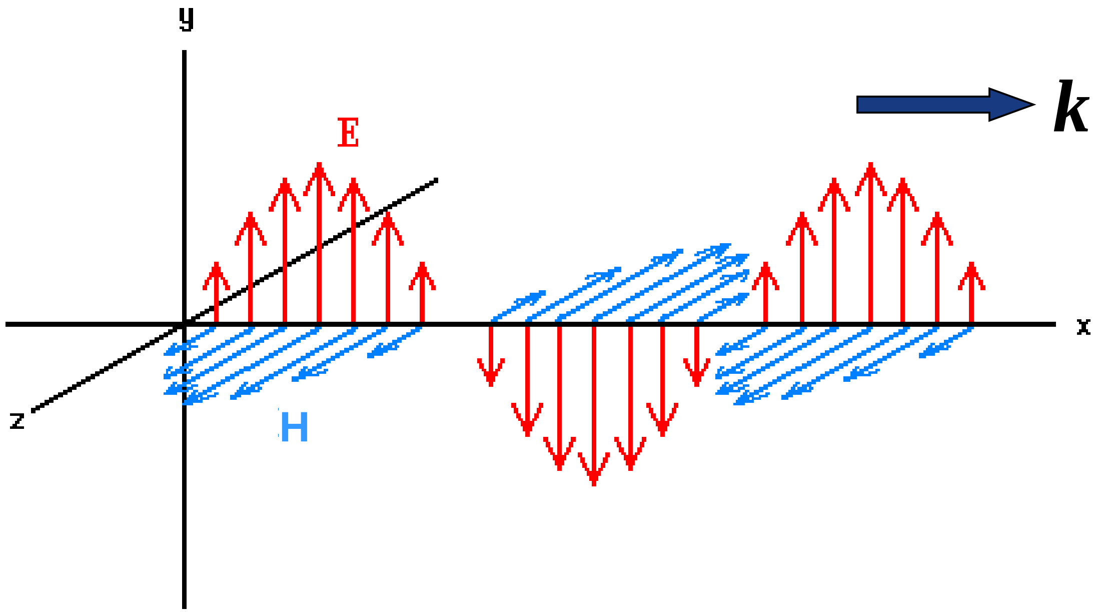
Maxwell’s Equations

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:

$\boldsymbol{\varepsilon}$ 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 ——Concept introduction

- **FDTD algorithm**：was put forth by K.S.Yee in 1966. It directly solve Maxwell equation using differential equations to solve the problems of beam propagation in medium, reflection, and transmission.

- **Basic idea**：based on finite element method，using Yee cell to calculate each spatial node. Meanwhile, the nodes are alternatively sampled for E and H calculation. Thus Maxwell wiring equations are changed to be discrete differential equations. Calculation is greatly simplified compared to previous solving wave equation.

Methodology：

FDTD algorithm directly replace differential form of Maxwell wiring equations using finite differential equations to obtain finite differential formula for field components. Using the same electric parameters to simulate the targets, selecting suitable spatial boundary conditions and fields initial values, obtain $\mathbf{E}(x,y,z,t)$ in time domain and 3D spatial domain after FFT.

Basic principle of FDTD

6 scalar equations:

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

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

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

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

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

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

Maxwell方程组

Vector equations:

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

From Maxwell wiring equations to deduce 6 coupling equations

FDTD ——concept intrduction

FDTD basic equations

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

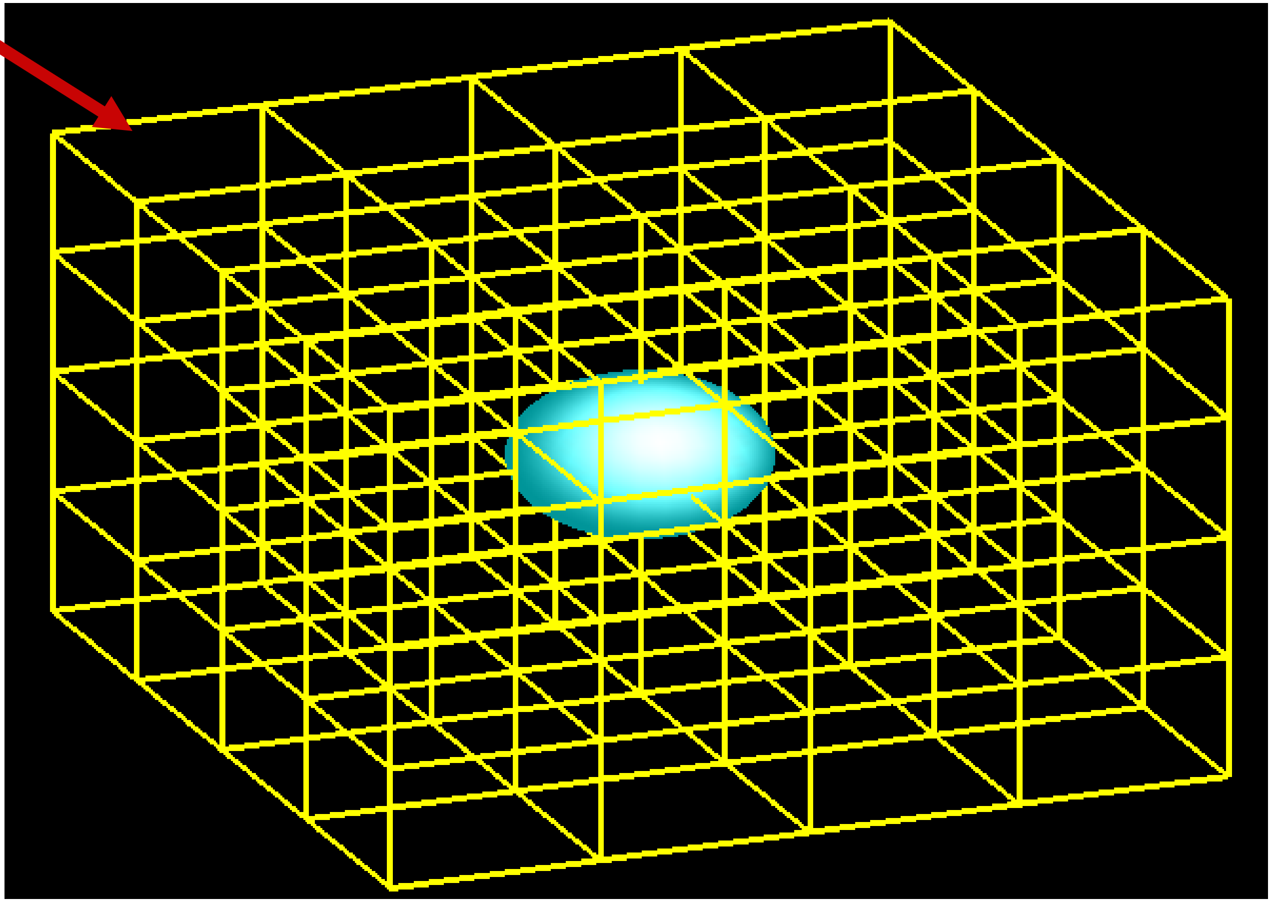
$$\frac{H_{y(t;x+\Delta x,y,z)}-H_{y(t;x-\Delta x,y,z)}}{2\Delta x}-\frac{H_{x(t;x,y+\Delta y,z)}-H_{x(t;x,y-\Delta y,z)}}{2\Delta y}=\tilde{\varepsilon}(x,y,z)\frac{E_{z(t\_\Delta t;x,y,z)}-E_{z(t-\Delta t;x,y,z)}}{\Delta t}$$

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

Maxwell Equations on a mesh

Yee cell

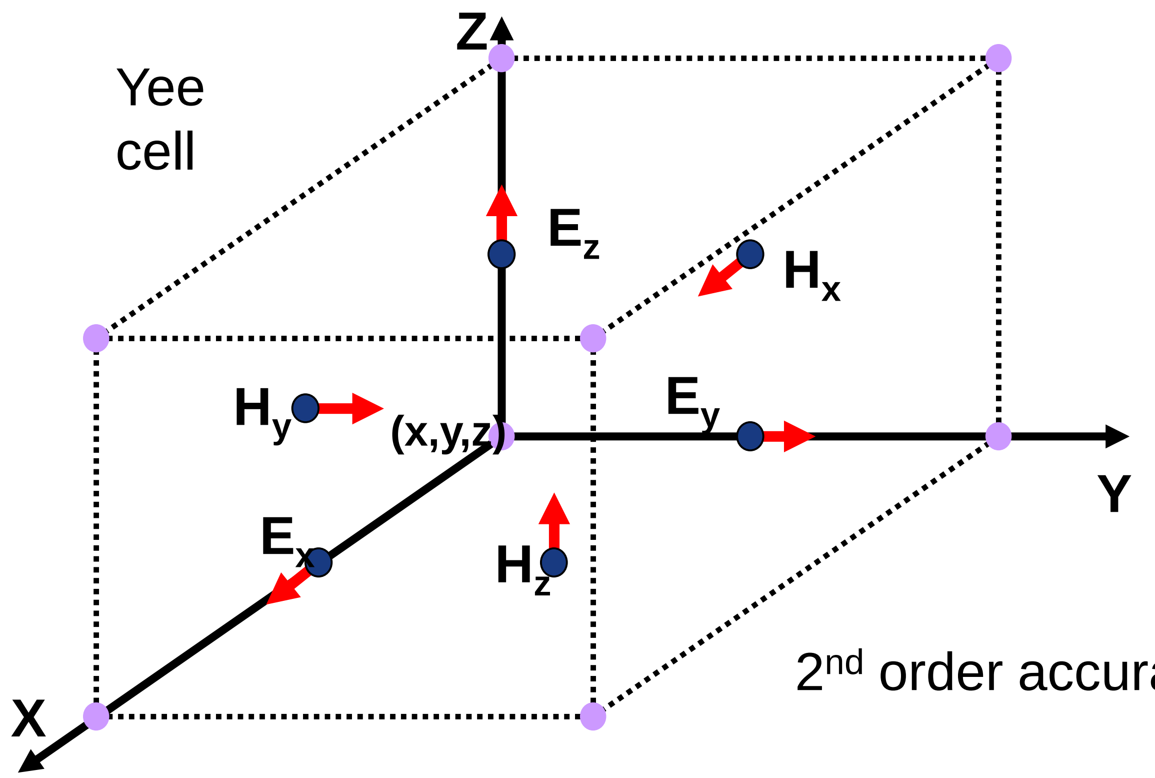
⇨ **E** and **H** are discrete in space



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 directly solve Maxwell equations: vector method

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

Firstly, discrete E 和 H in time domain

$$E(t) \to E^{n\Delta t} \qquad H(t) \to H^{(n+\frac{1}{2})\Delta t}$$

Basic stepping relation in FDTD：

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

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

Frog jumping—data iteration，
No need to solve the matrix

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

Accuracy in time is: ~ Δt^2

How the FDTD method works?

In order to make sure stability of time step in the long time calculation, time increament **Δt** should satisfy the following formula：

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

i.e.： if Δx_{min}, Δy_{min}, Δz_{min} are variable, select the minimum value for the time **Δt** calculation.

"Auto shutoff "function to ensure the time in the software of FDTD Solution

FDTD Solutions: unique features

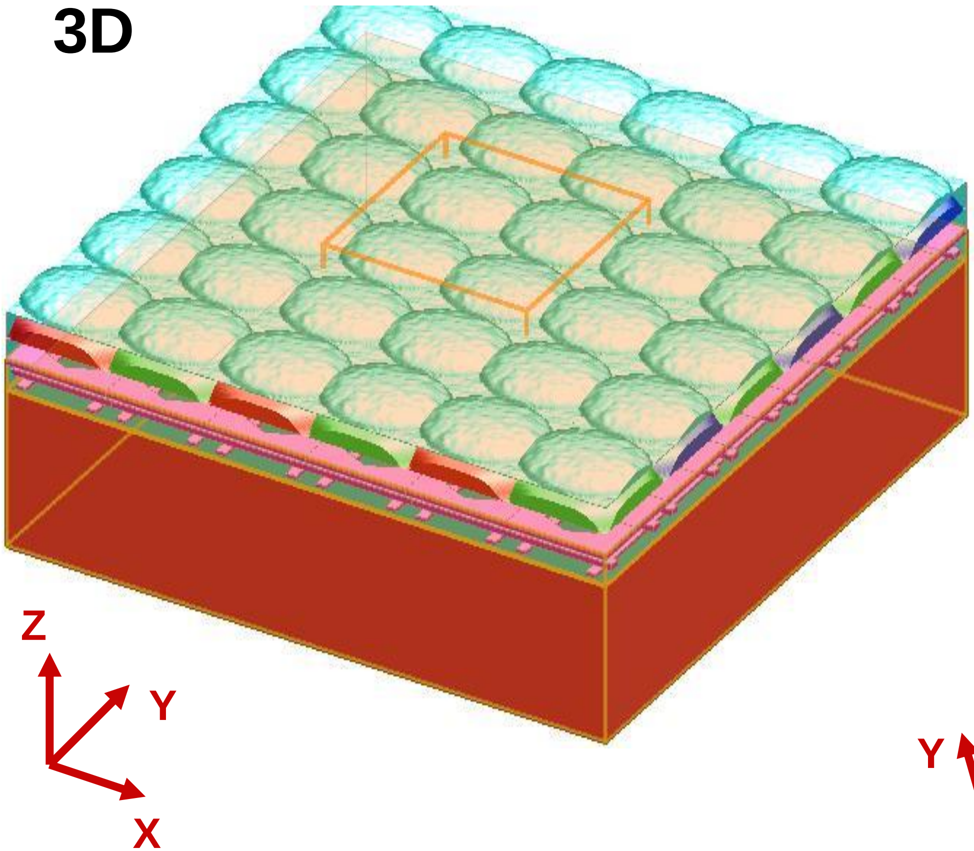
- *Fastest*
  - Parallelism/very short pulse/*automatic grading mesh*/BCs/(real E,H)
- Accurate
  - Full-vectorial accuracy (staircasing: average & 1/0?)
- Multi-wavelength analysis & Broadband
  - Accurate *broadband modeling* of dispersive materials and devices
- Geometric objects
  - Representation 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*

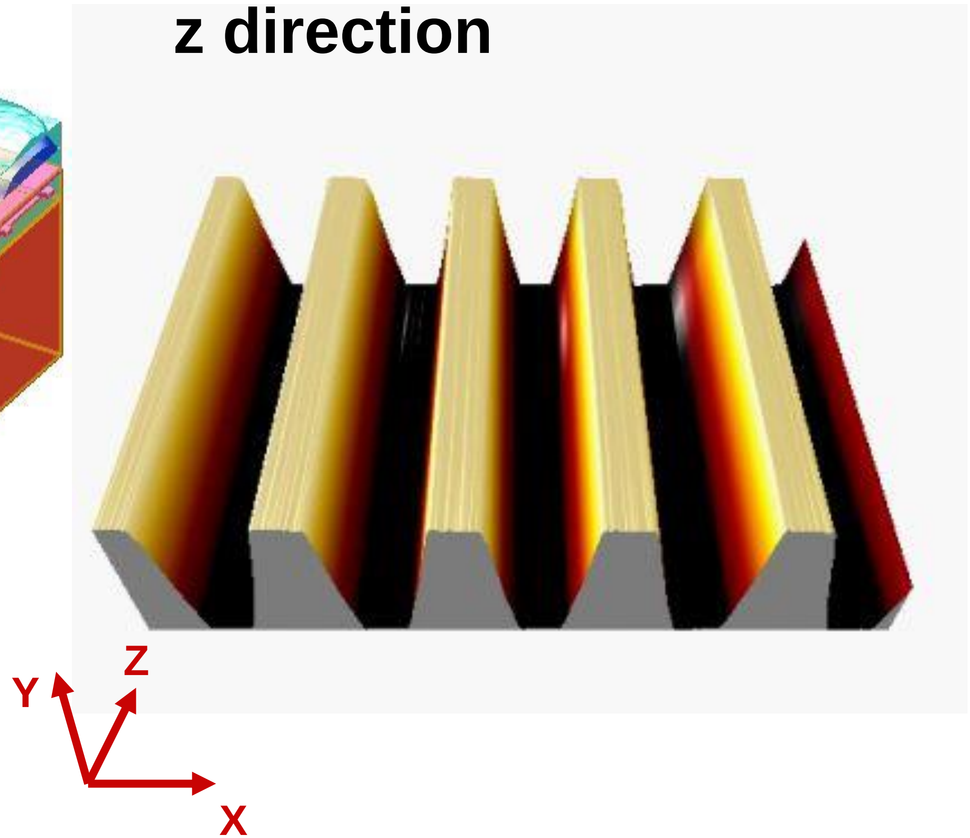
2D vs. 3D

- **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.

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:

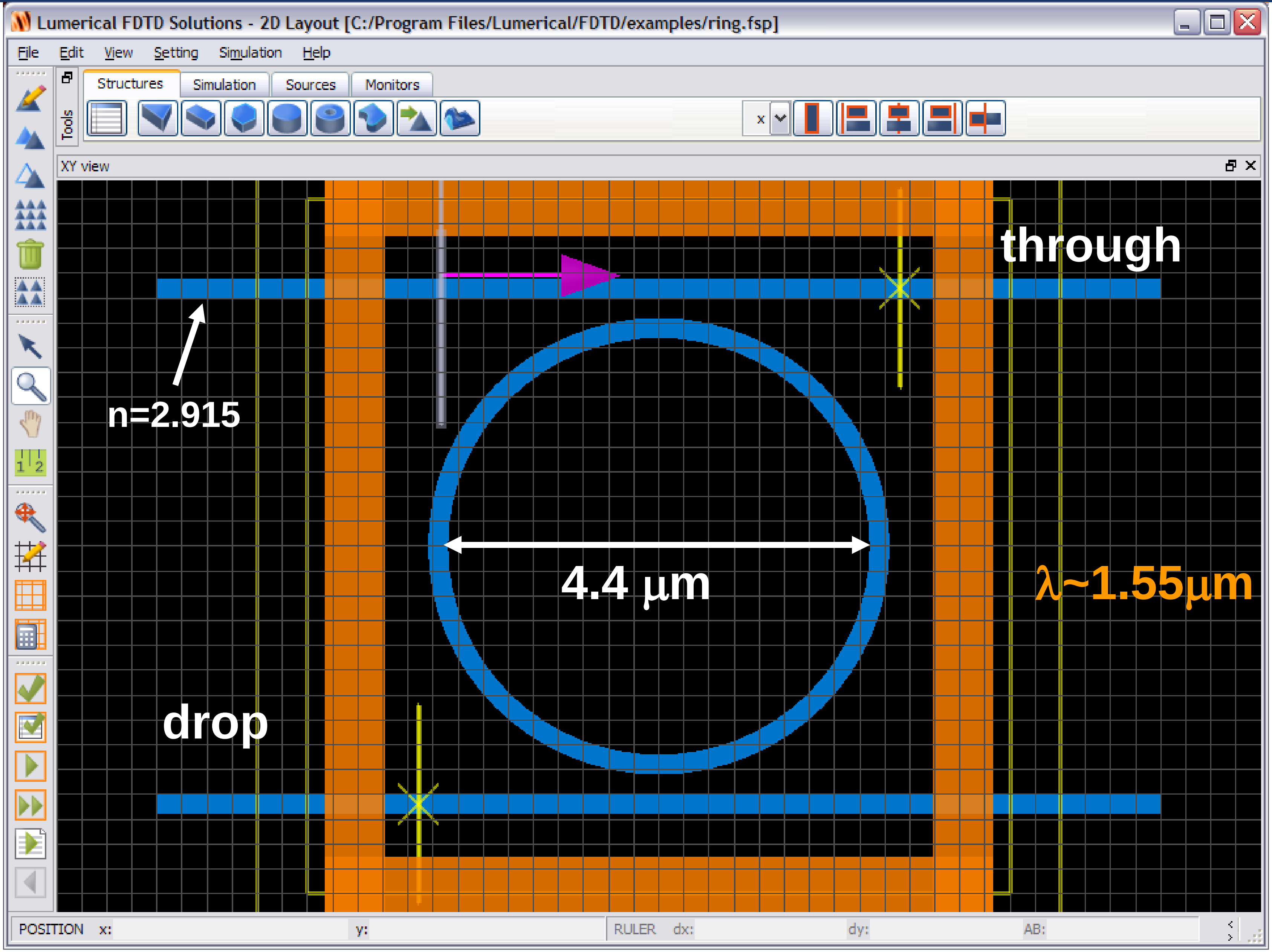
1. Ability to distribute optimizations and parameter sweeps
2. Movie monitors in parallel simulations
3. New script commands

New version improvements

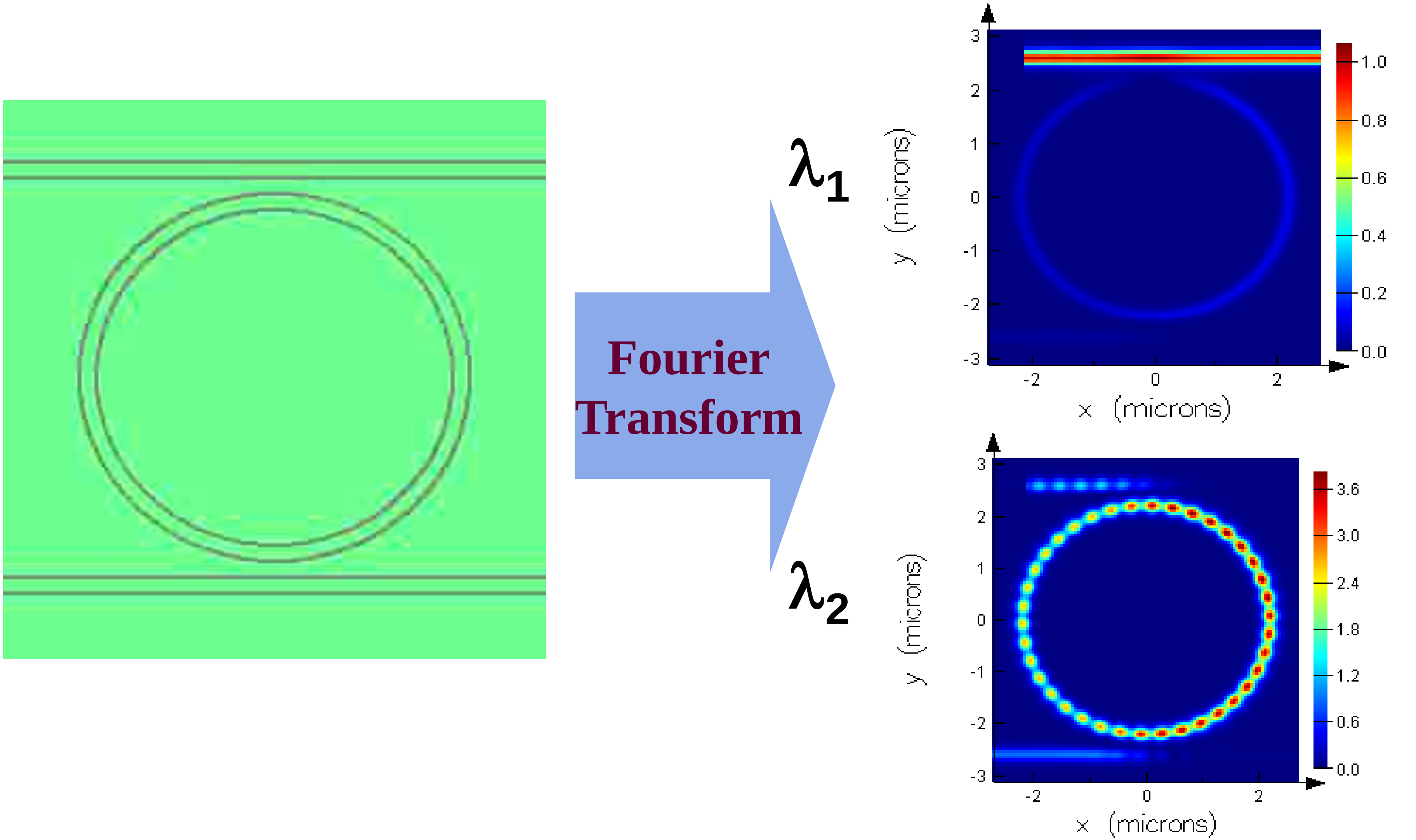
FDTD Solution 8.0:

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

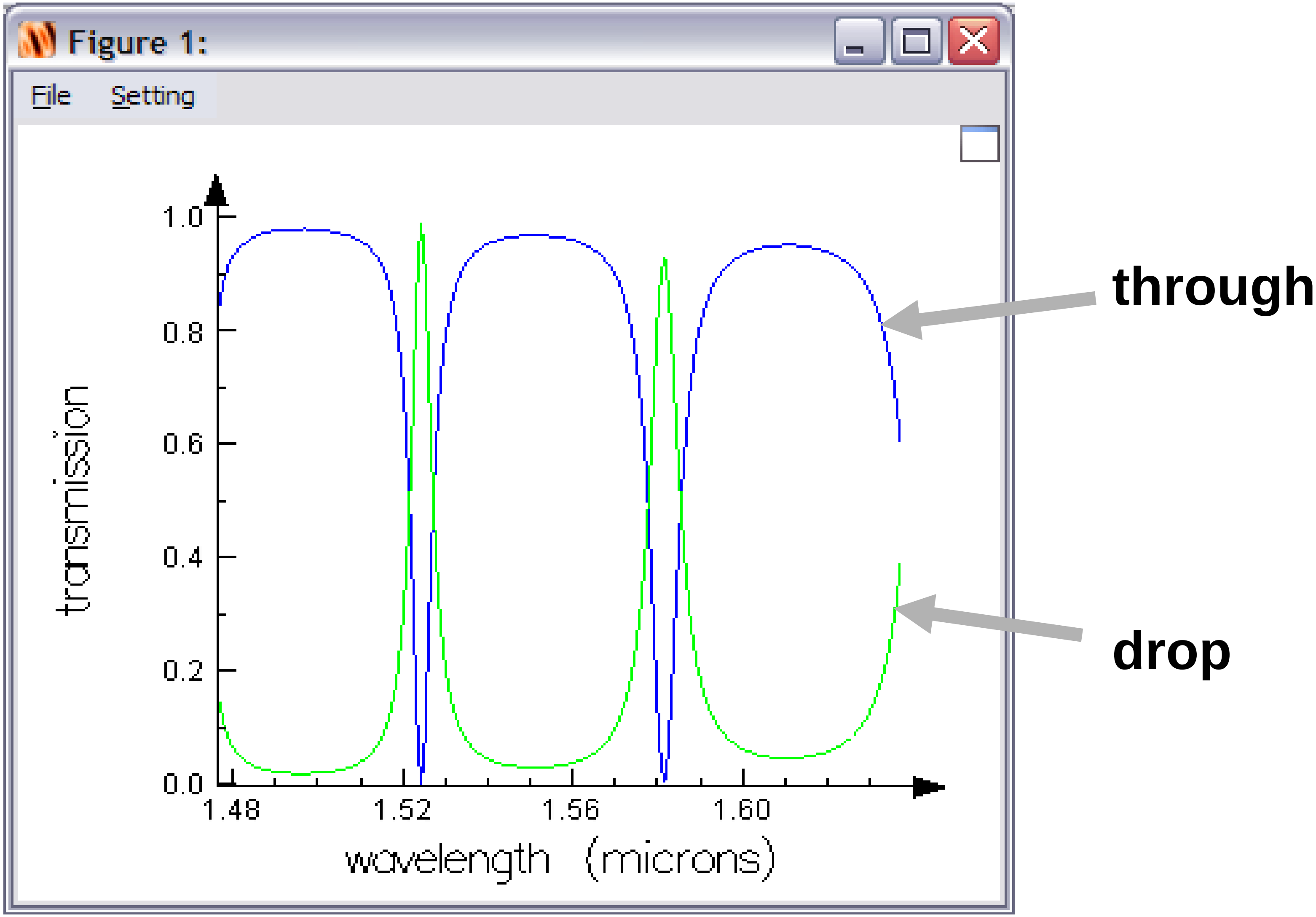
Example, ring resonator



Example: waveguide ring resonator



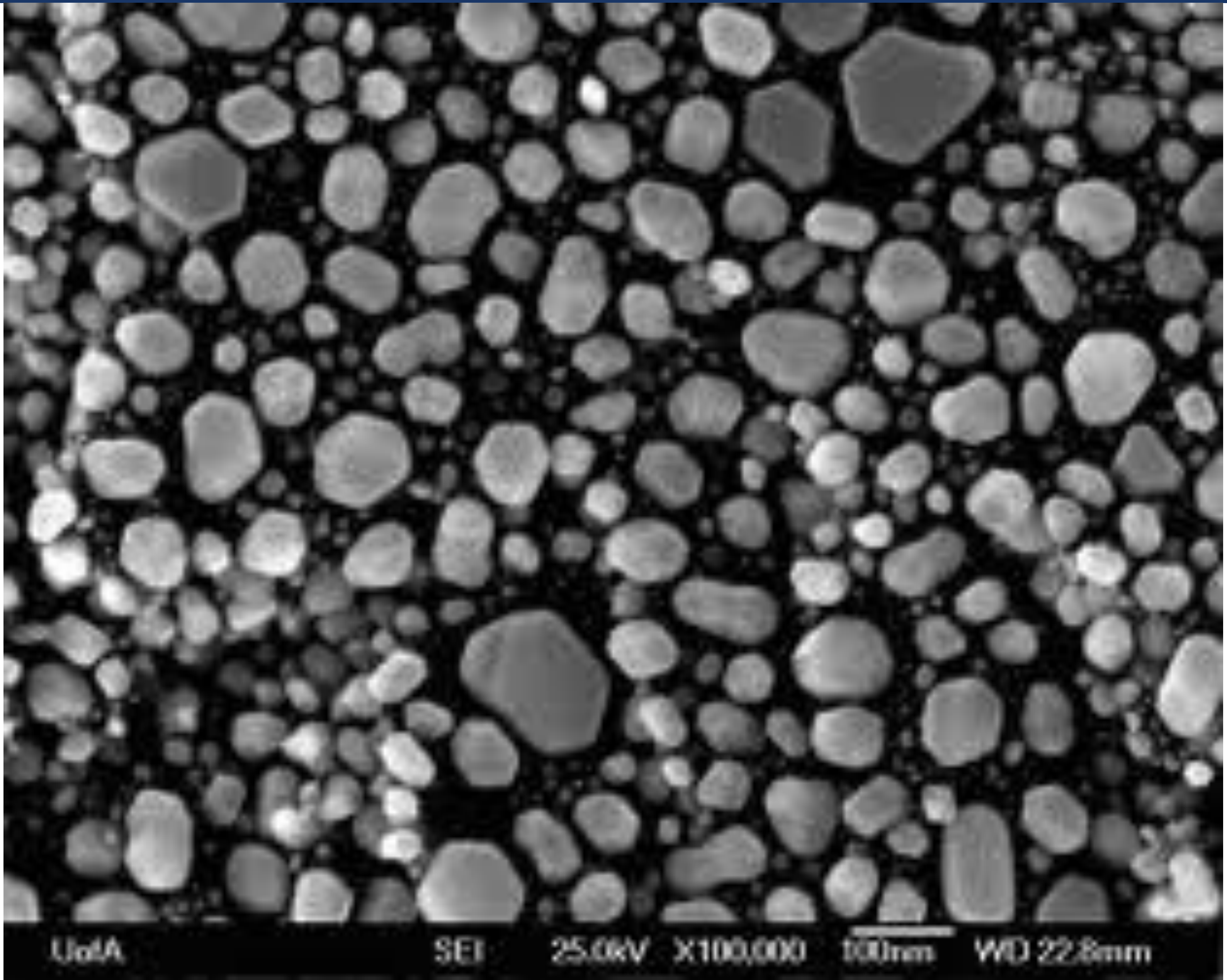
Example: waveguide ring resonator



Install FDTD Solutions

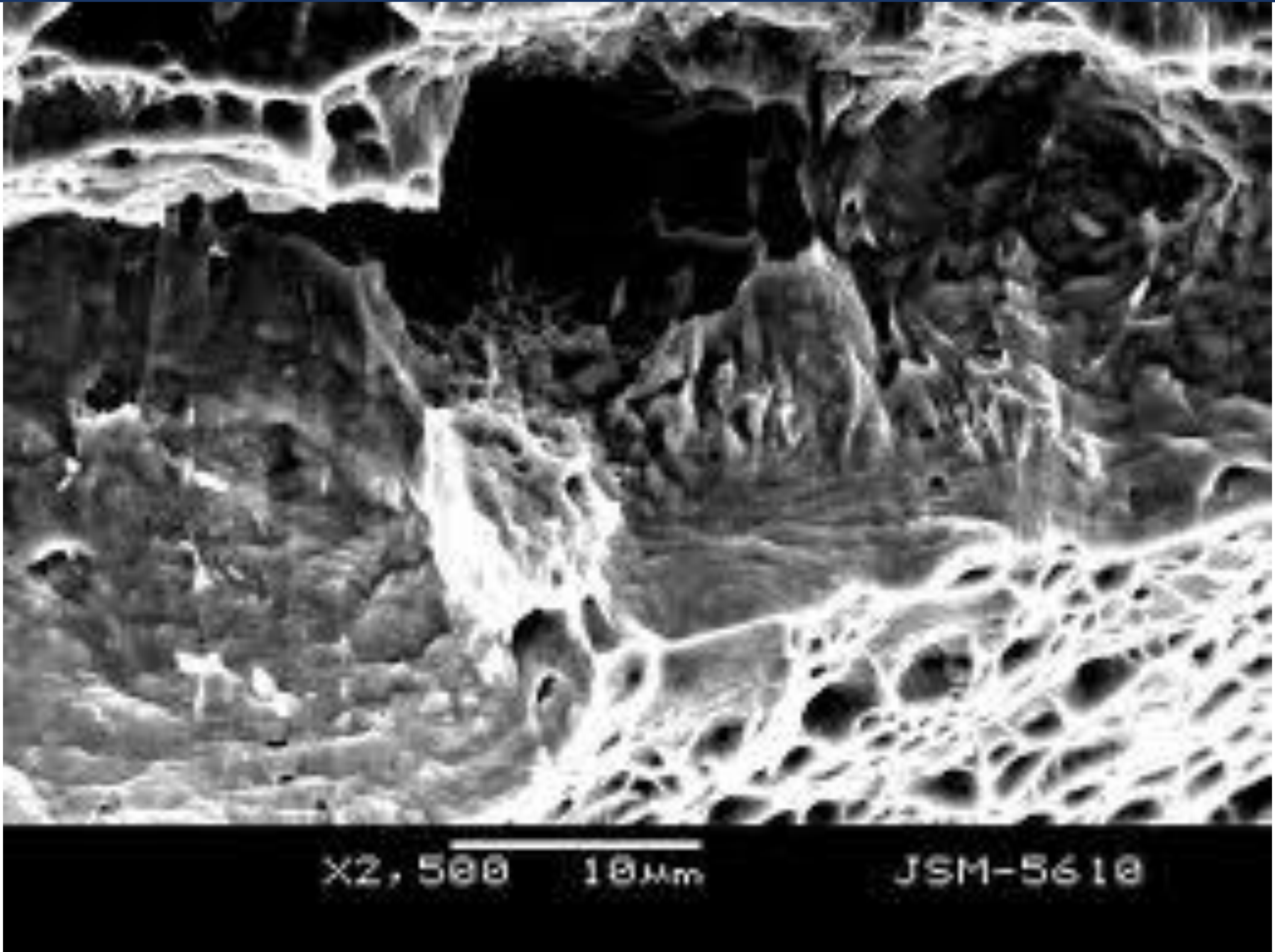
- We will now take a quick break and install FDTD Solutions on your computers.
- A portable license will be used.
- You will need a product CD and Hardware Key.

Function of import image



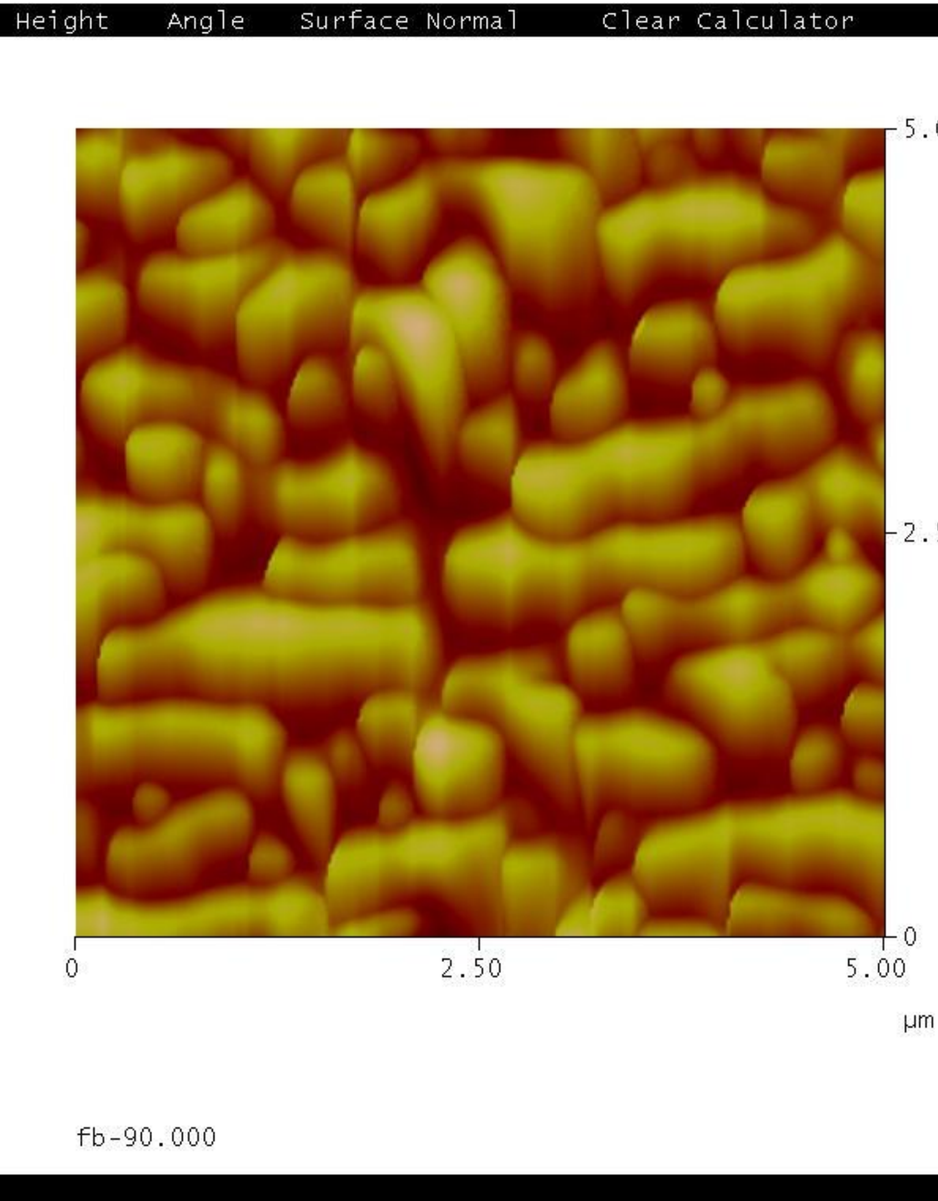
Top view SEM image

Function of import image

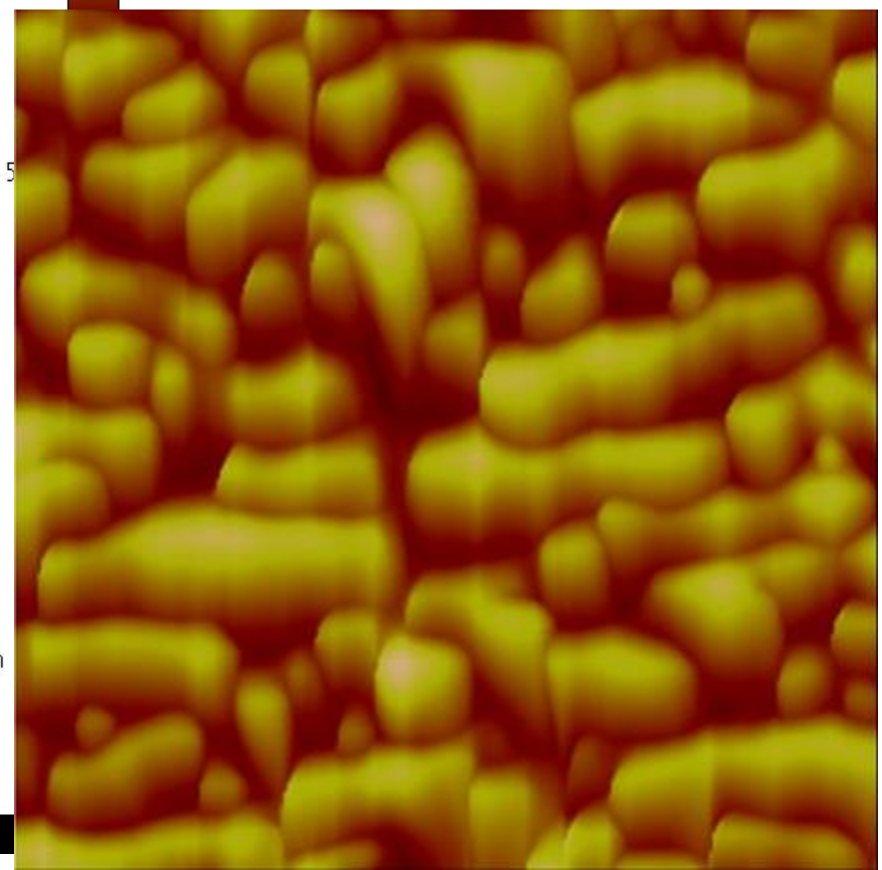


Side view SEM image

Function of import image



AFM image



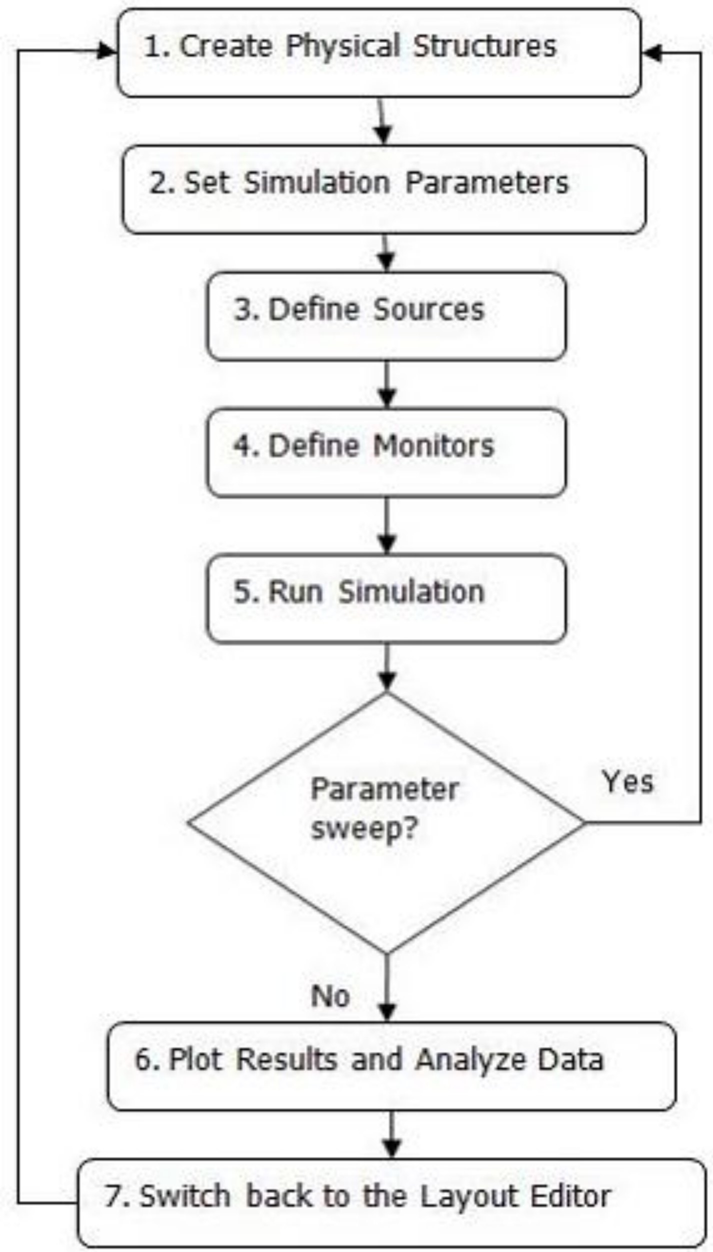
FDTD Solution onsite demonstration

FDTD *Solutions* **7.5**

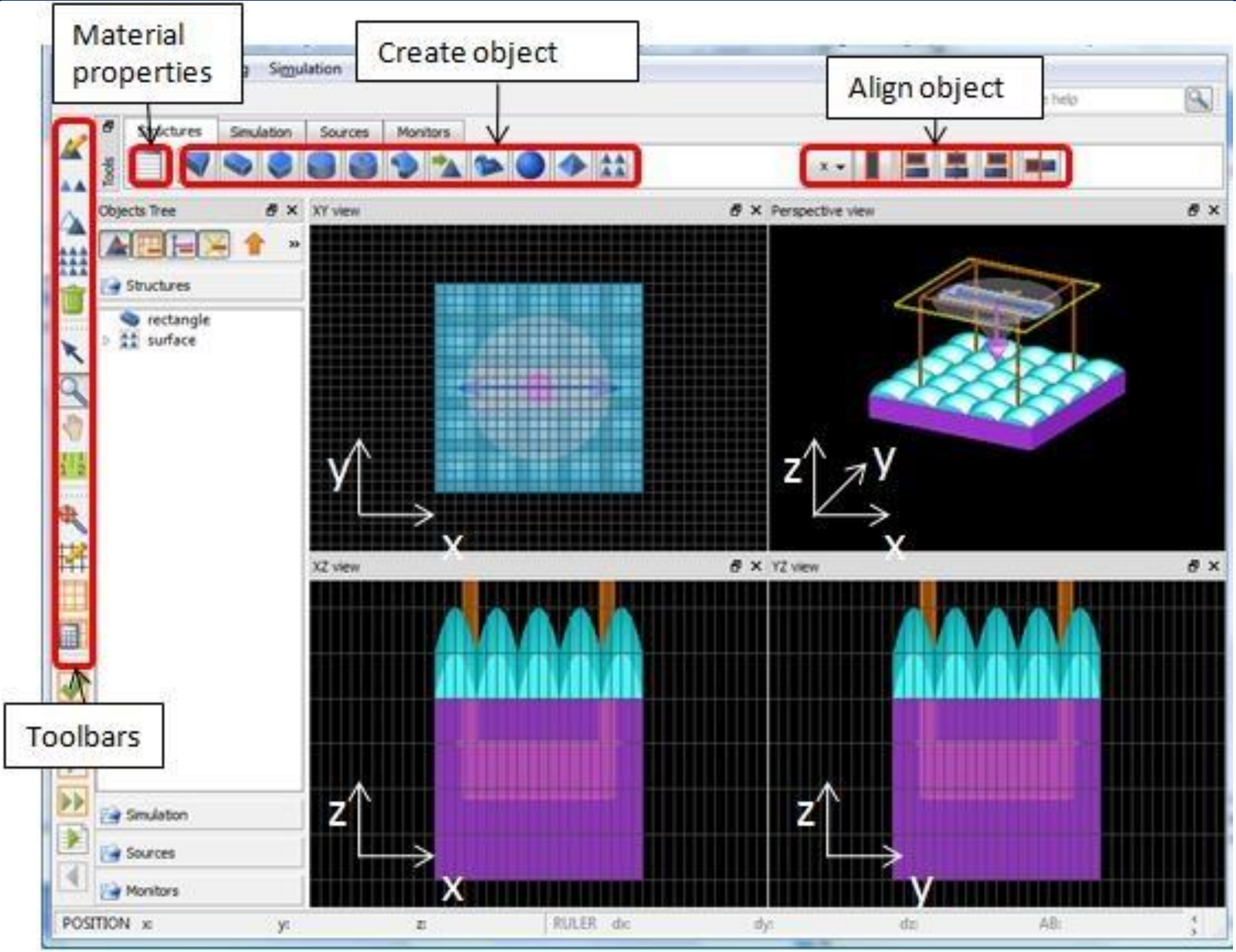
Tea Break

FDTD Solutions Features and Workflow

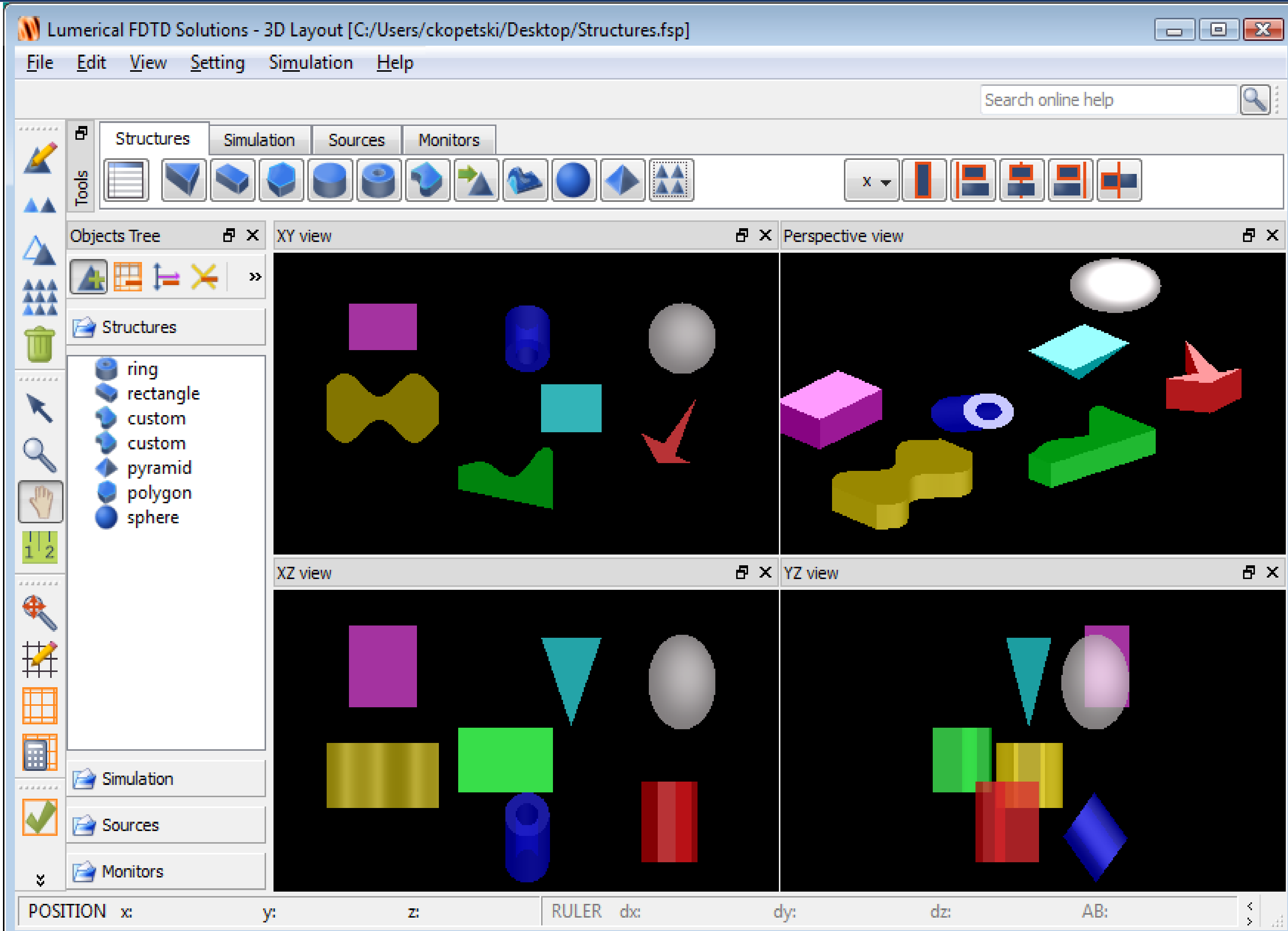
- Starting FDTD Solutions
- Basic program layout
- Structures
- Simulation region
- Sources
- Monitors
- Analysis
- Script commands



Features – General layout



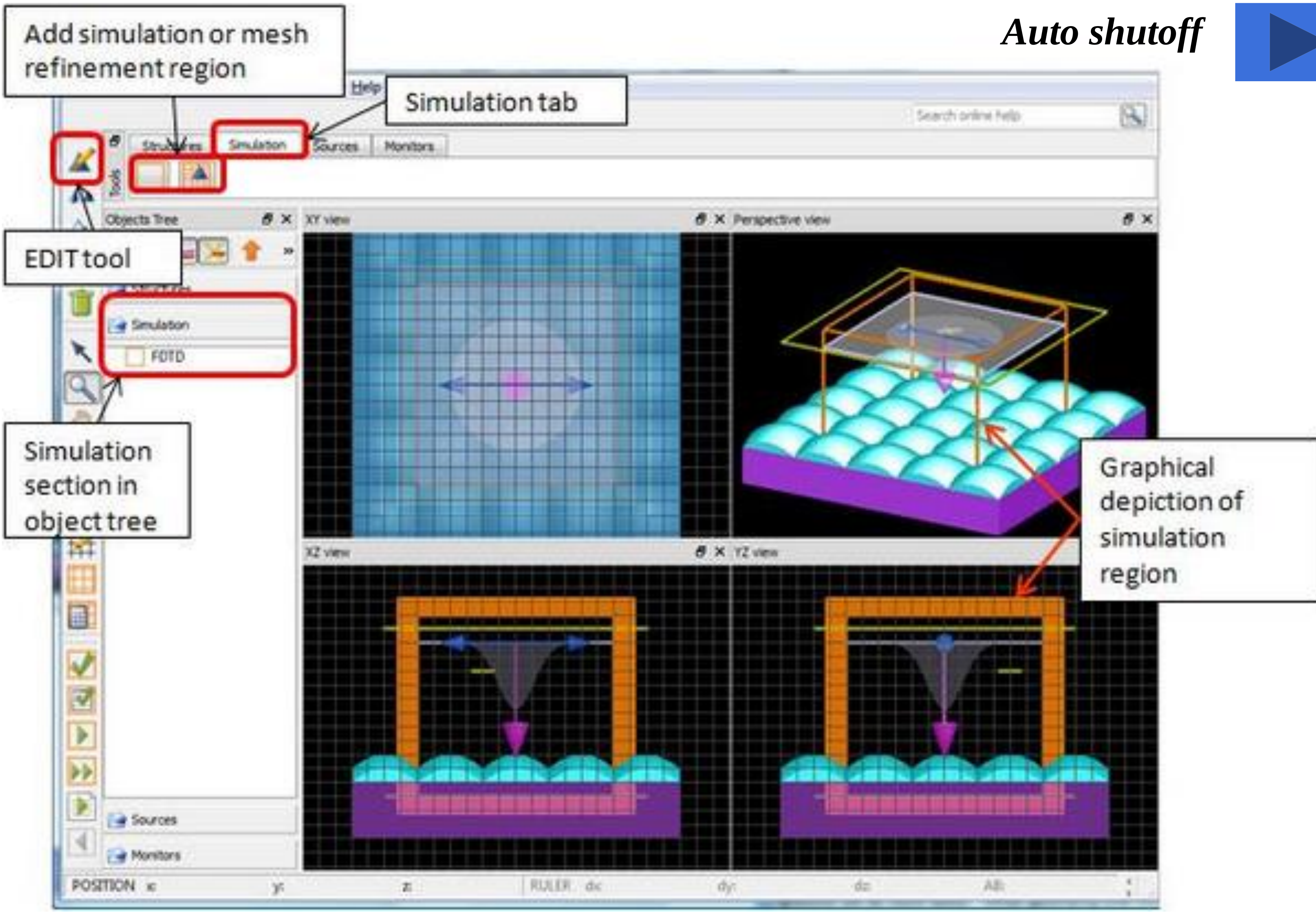
Structures



Lumerical FDTD Solutions - 3D Layout [C:/Users/ckopetski/Desktop/Structures.fsp]
File Edit View Setting Simulation Help
Search online help
Structures Simulation Sources Monitors
Tools
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:

Simulation

Auto shutoff



Boundary conditions

PEC (Perfect Electrical Conductor) : E is continuous where perpendicular to the boundary; E=0 for parallel case; Opposite for H.

PML (Perfect Matching Condition) : eliminate the influence of scattering field on calculation results. In this case, ε and μ satisfy：

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

Periodic boundary condition

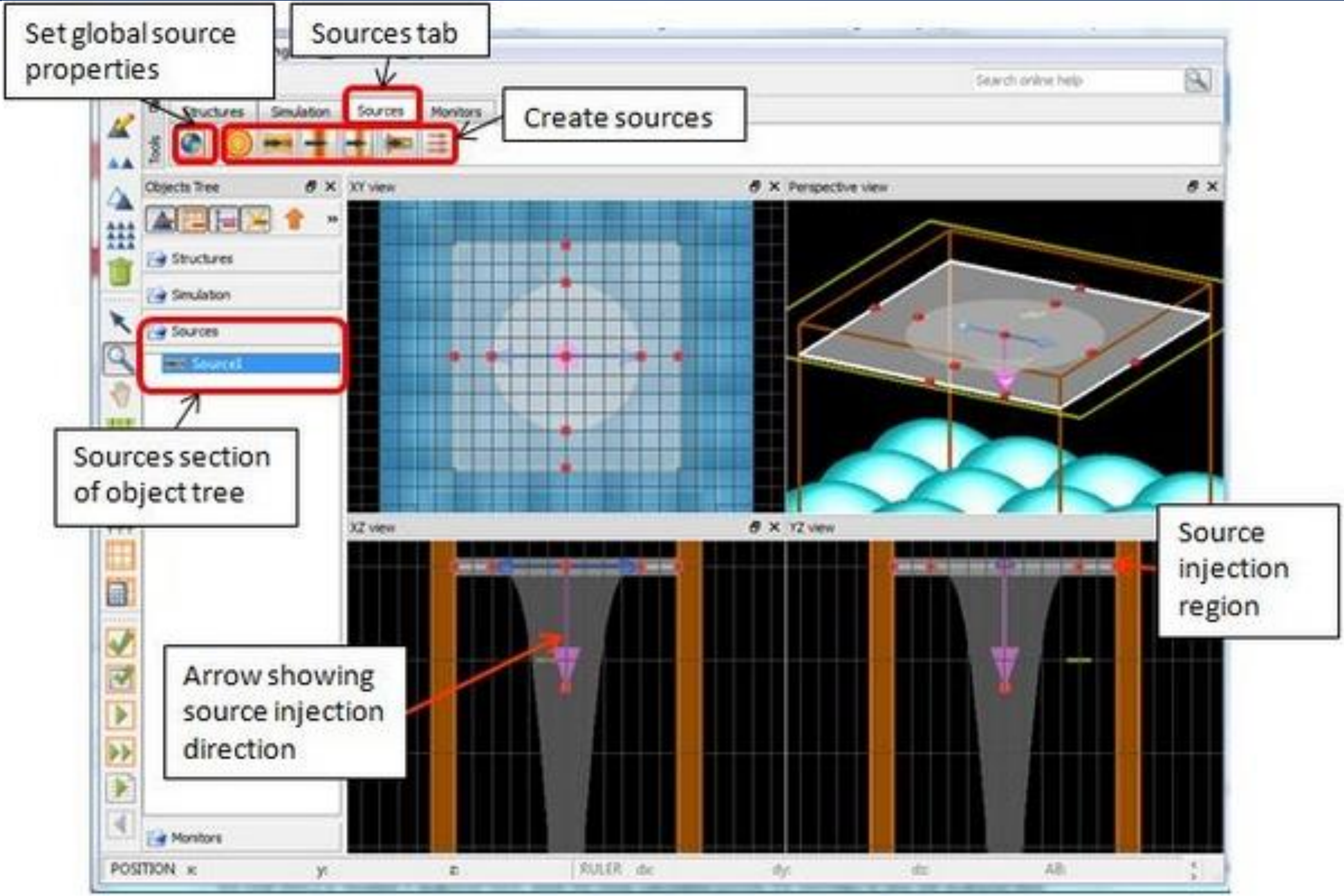
Symmetric

Anti-symmetric

Bloch Boundary: Plane wave oblique incident to a periodic structure.

Metal boundary: diagnose the cause of calculation divergence.

Sources


Set global source properties
Sources tab
Create sources
Structures
Simulation
Sources
Monitors
Objects Tree
XY view
Perspective view
XZ view
YZ view
Sources section of object tree
Source injection region
Arrow showing source injection direction
POSITION

Sources

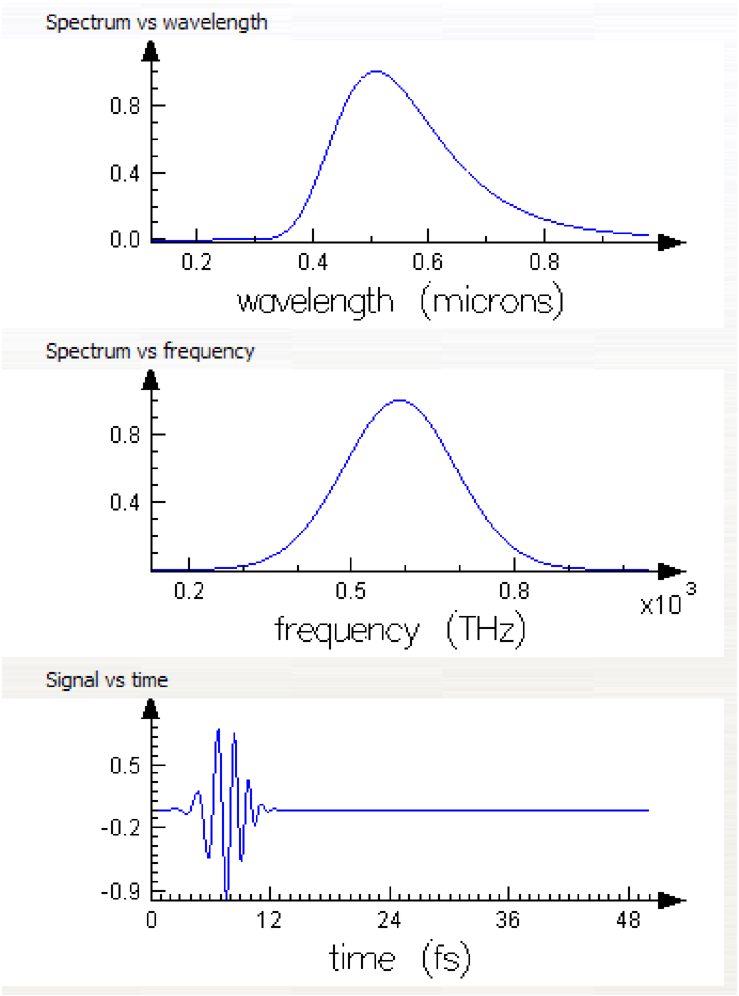
FDTD Solutions has a variety of sources available:

Basic Sources

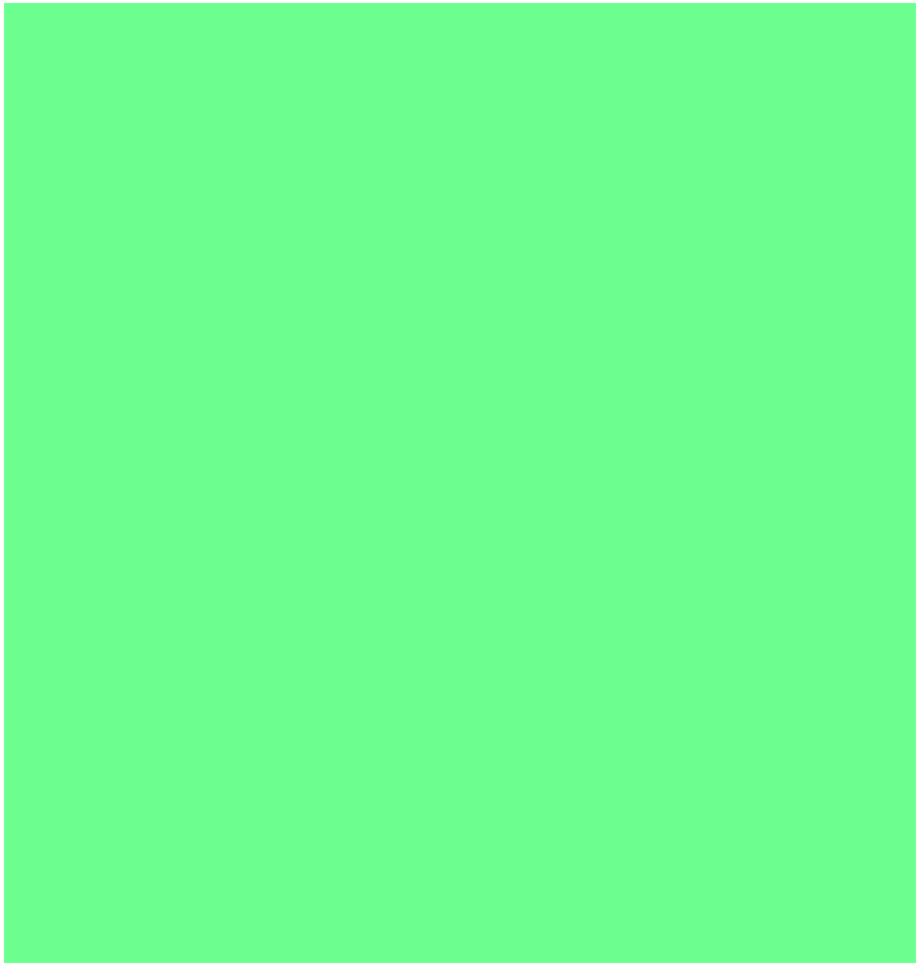
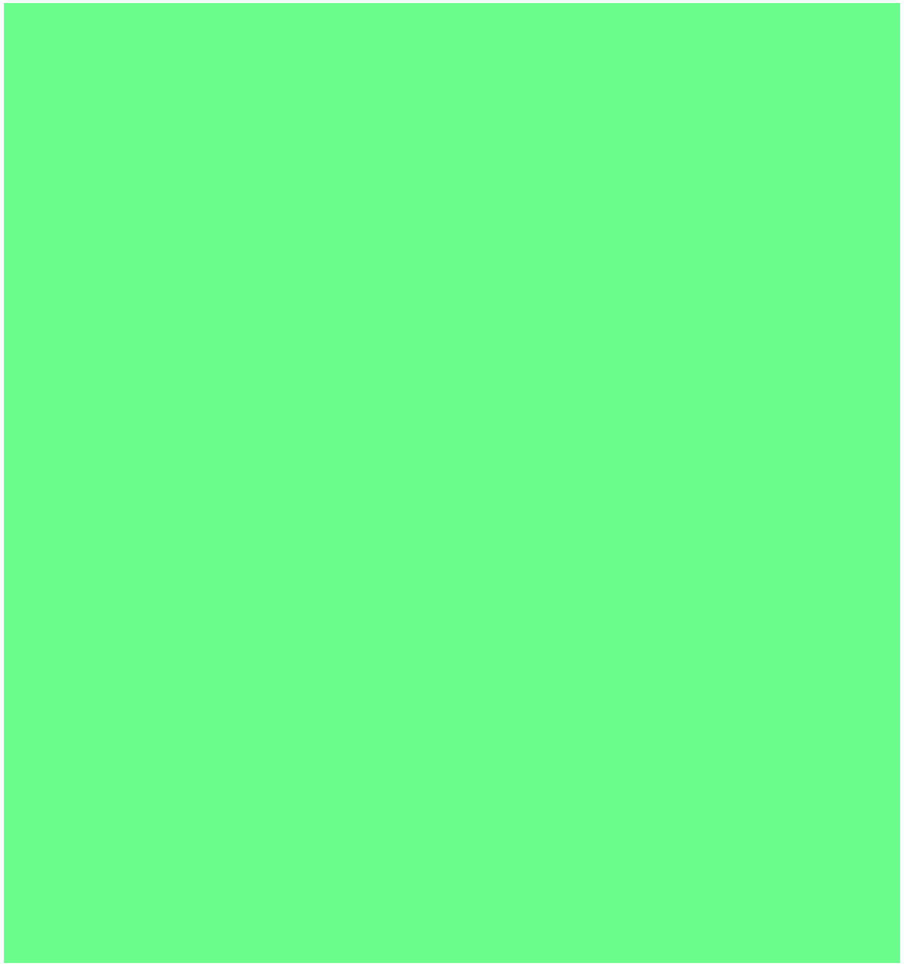
- Dipole
- Gaussian beam
- Plane wave
- Mode

Advanced sources

- Total field/scattered field
- Large NA source
- ASAP (with aberration)
- User-defined

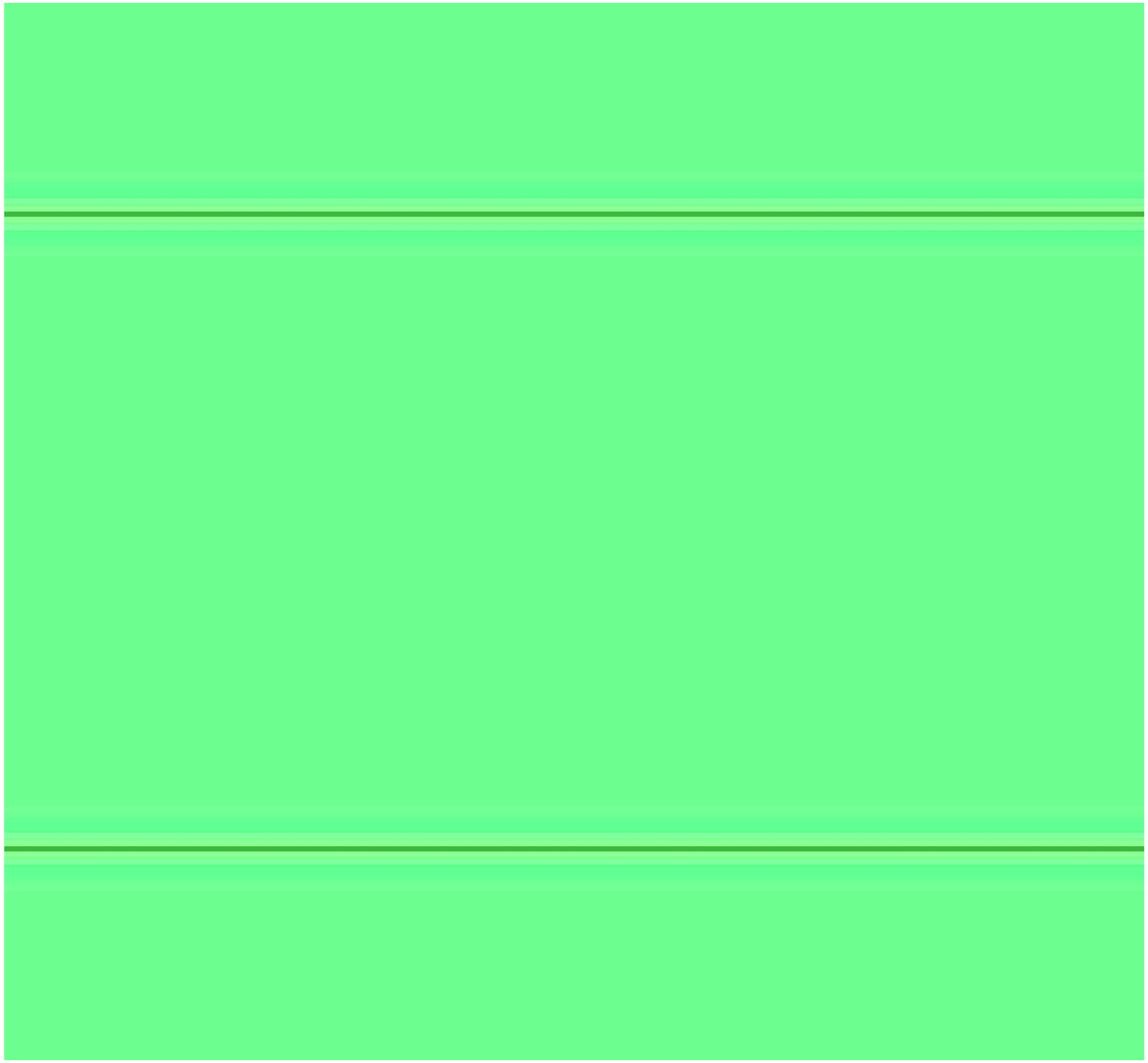


Dipole

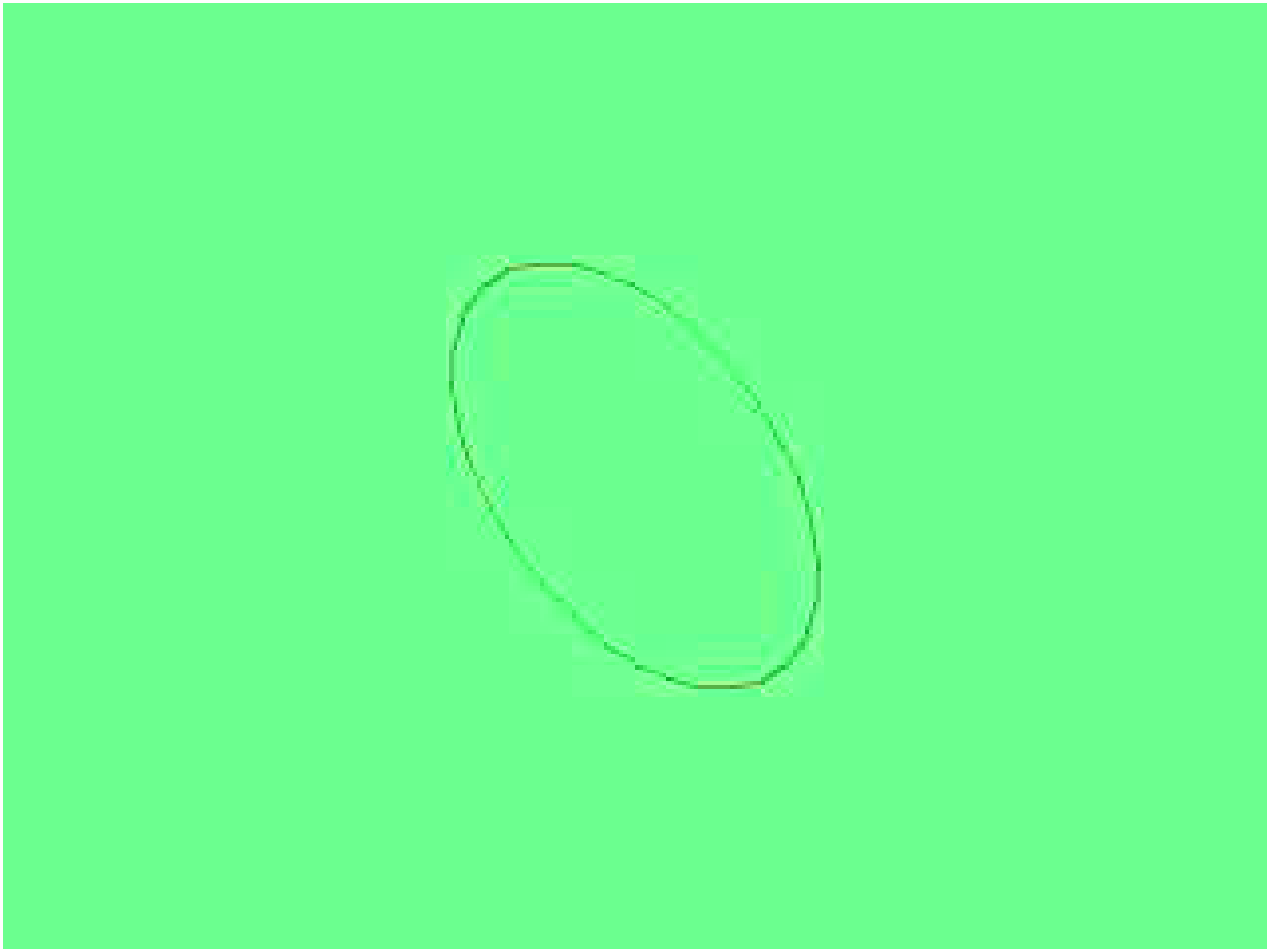
TM	TE
	

Gaussian and plane wave

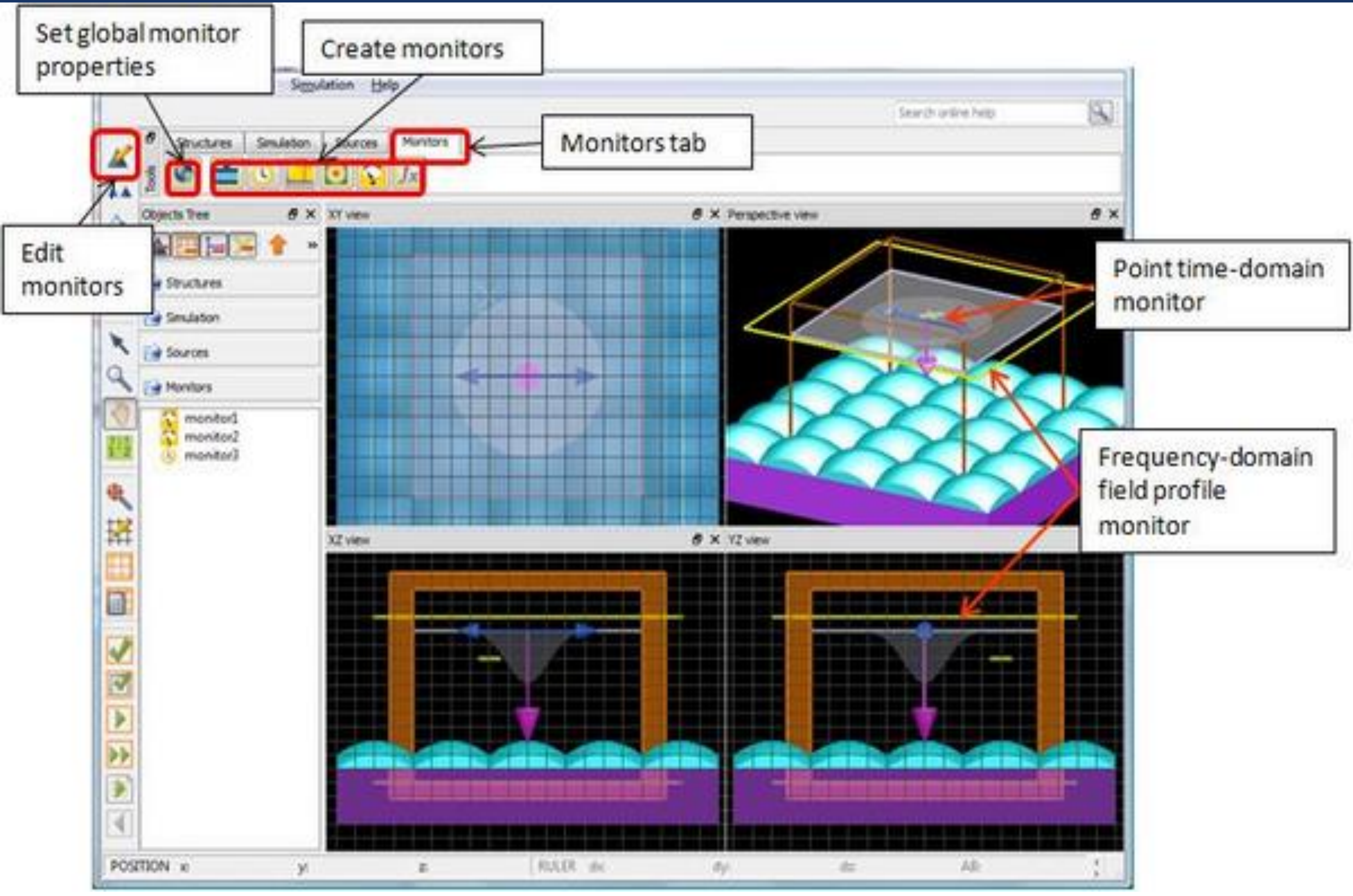
Mode source



Total-Field Scattered-Field (TFSF)



Monitors


Set global monitor properties
Create monitors
Monitors tab
Edit monitors
Point time-domain monitor
Frequency-domain field profile monitor
Simulation
Help
Structures
Simulation
Sources
Monitors
Objects Tree
XY view
Perspective view
XZ view
YZ view
monitor1
monitor2
monitor3
POSITION
RULER

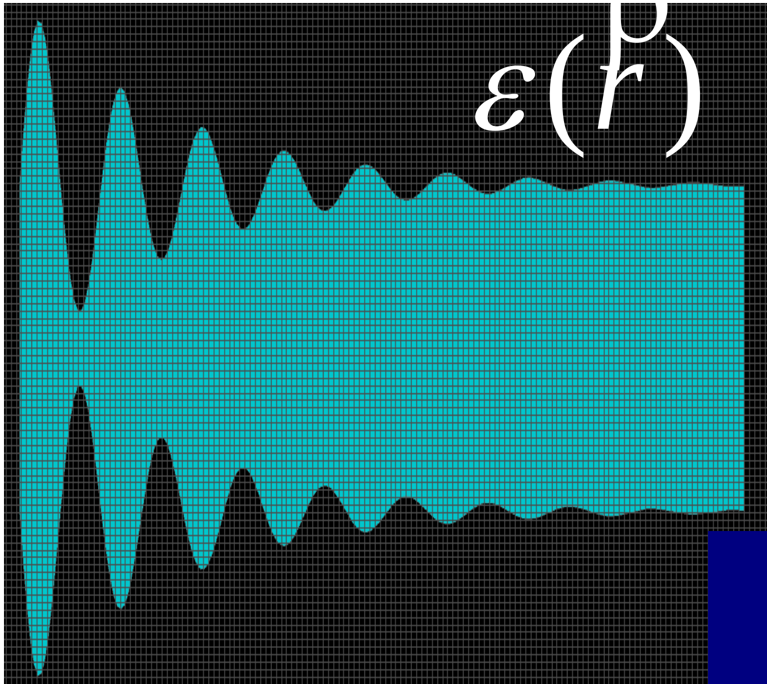
Monitors

FDTD Solutions has several monitors

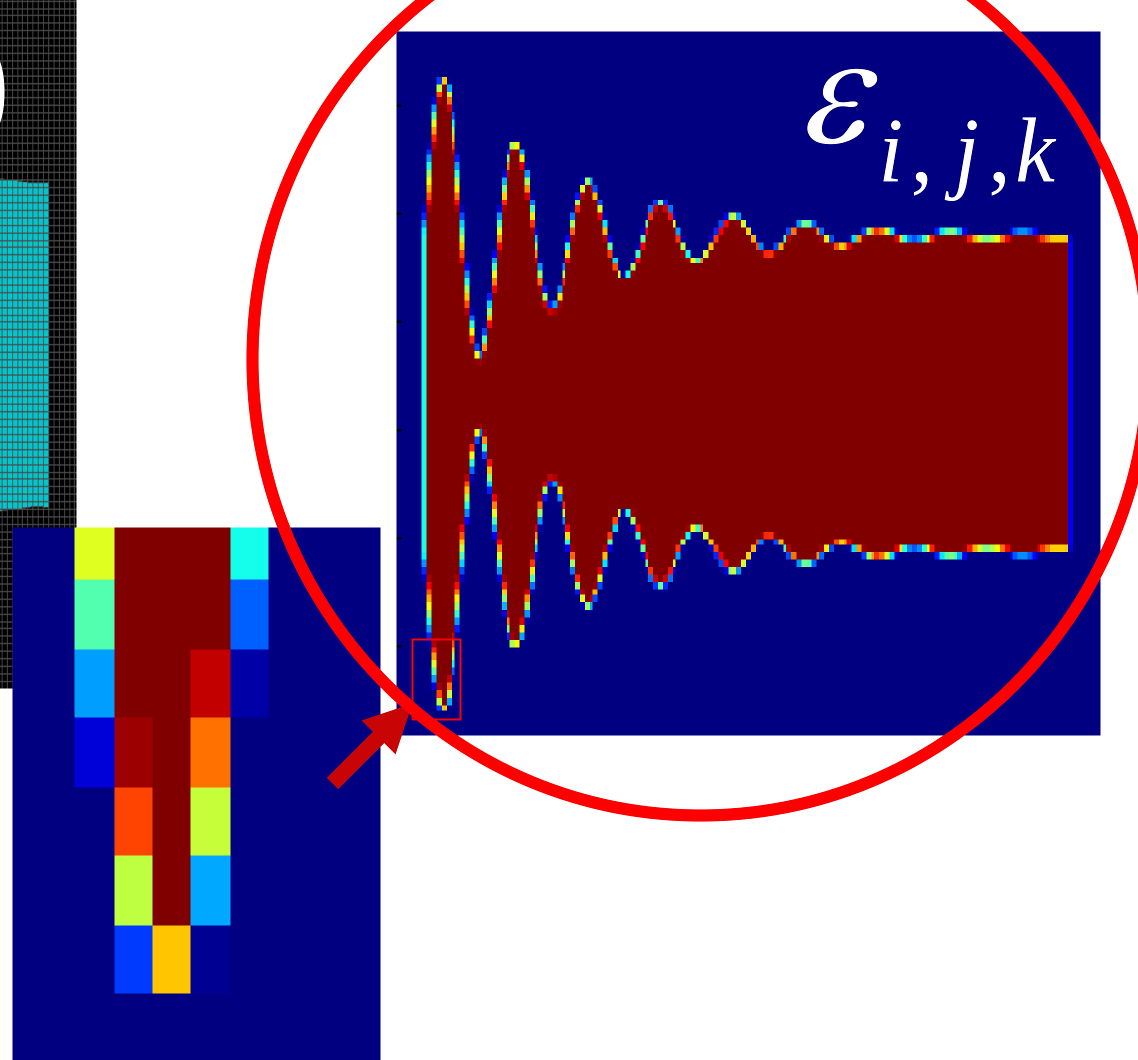
- **Index** monitors to record material properties
- **Movie** monitors to create mpg movie files
- **Time** monitors to record electromagnetic fields as a function of time
- **Frequency** monitors to perform Fourier transforms during the simulation
  - : **Profile** monitors
  - : **Power** monitors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

Index monitors

The true structure



The meshed structure

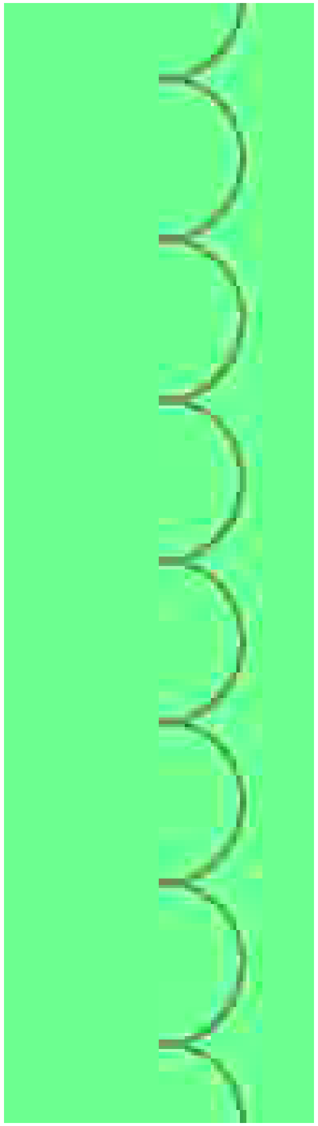


1. 检查材料的设定是否正确；
2. 显示复杂拐点处的平均网格精度。

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.

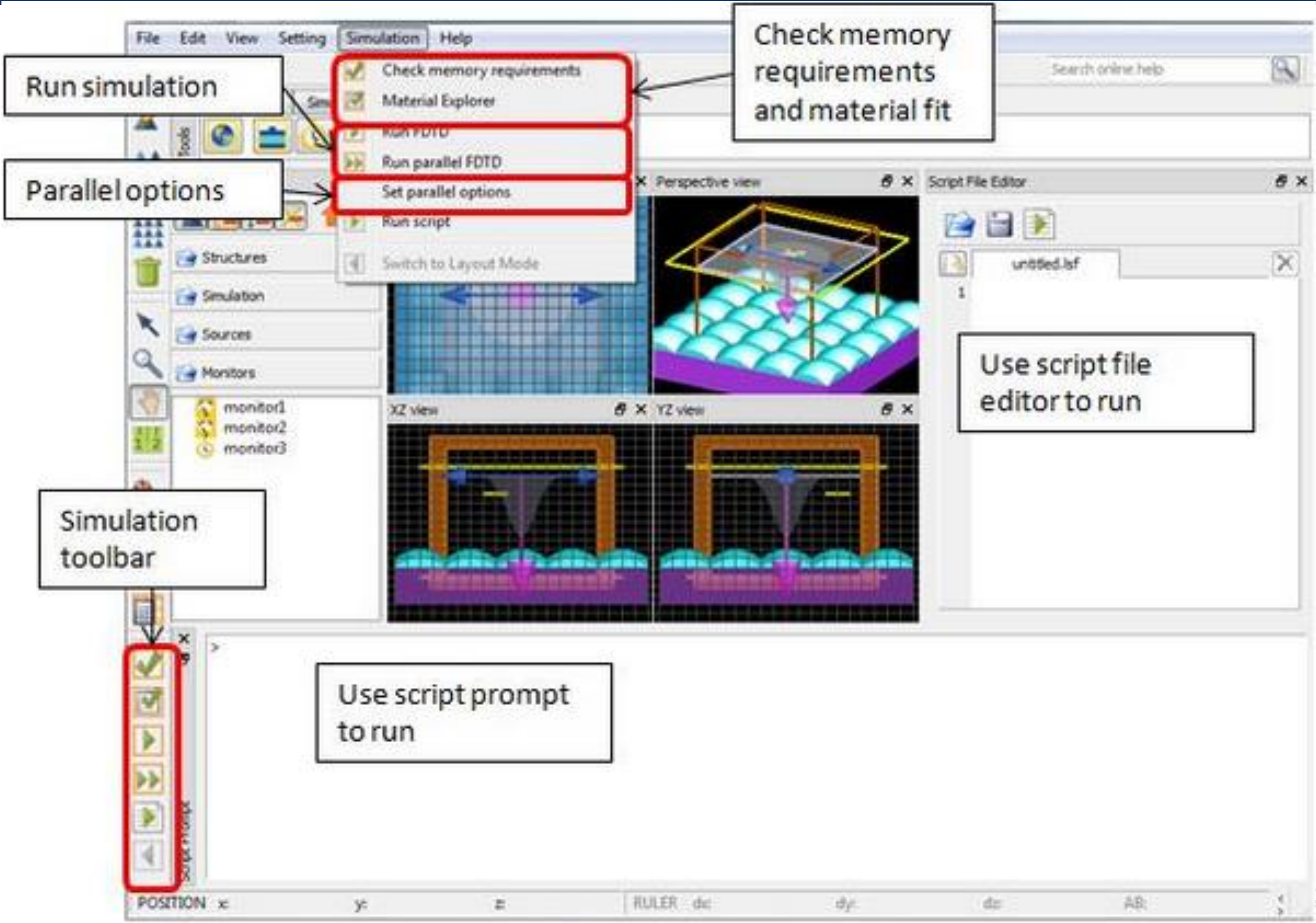
: **Wavelength range** must be specified in advance.

Frequency monitors

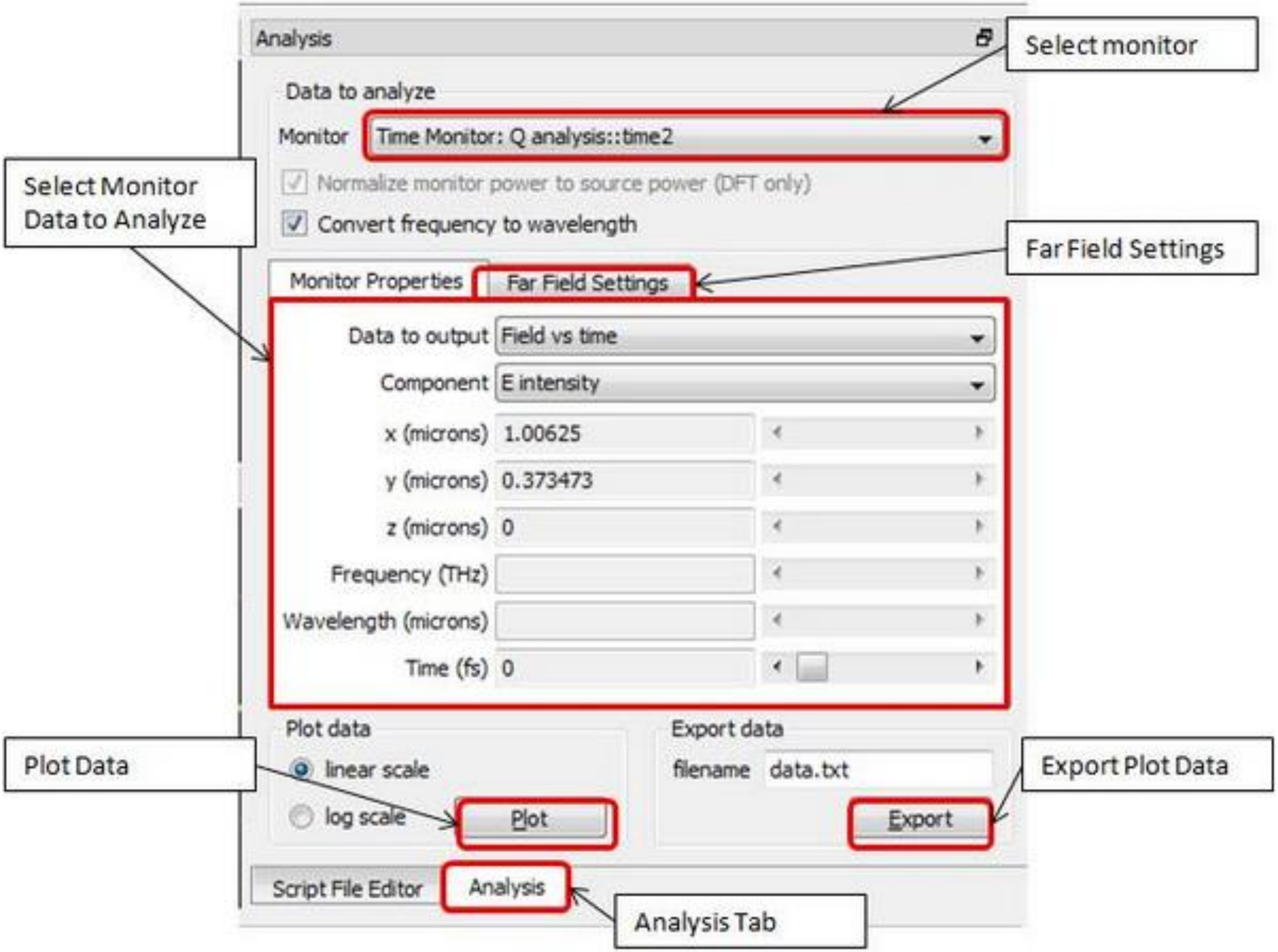
- Quantitative monitors used in simulations allow us to calculate:

  : transmission
  : reflection
  : absorption
  : scattering
  : spatial field profiles
  : far field projections
  : local (near) field enhancements
  : light extraction enhancement

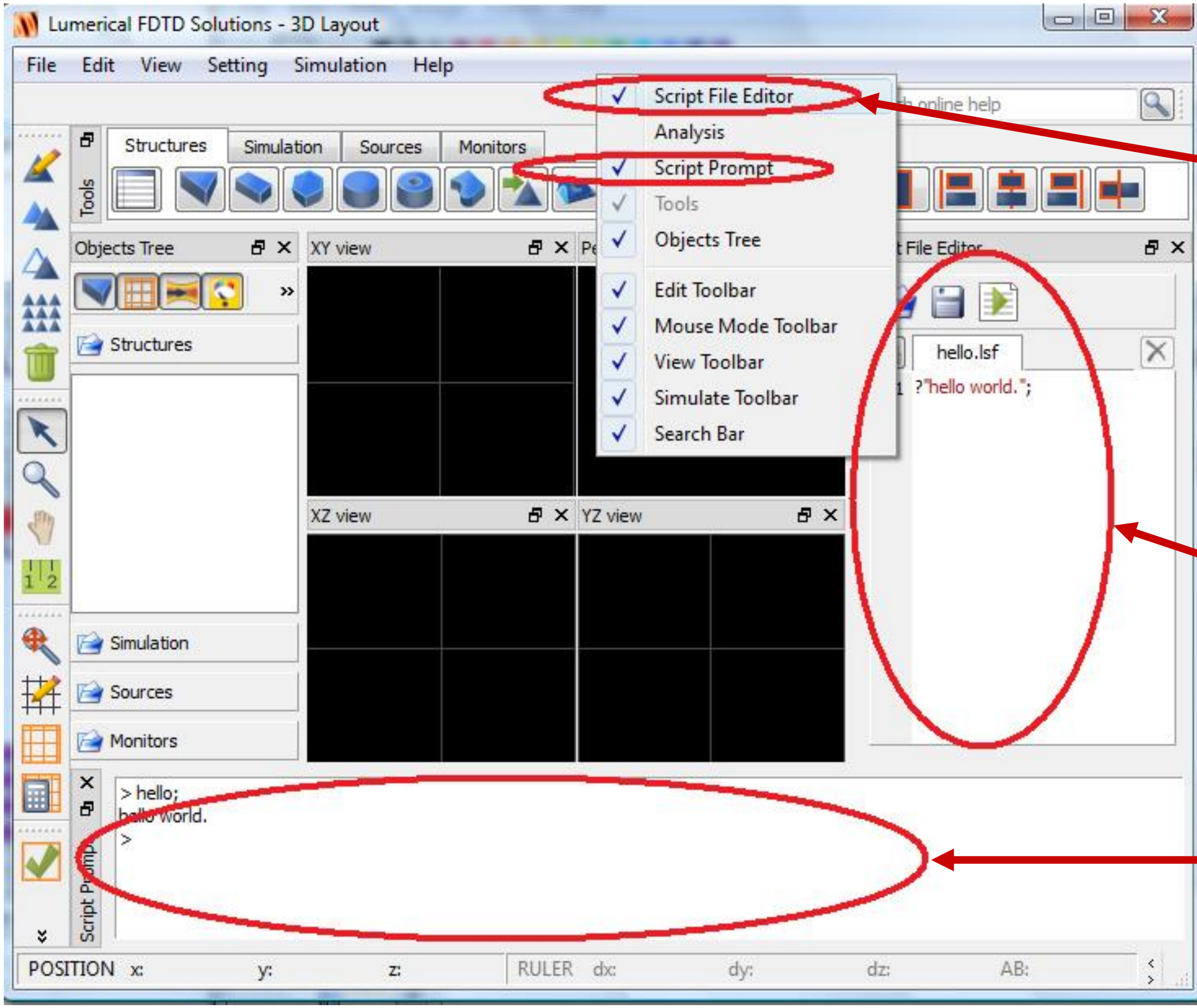
Run simulation



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

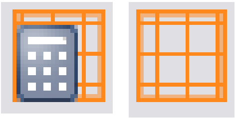
- Sources
  - Plane wave source, from glass side to air
  - Wavelength 400 to 800nm

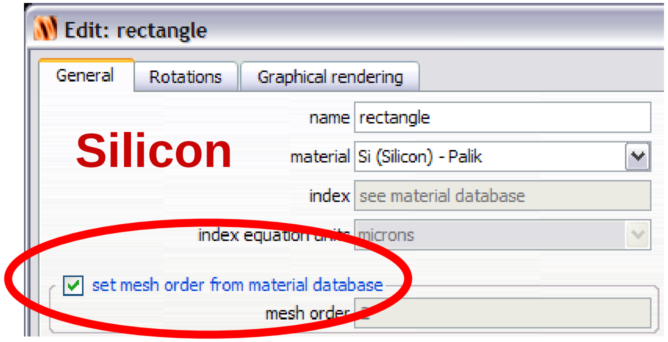
- Monitors
  - Movie monitor name movie
  - Index monitor over the entire structure name index
  - Time monitor in Si layer name time1
  - Transmission/Reflection monitors (100 frequency points each)
    - Name them "R" and "T" name T name R
  - Full profile over entire structure (3 frequency points)

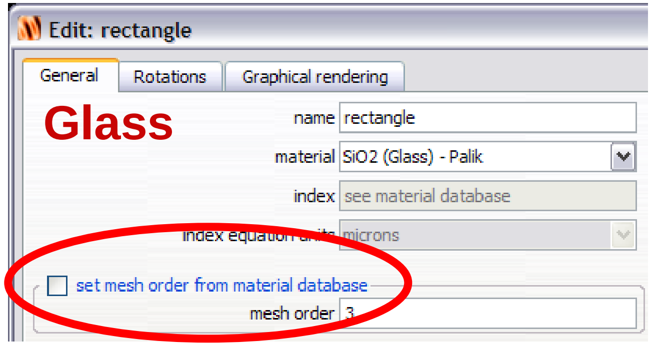
    name full_profile

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

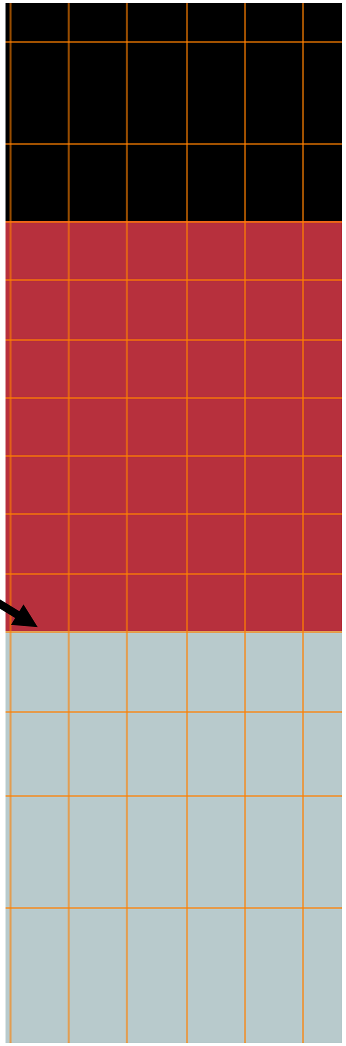






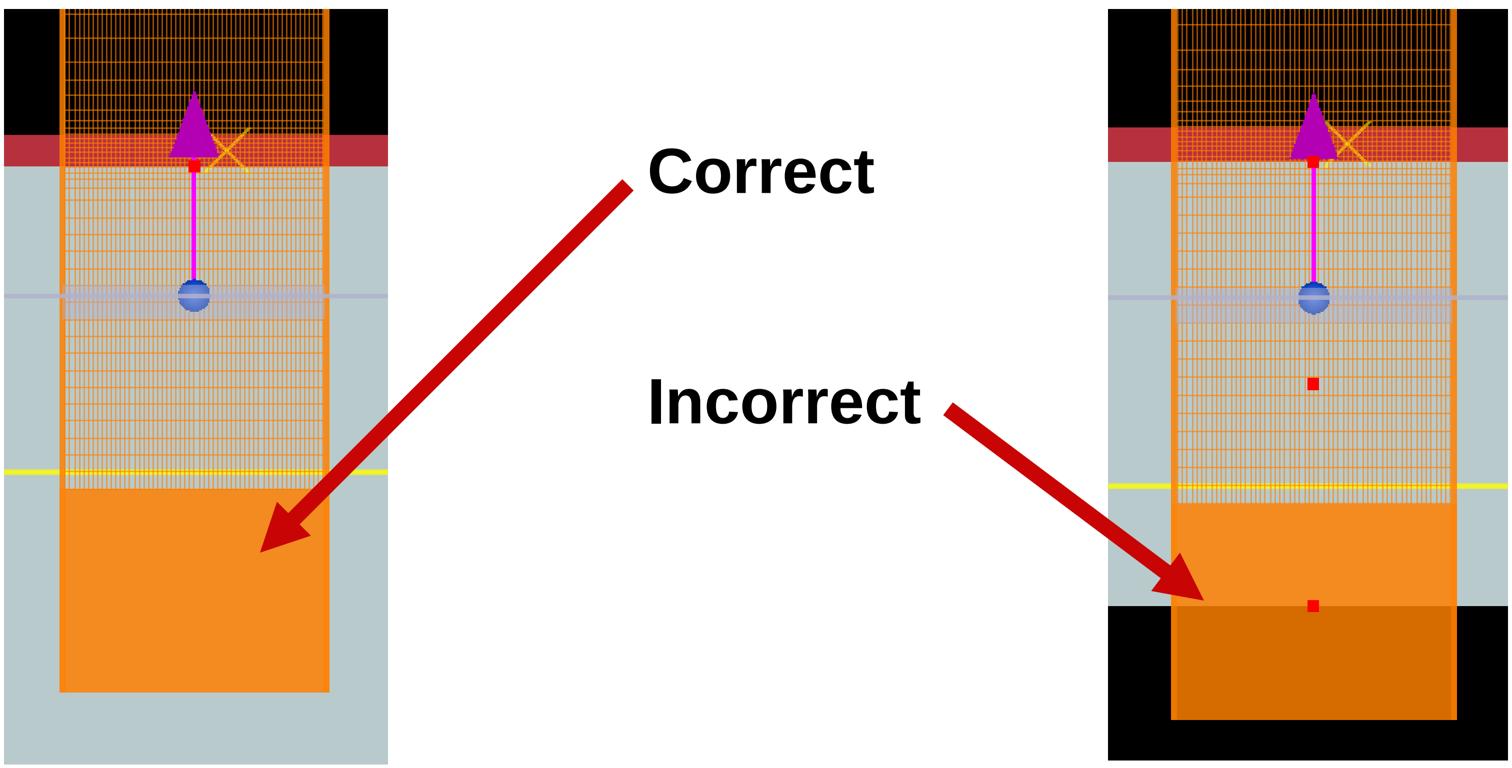
- Set Silicon mesh order to 2
- Set Glass mesh order to 3

The interface point will be Silicon!



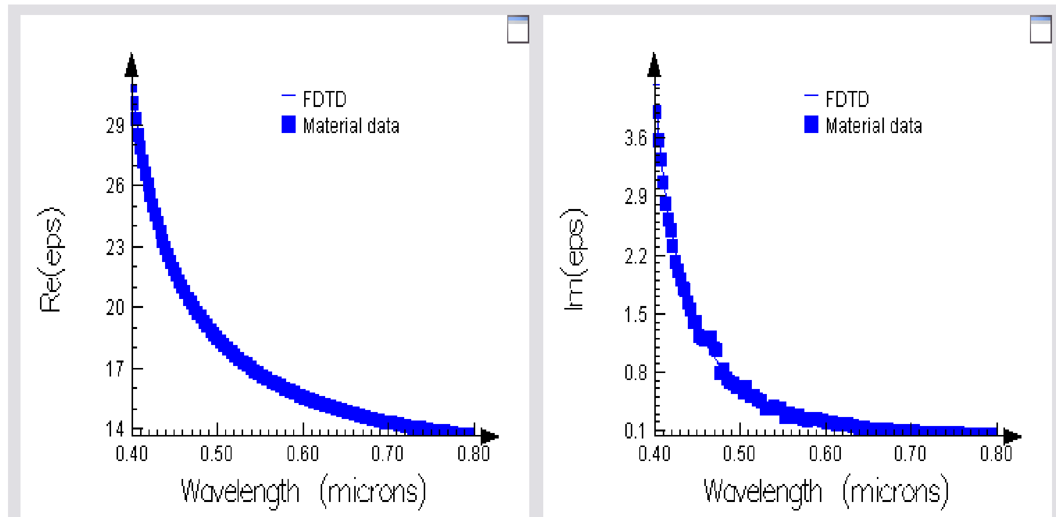
Simple example

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



Simple example

- Check memory requirements!
- Check material fits



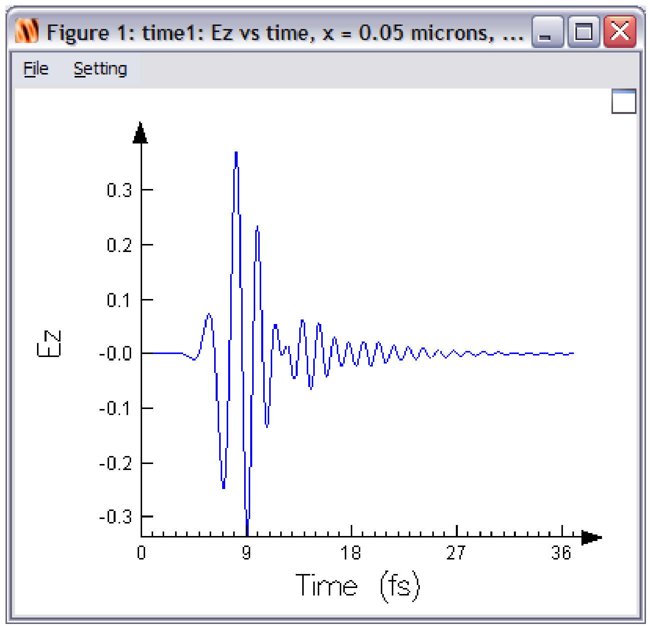
- Save simulation file under name **simple_example.fsp**
- Run simulation
  - Note when the simulation "auto-shutoff" occurs
    - Can we reduce the maximum simulation time for the next simulation?

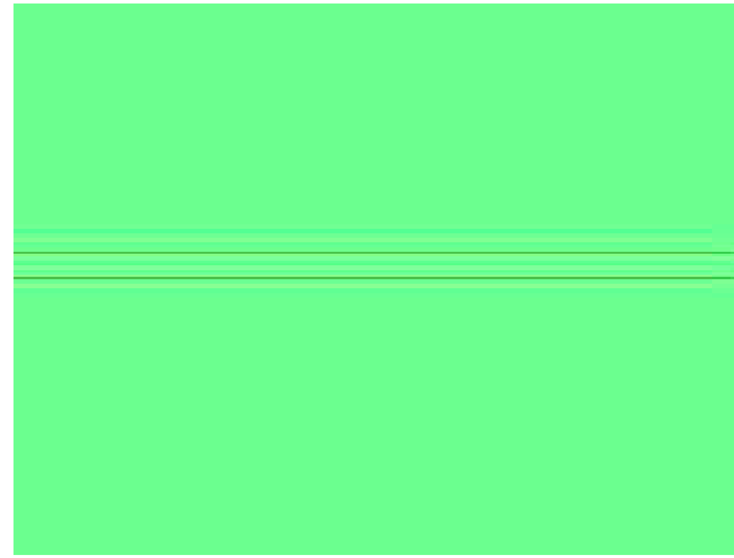
: Can!

- Analyze results

  : Run the movie: movie.mpg

  : Plot Ez vs time

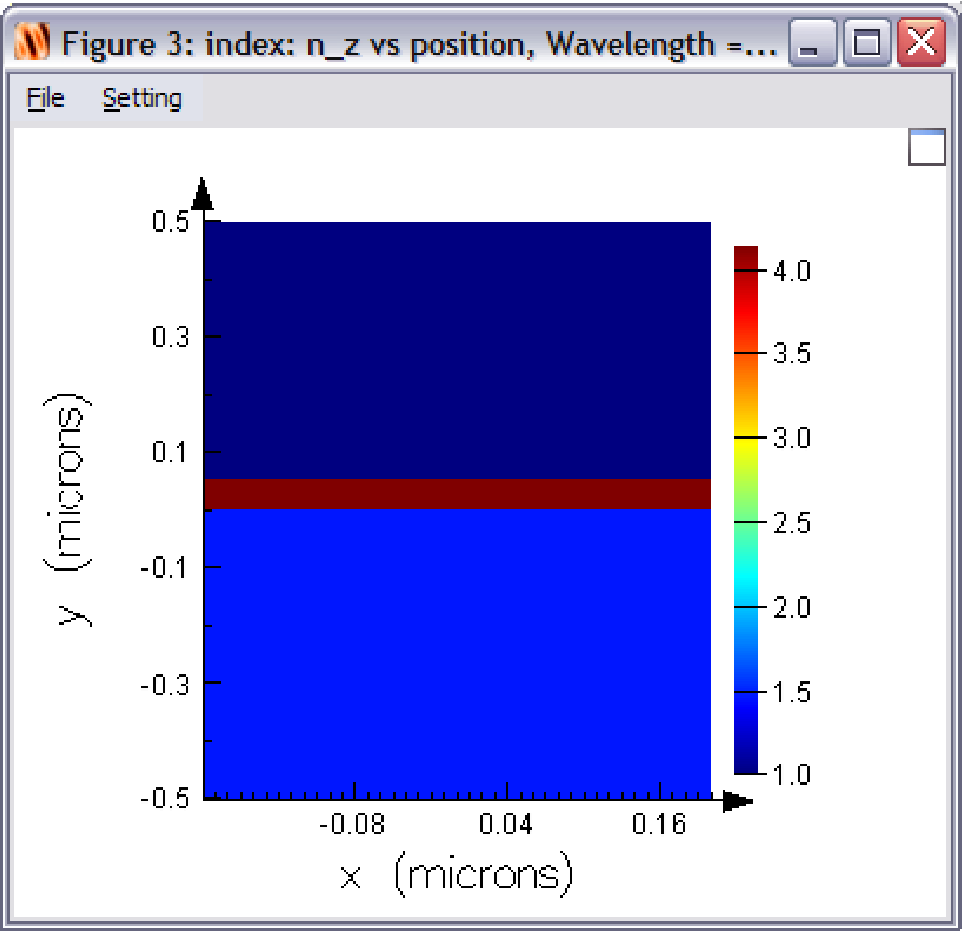


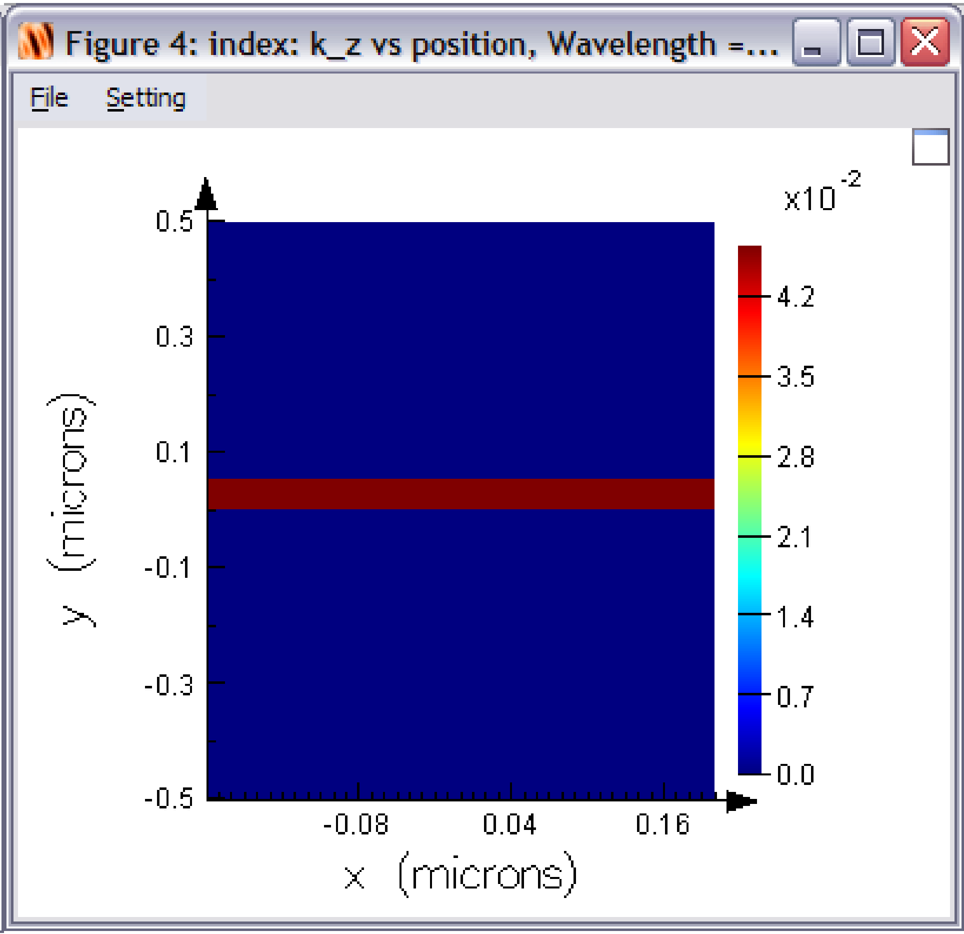


  : Did the auto-shutoff work?

Simple example

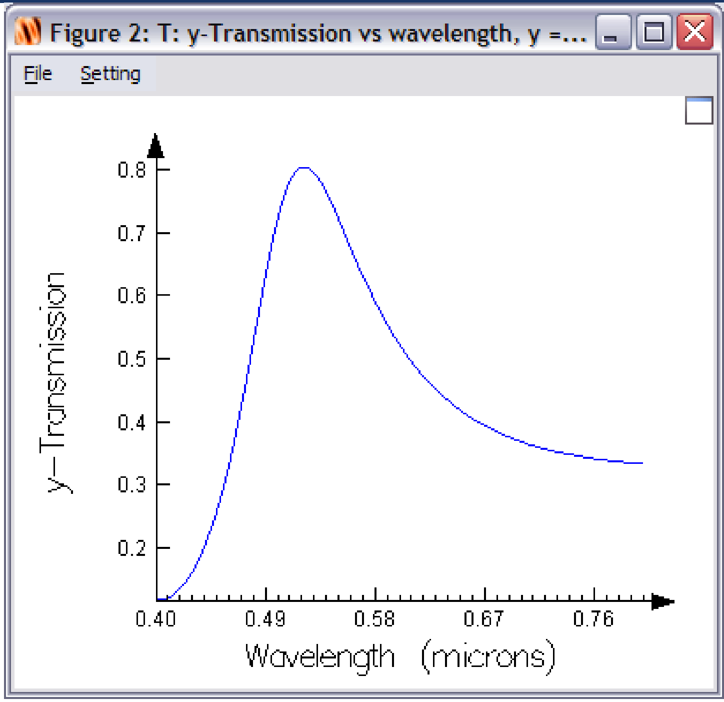
- Analyze results
  - Image ***n*** and ***k***. Is the structure correct?



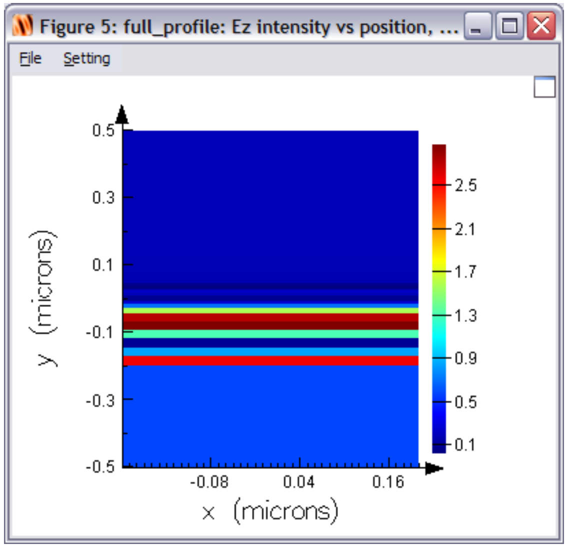


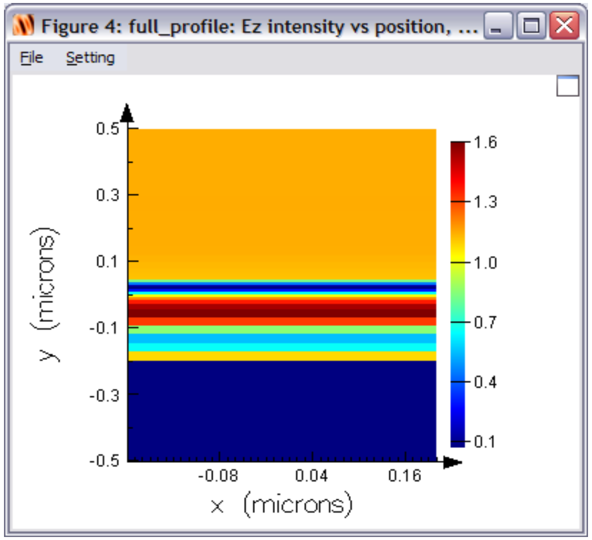
Simple example

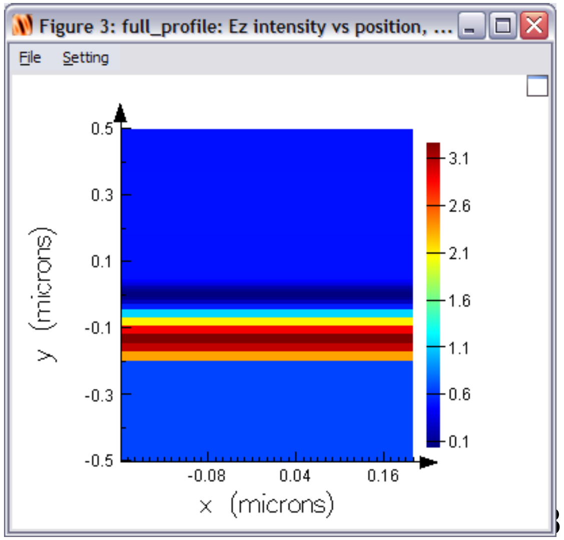
- **Analyze results**
  - Plot transmission vs wavelength



  - Image $|E_z|^2$ at 3 different wavelengths



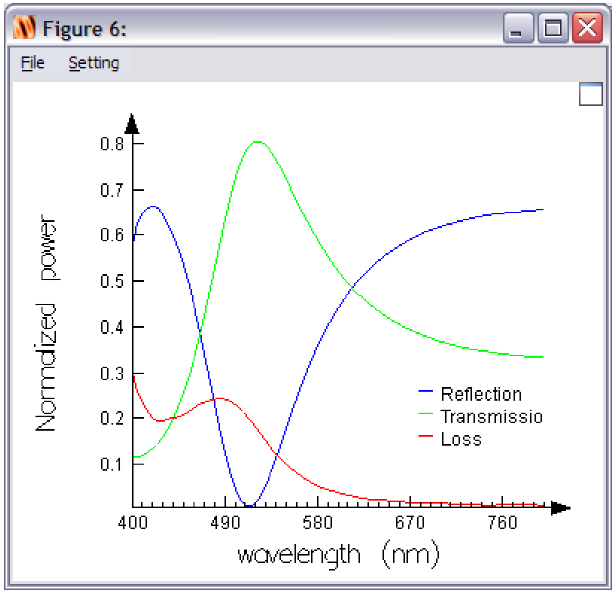




Simple example

- 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?

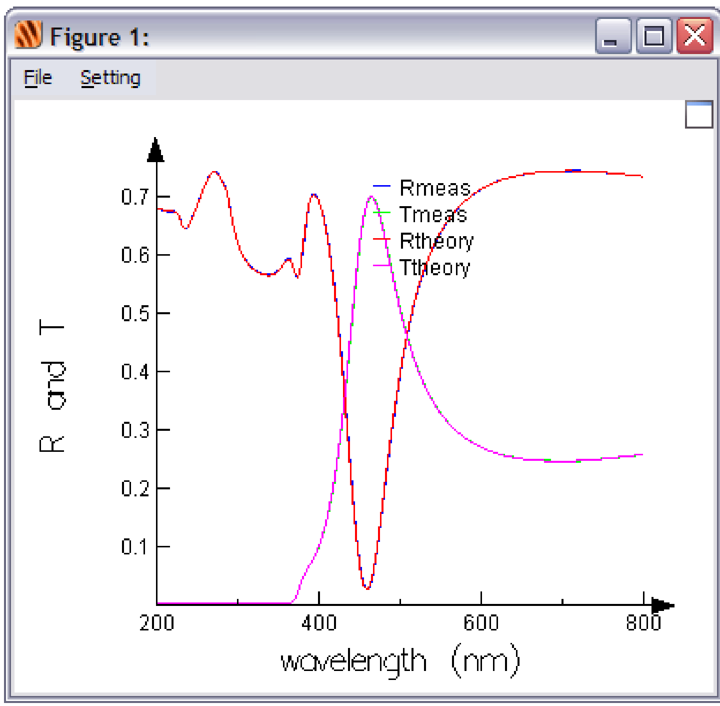


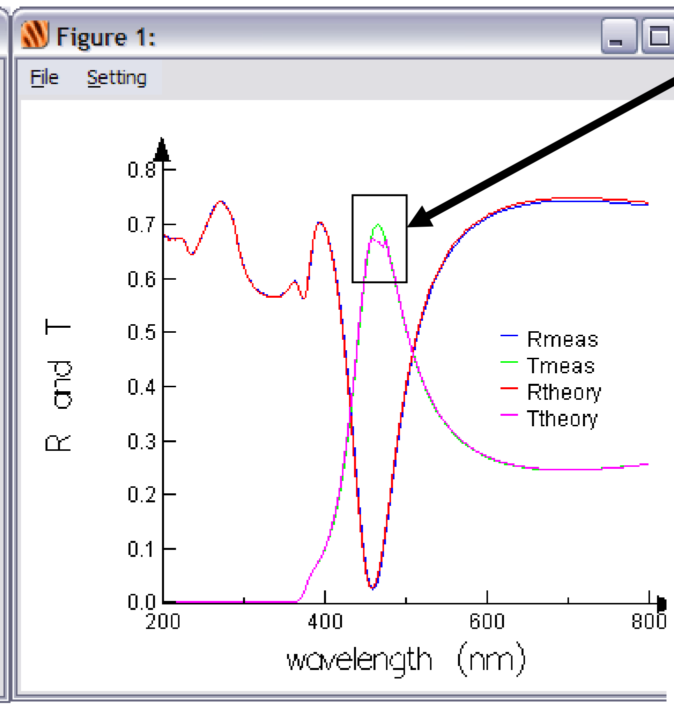
Simple example: accuracy

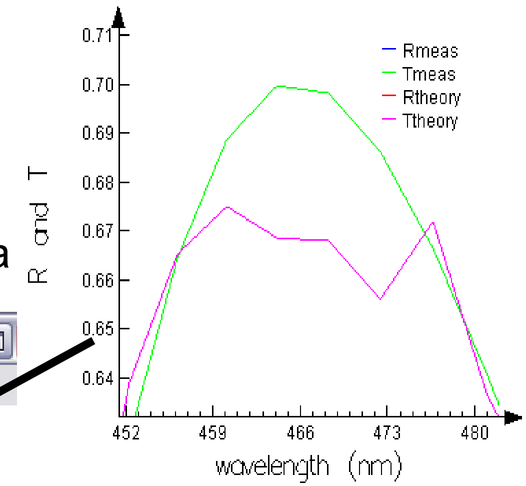
- Is this accurate?
  - Here is a 50 nm slab of Si in air, 200-800nm

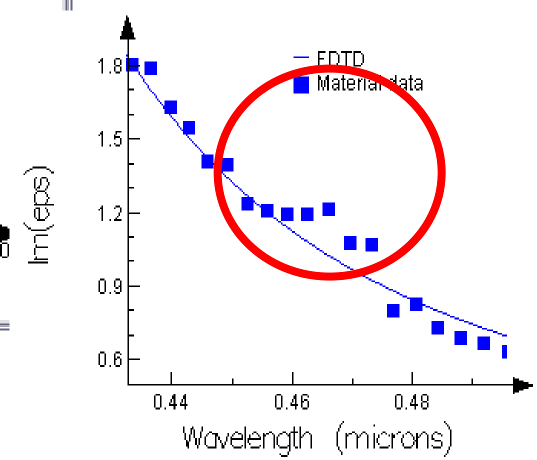
Theory based on FDTD material model

Theory based on Palik's Si data





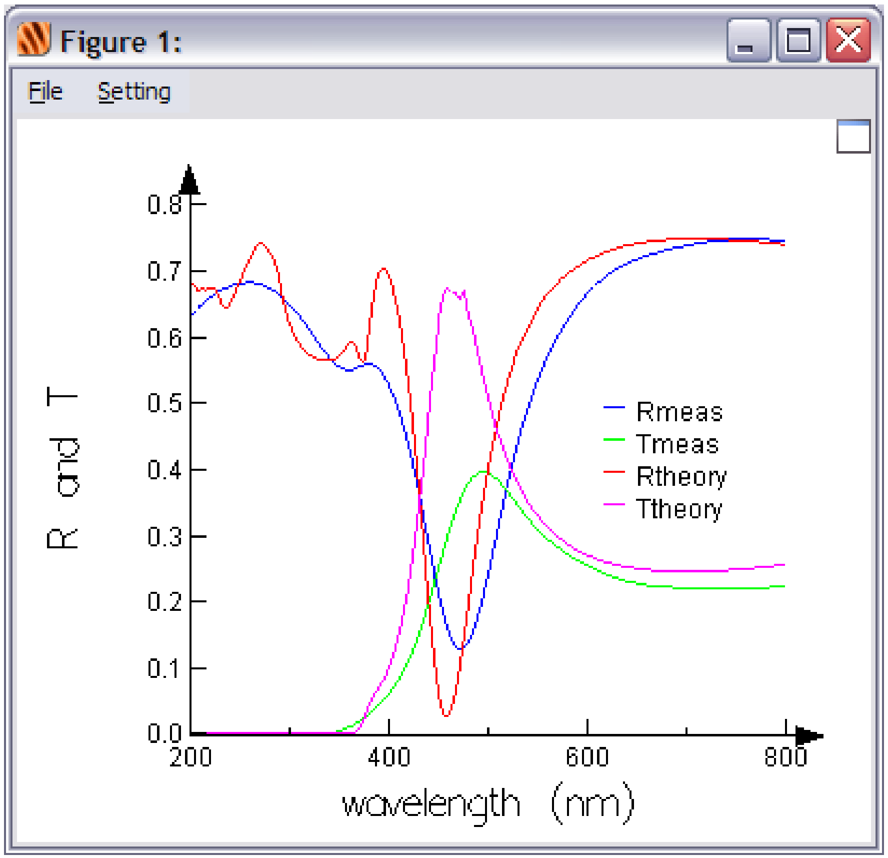




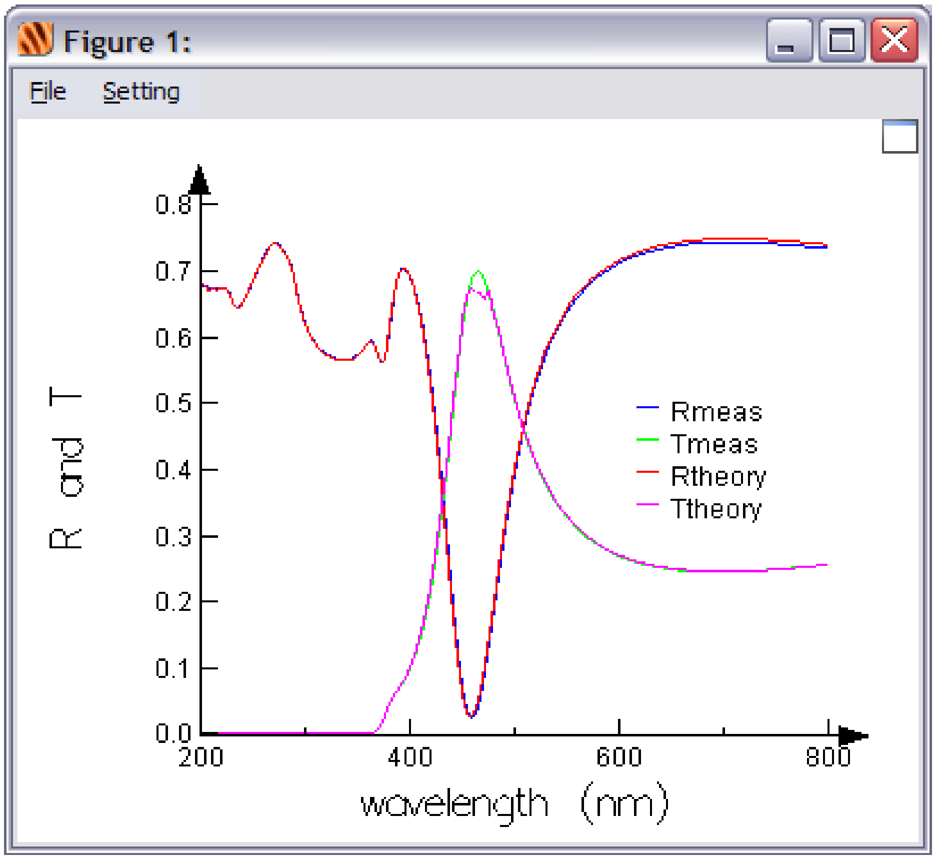
Simple example: accuracy

- Compare Lorentz model with multi-coefficient model

Lorentz model

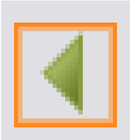


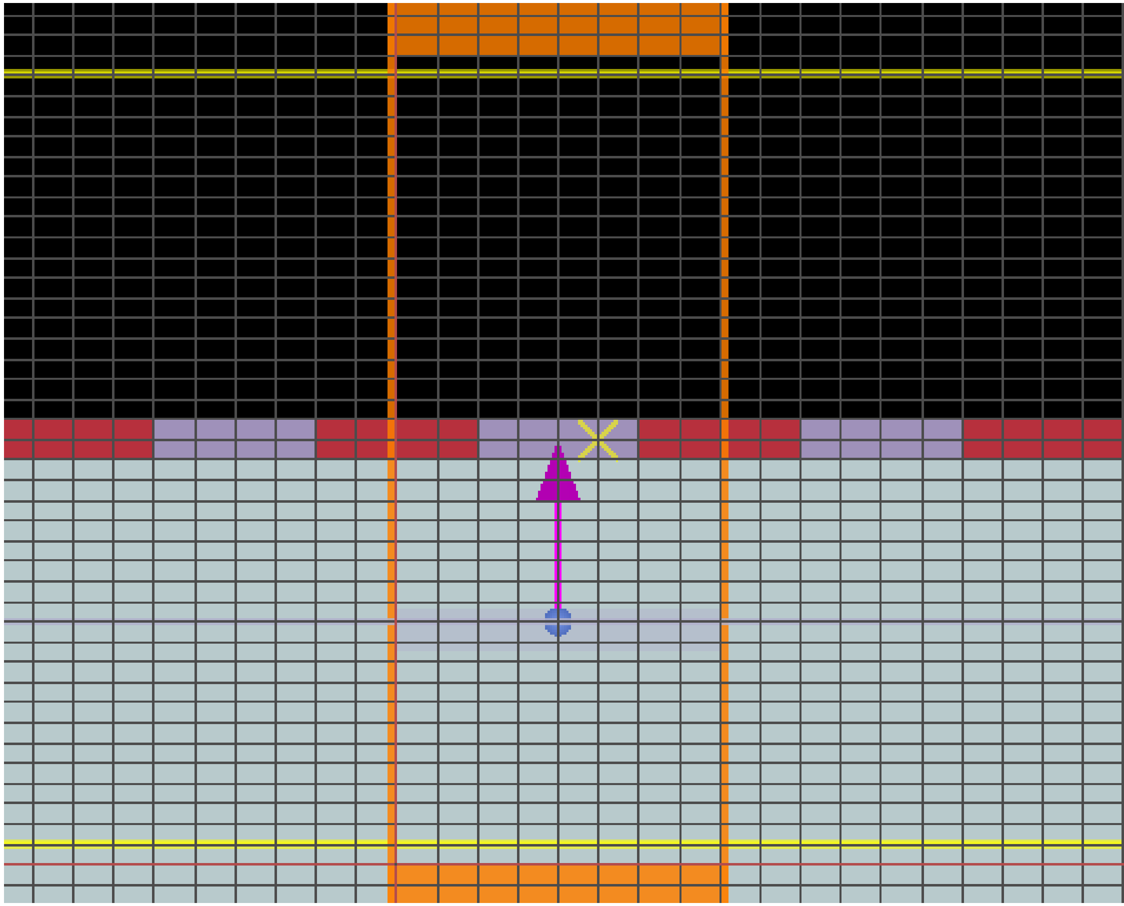
Lumerical's multi-coefficient model



Simple example

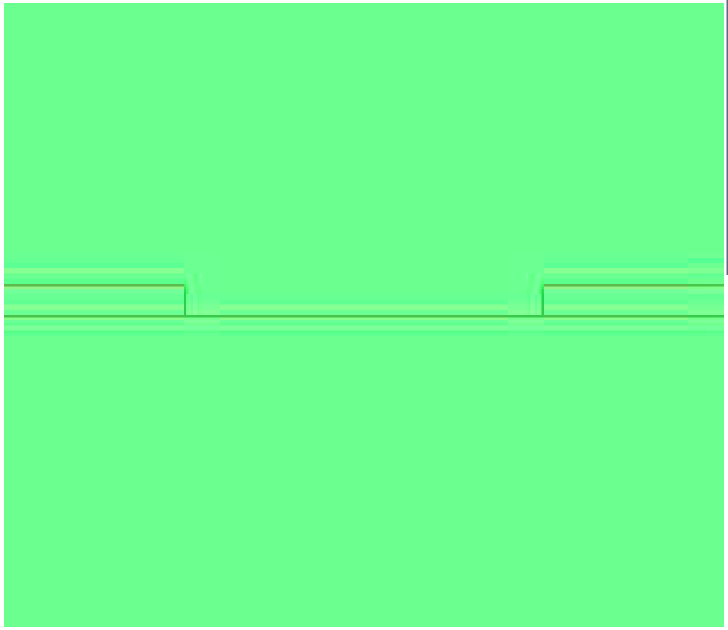
- **Switch back to Layout mode**
- **Add etched lines (200nm wide, 400 nm period)**
  - Adjust the drawing grid OR
  - Use the array feature

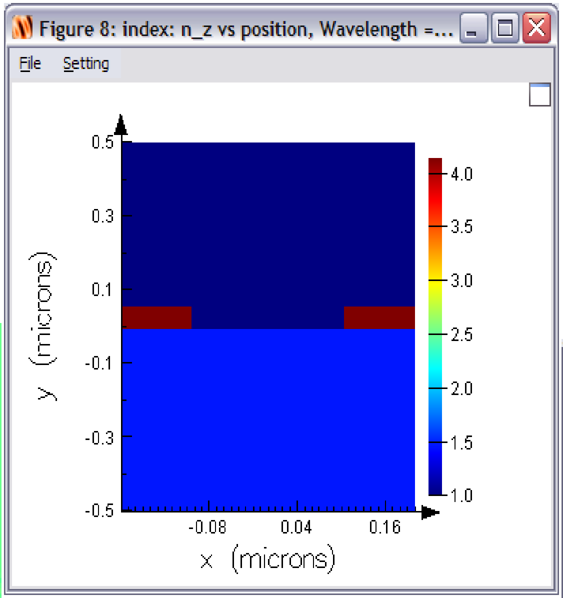


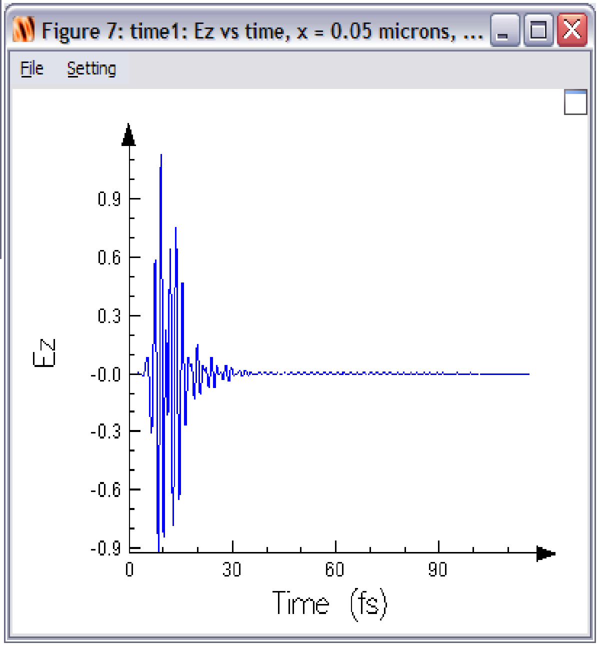


Simple example

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

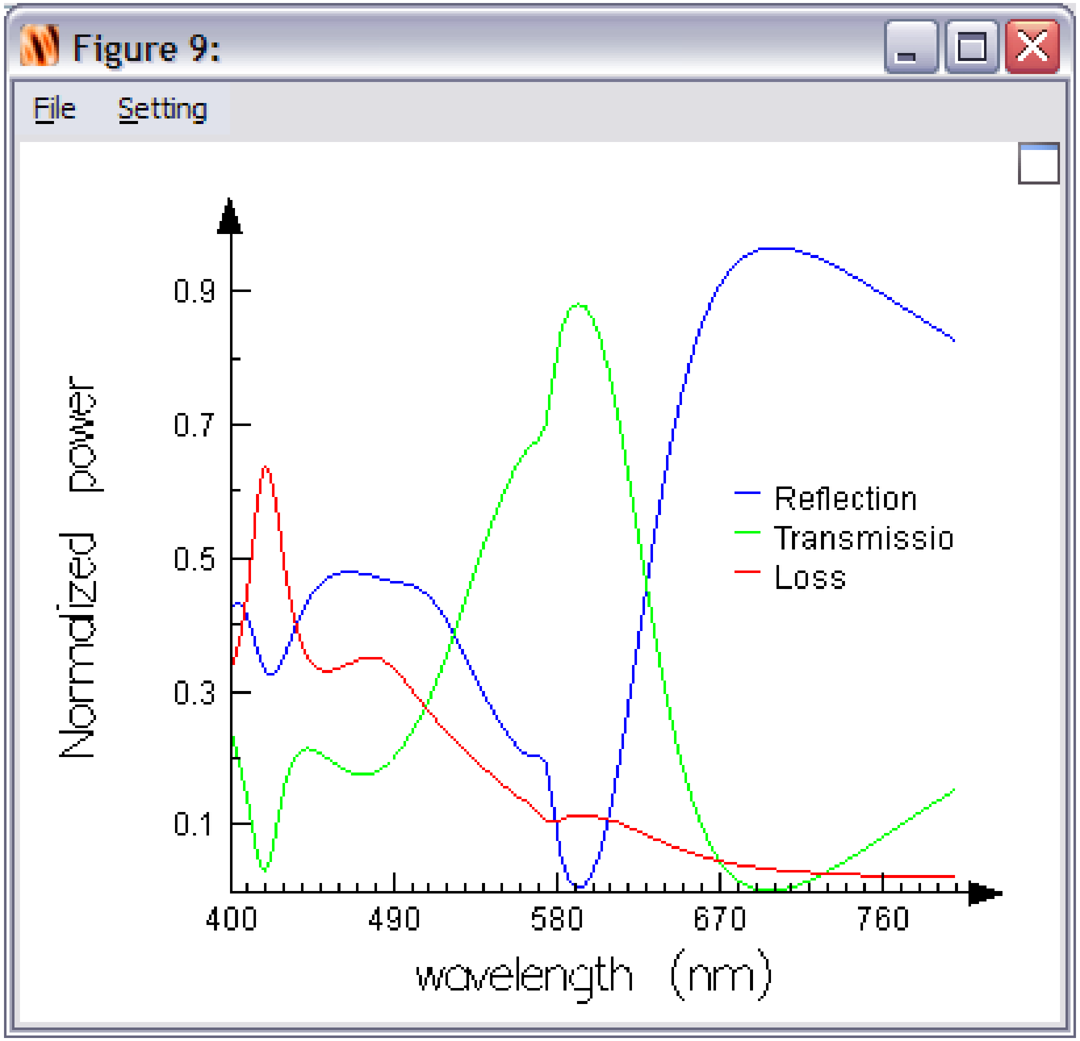






Simple example

- **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)

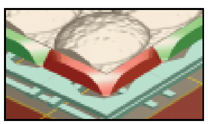
Applications Library

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

Applications of FDTD Solutions to microscale optics and nanophotonics

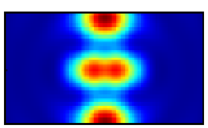
FDTD Solutions addresses a wide variety of applications involving the scattering, diffraction, and propagation of optical radiation. FDTD Solutions is useful for many engineering problems of interest, including:

CMOS Image Sensor Pixel



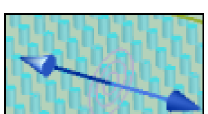
As CMOS pixel sizes decrease to reduce costs of digitial camera systems, there is a corresponding reduction in signal to noise and an increase in pixel cross-talk. Learn more ⇒

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

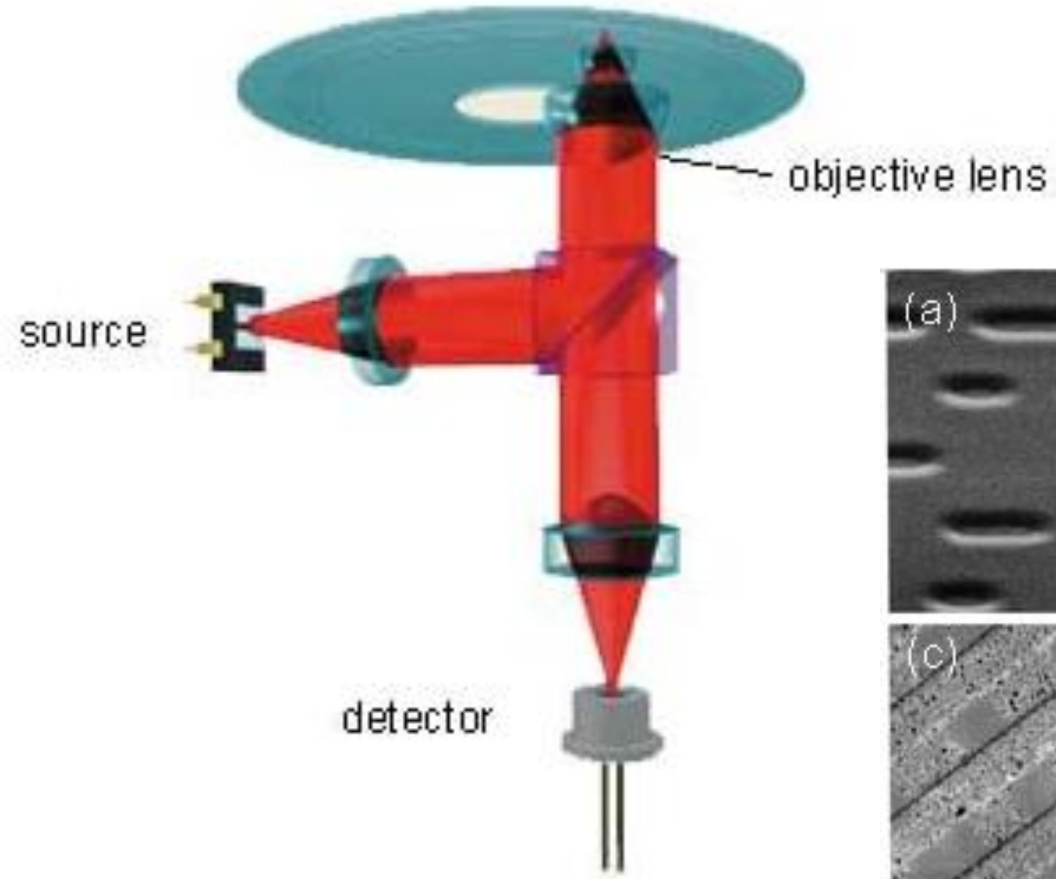
FDTD Solutions

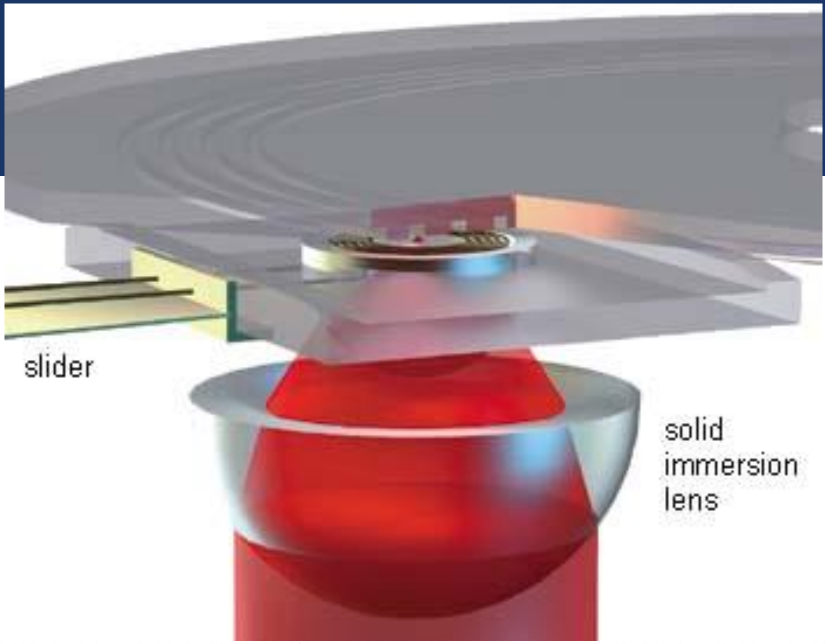
FDTD Solutions Applications Library
- CMOS Image Sensor Pixel
- DUV Lithography Simulation
- DVD Surface Analysis
- LED Light Extraction
- Nanoparticle Scattering
- Nanowire Grid Polarizers
- Photonic Crystal Cavity
- Photonic Crystal VCSEL
- SPR Nanolithography
- Thin Film Solar Cells
- Waveguide Microcavity

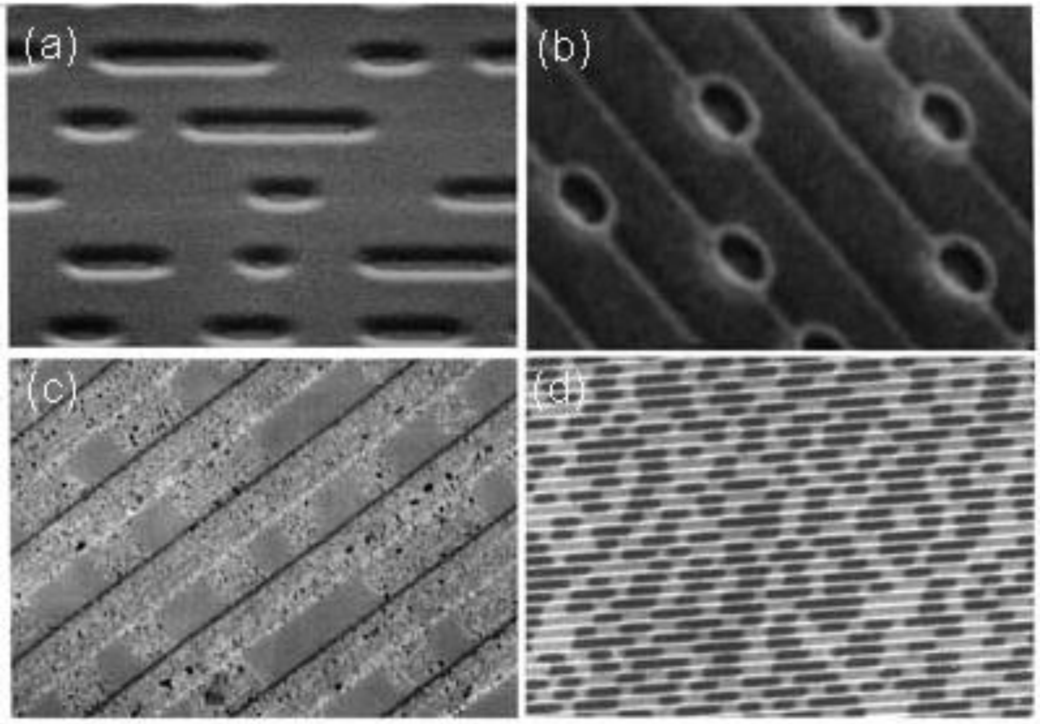
Supported Systems

DVD surface analysis

Optical reading/writing head

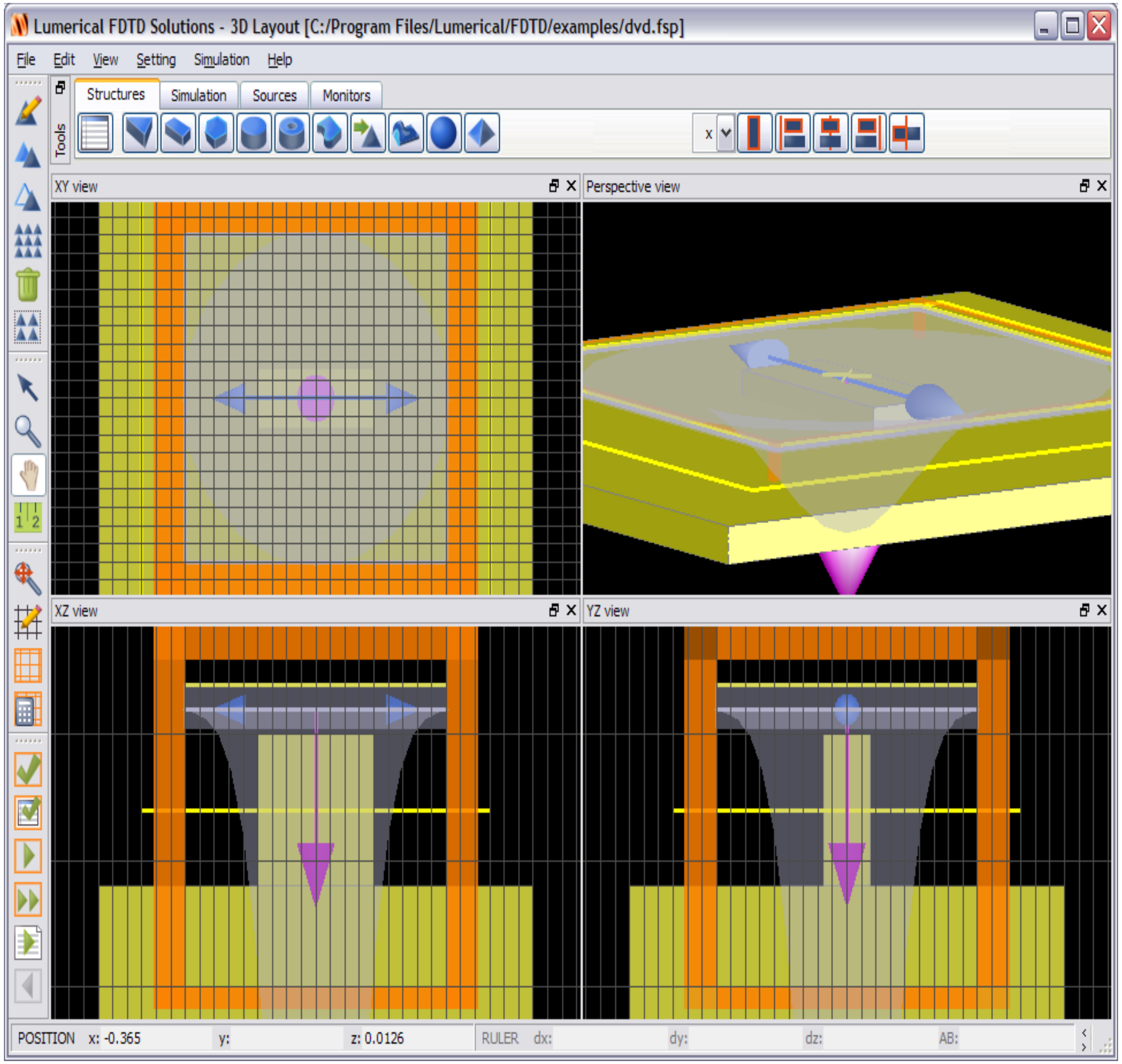






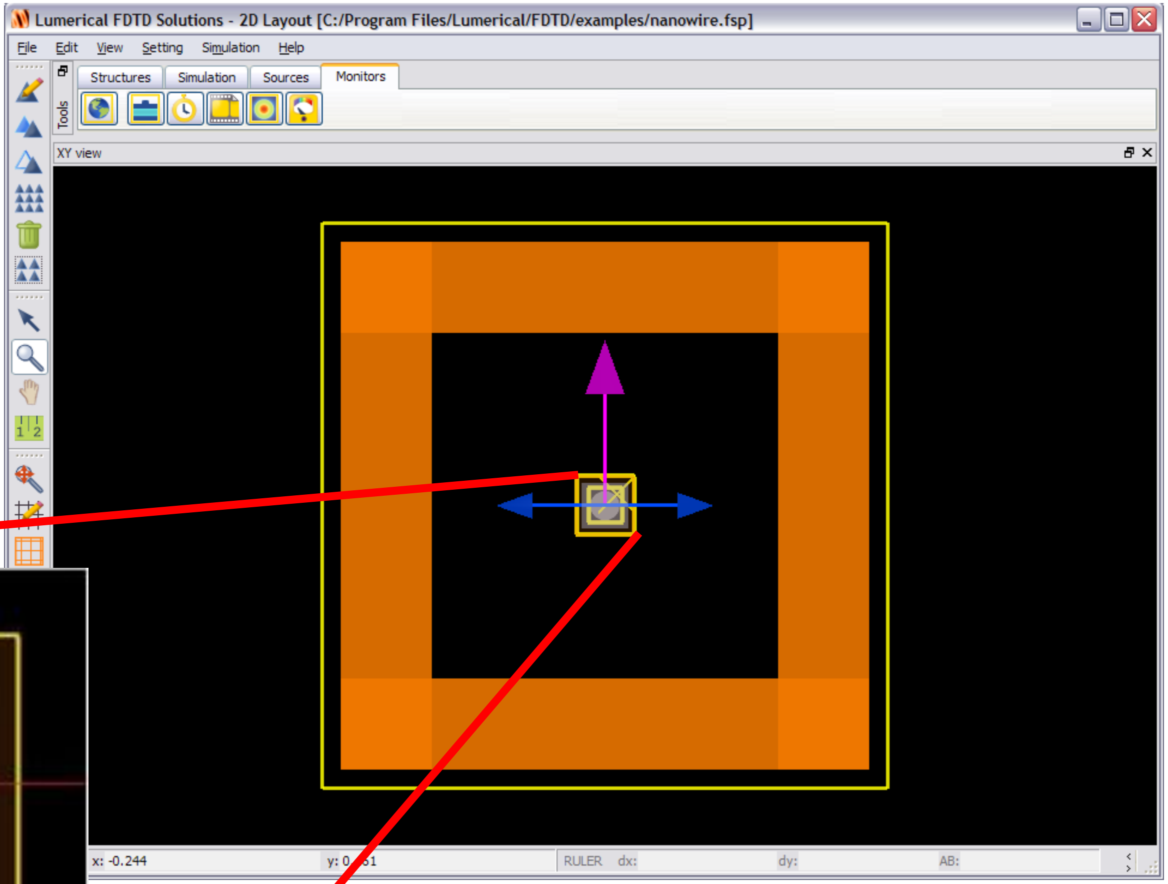
DVD surface analysis

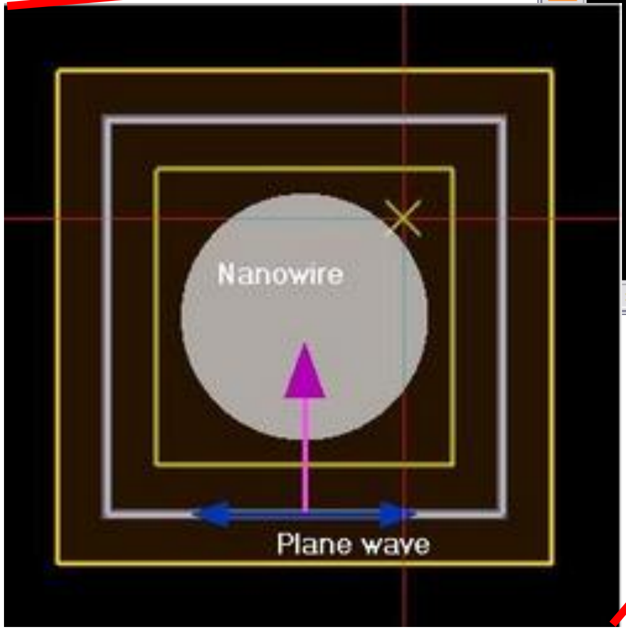
- **Investigate reflections of a focused beam from DVD surface features**



Silver nano-wire

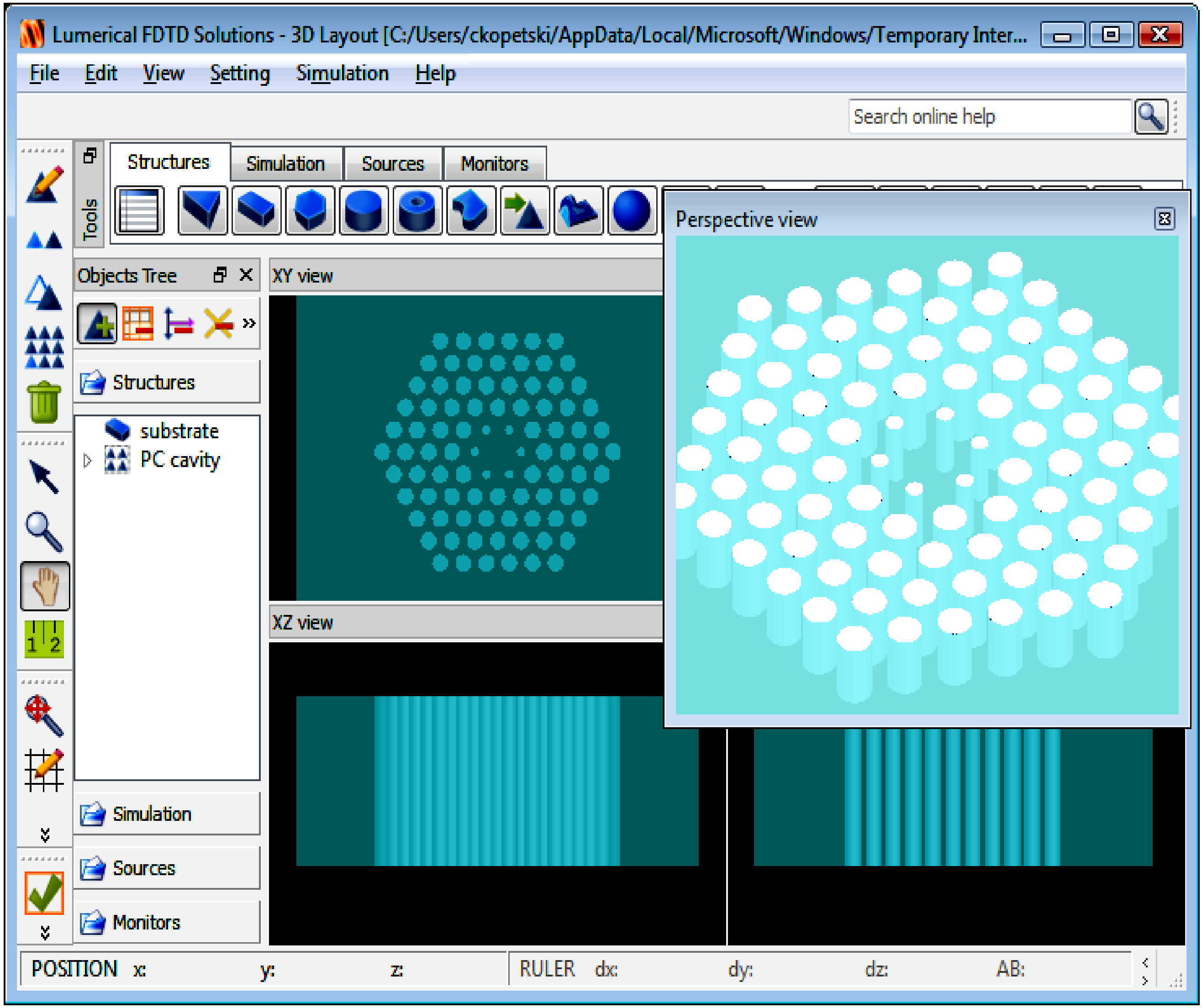
- Study surface plasmons



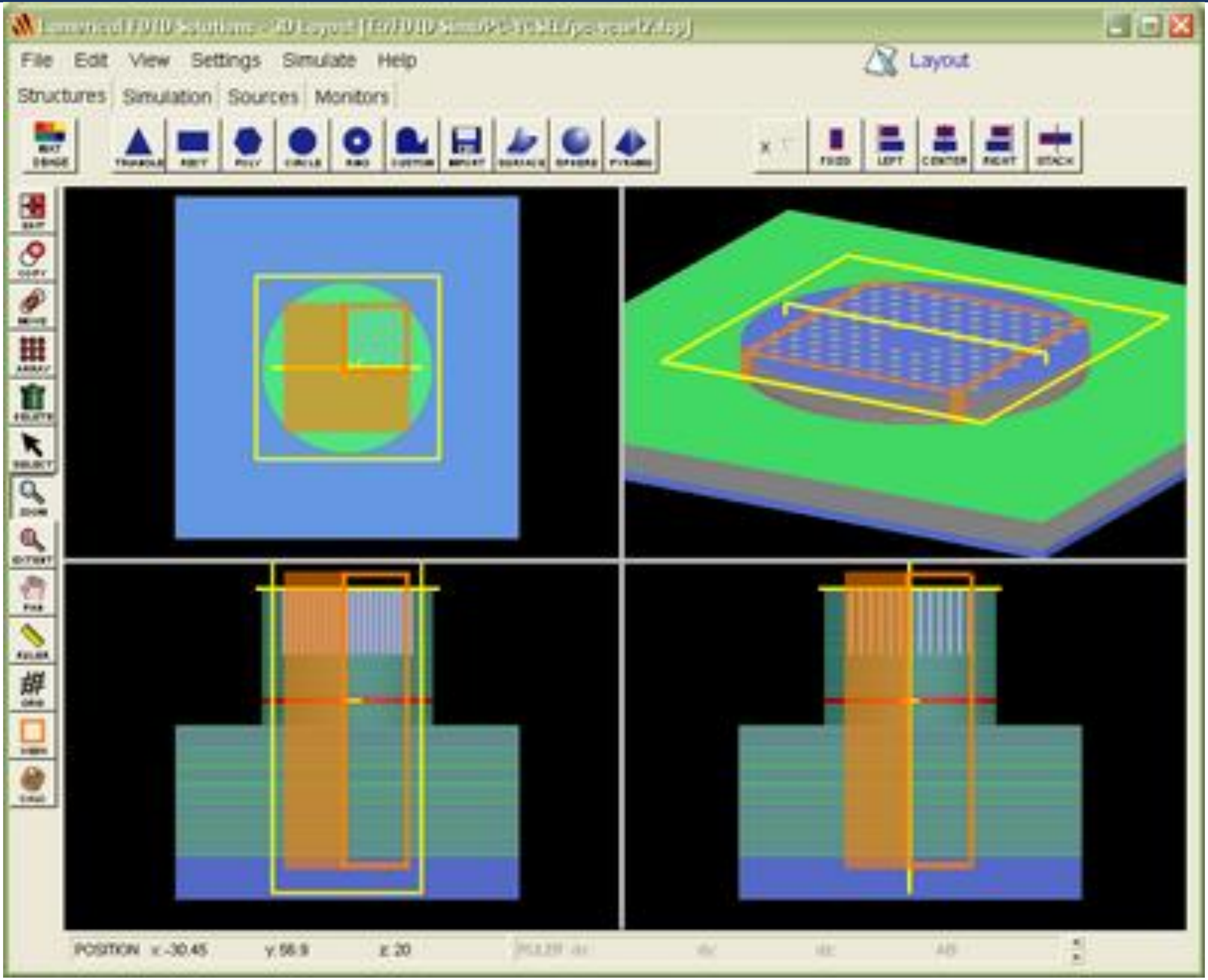


Photonic crystal cavity

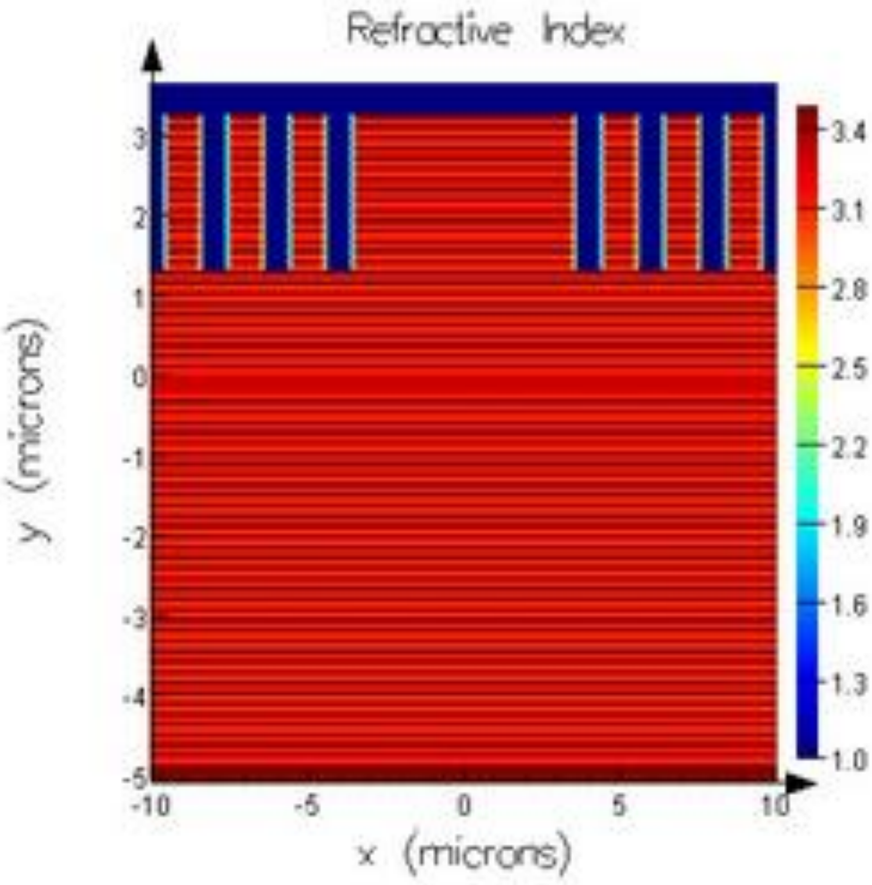
- Determine resonant frequencies of PC cavity



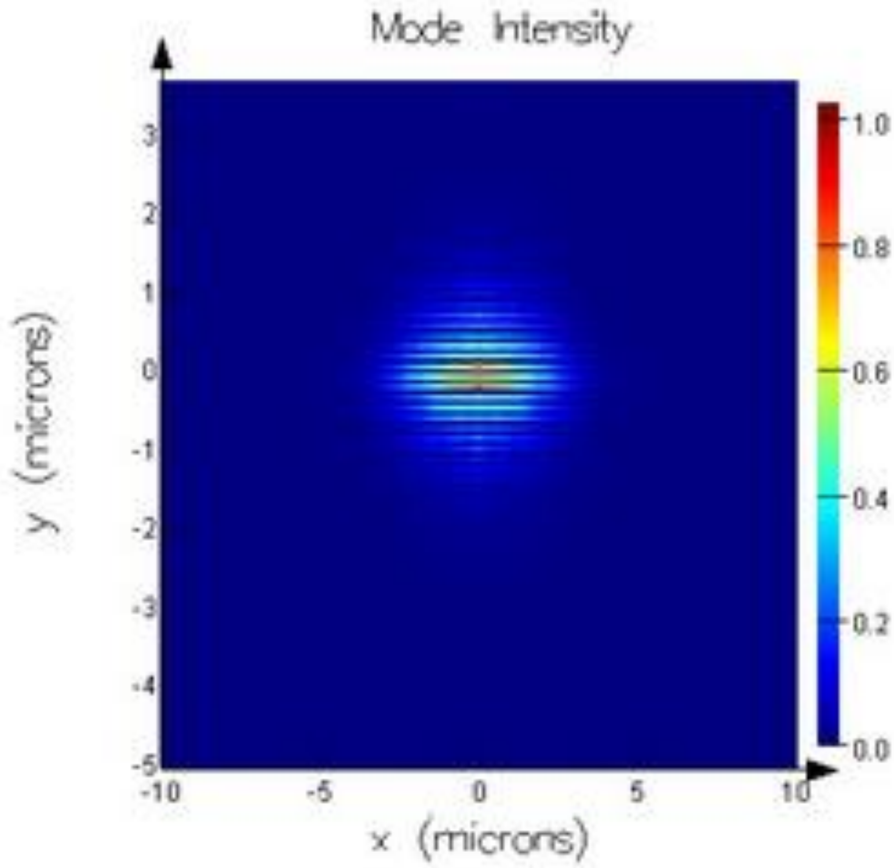
Integration of Photonic Crystal and VCSEL



Integration of Photonic Crystal and VCSEL

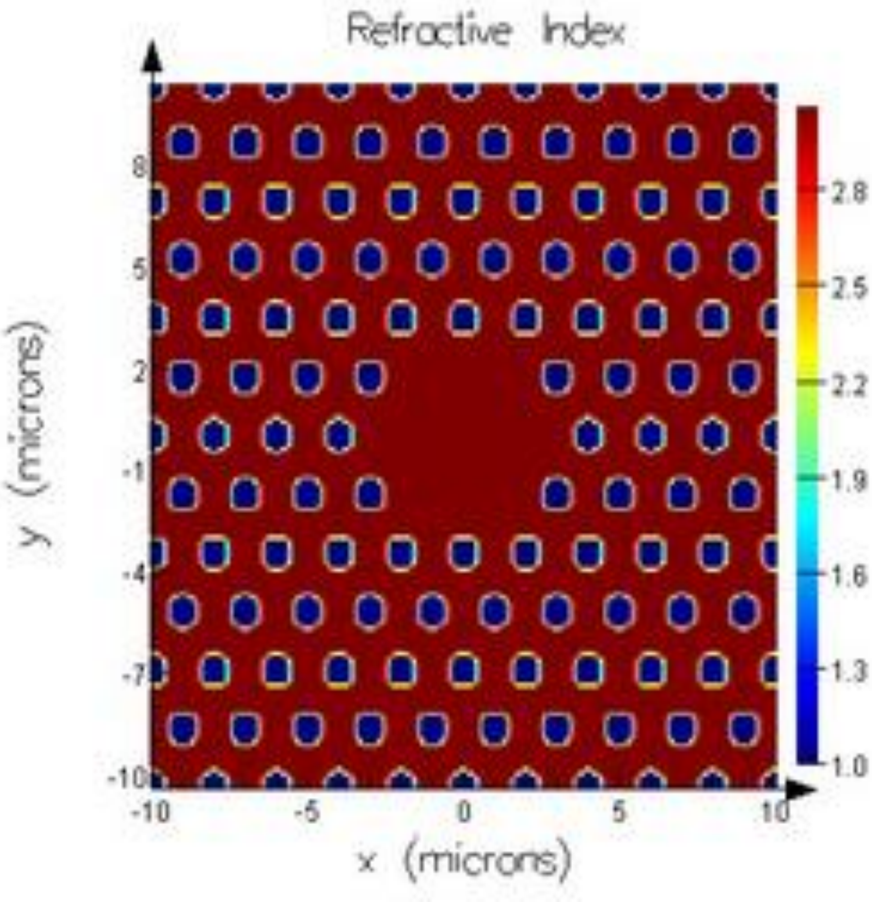


Cross-sectional refractive index distribution of VCSEL

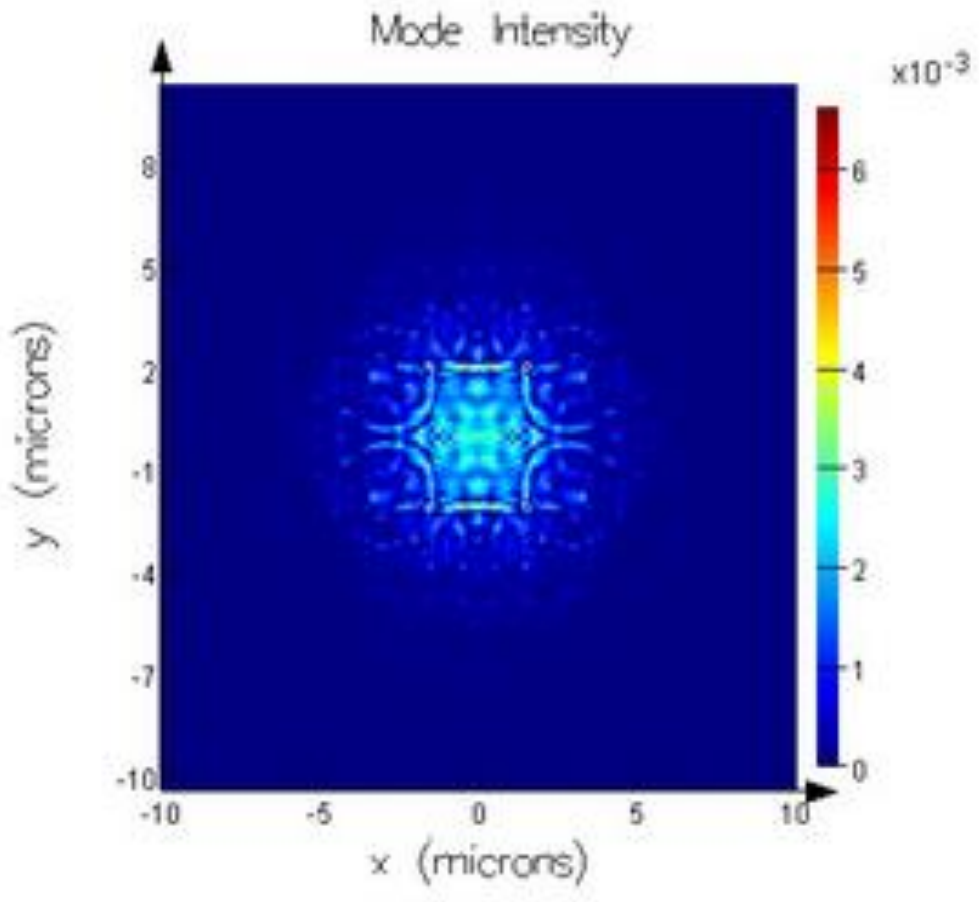


Cross-section of intensity profile of PC-VCSEL cavity mode

Integration of Photonic Crystal and VCSEL

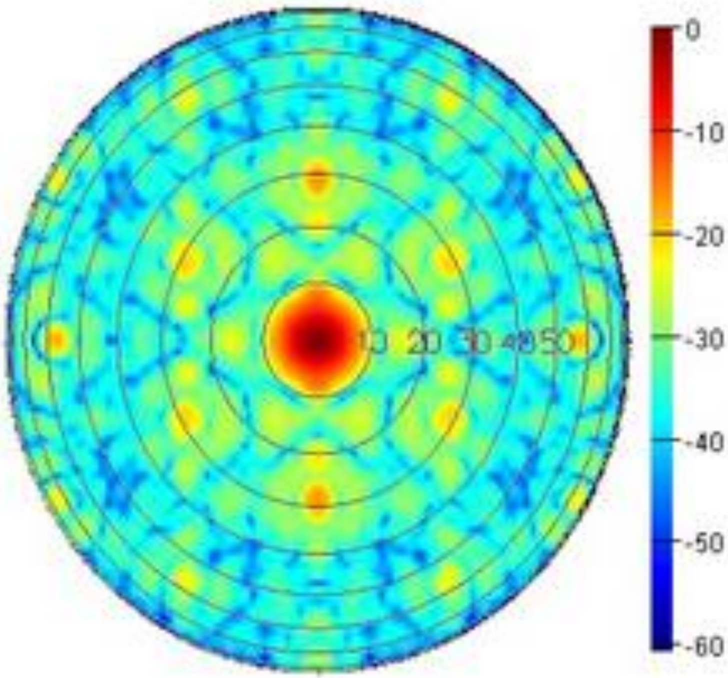


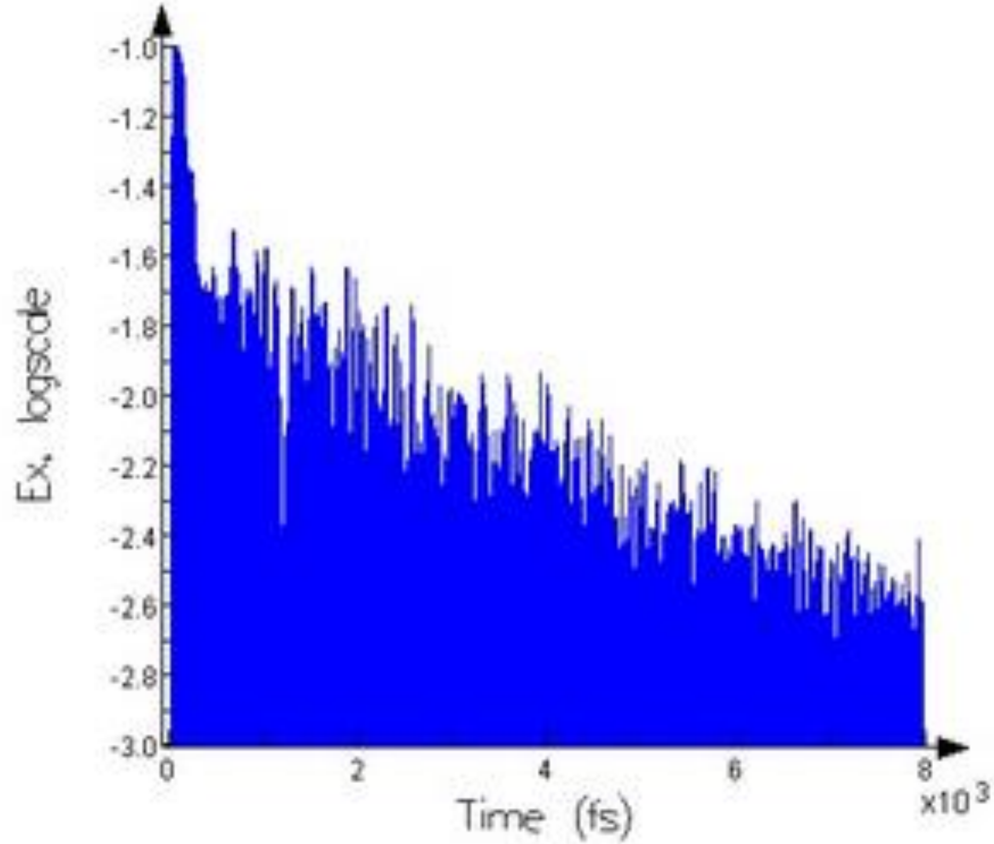
Planar refractive index distribution of PC-VCSEL



Planar intensity profile at surface of PC-VCSEL

Integration of Photonic Crystal and VCSEL



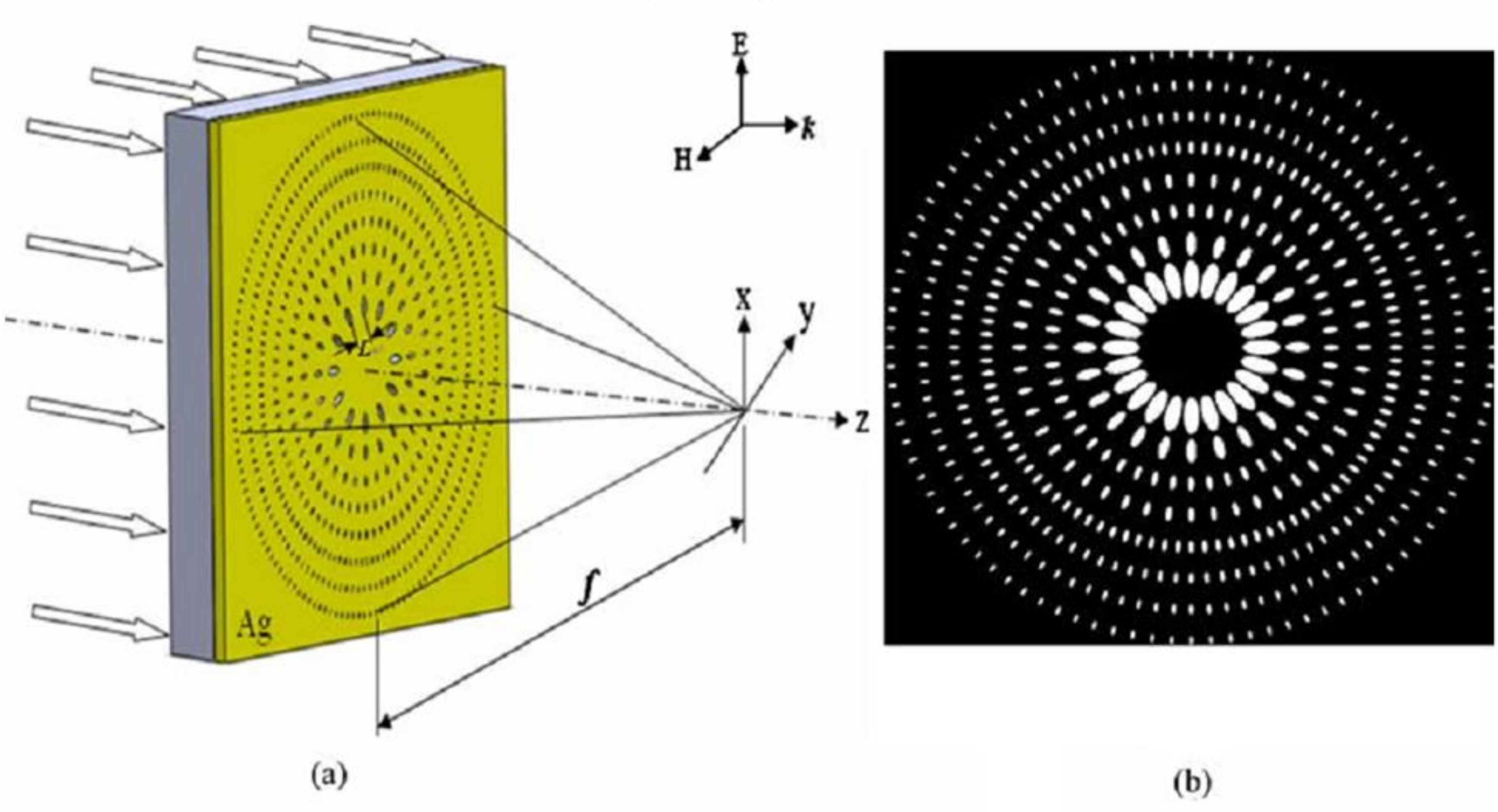


Far-field intensity distribution for PC-VCSEL cavity mode (plot scale in dB).

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

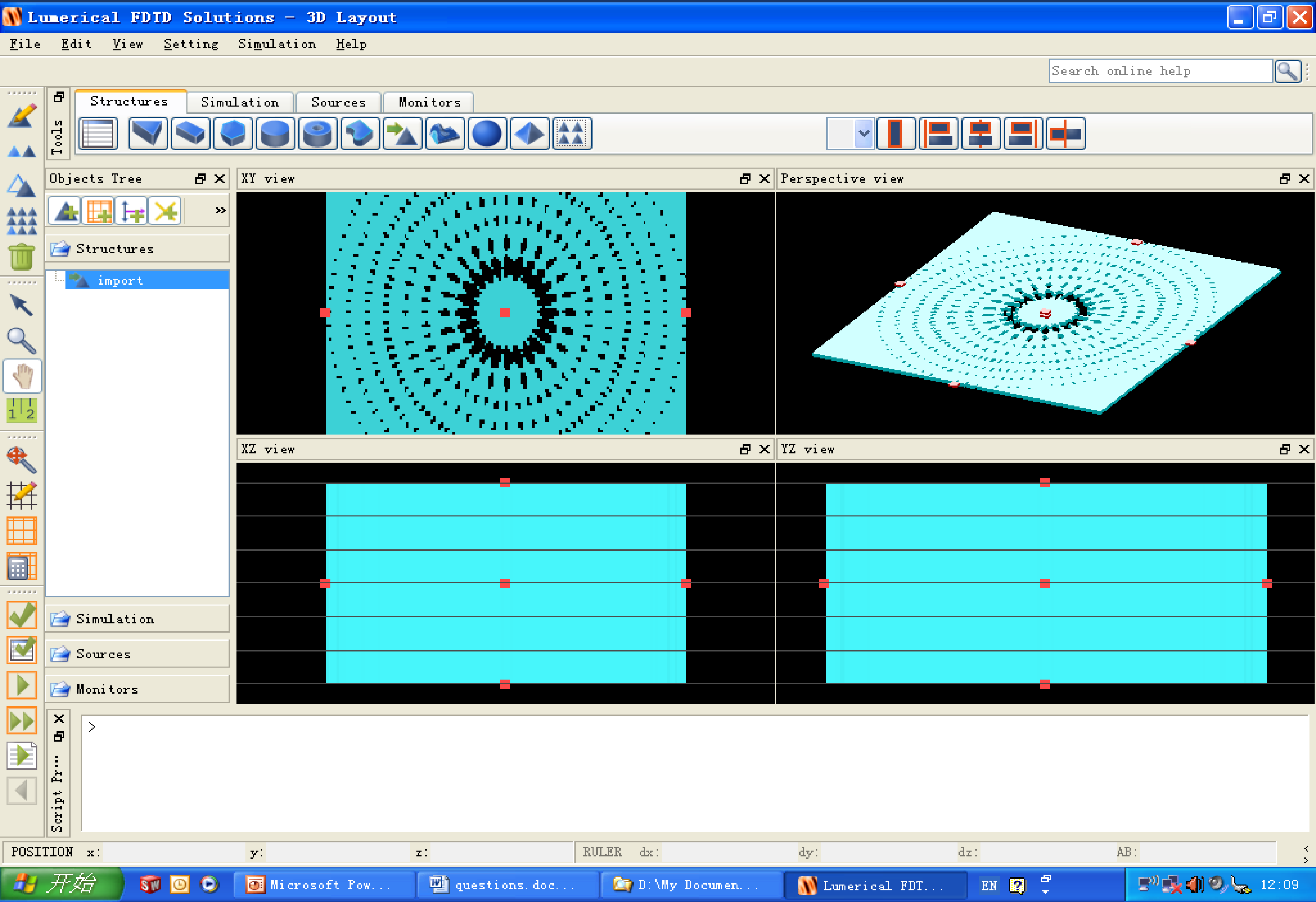
Scripting: Editor and prompt

Structure creation using script



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)

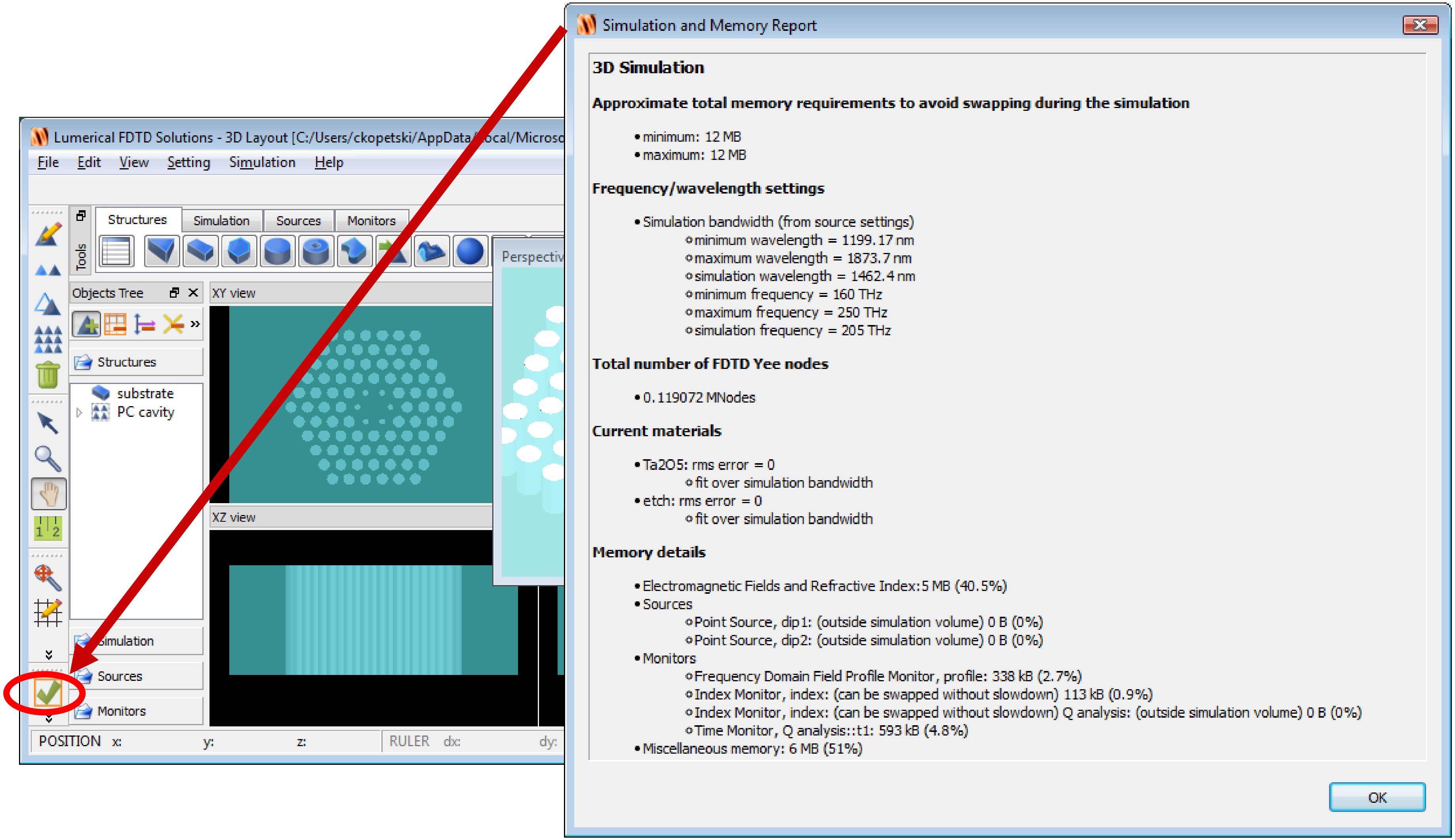
Comparison to the bitmap import method



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**

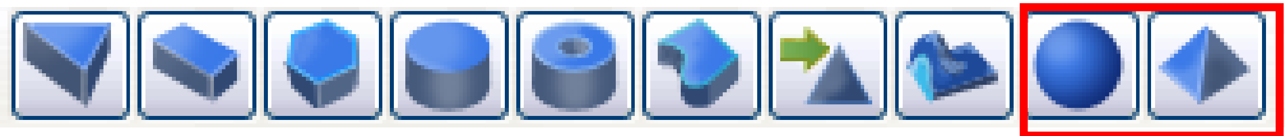
For Your Attention

Thank You

Appendix

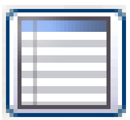
FAQ 1. Creating Physical Structures

- 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?

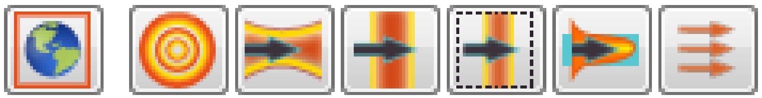
  : **Yes**

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

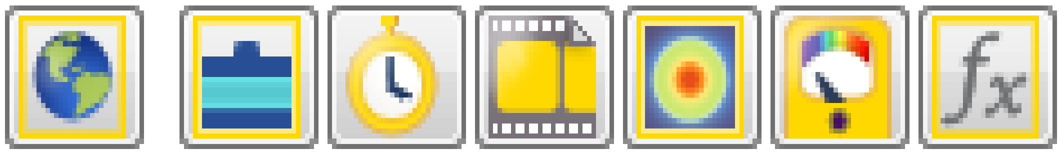
- What sources can I use in FDTD Solutions?



- 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