Tidy3D iOptics OPTICA

FLEXCOMPUTE

Future-Ready FDTD Skills

A Virtual Workshop Series for **All Levels**

Session 1

The FDTD Method Demystified



Dr. Weiliang Jin

Sr. Research Scientist

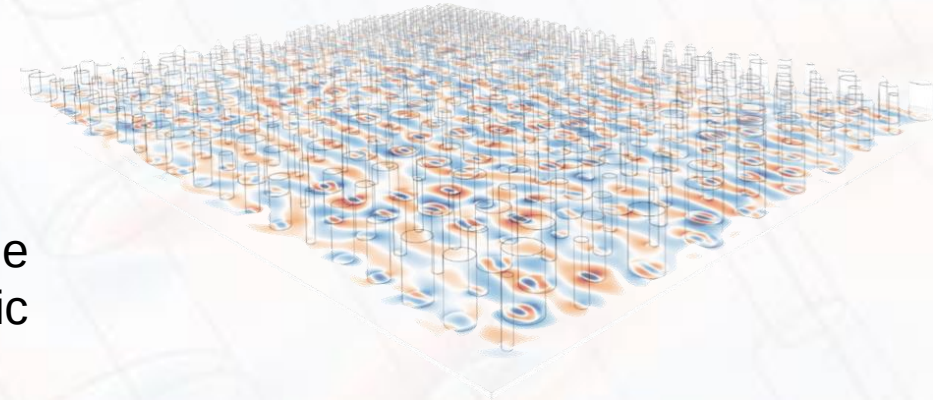
Ph.D. Princeton, Post-Doc Stanford

February 9, 2023 • 1PM CST

OVERVIEW

- A broad understanding of FDTD:
  - How it works (at a high level)
  - Where it is useful

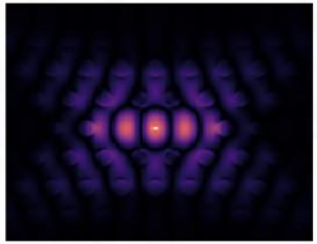
- Get started:
  - FDTD simulations to calculate the scattering efficiency of a dielectric sphere



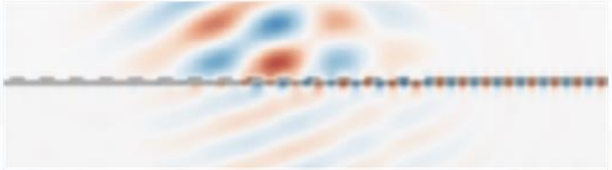
ELECTROMAGNETIC SIMULATIONS

- How to simulate interaction of light with structures and materials?
- General-purpose method: applicable to a wide range of photonics phenomena.

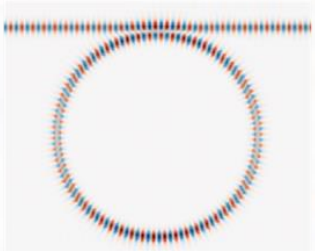
Photonic crystal cavity



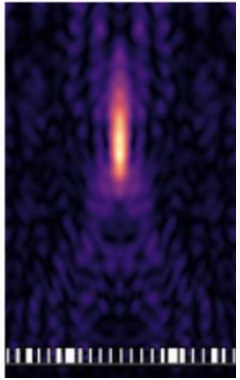
Grating coupler



Ring Resonator



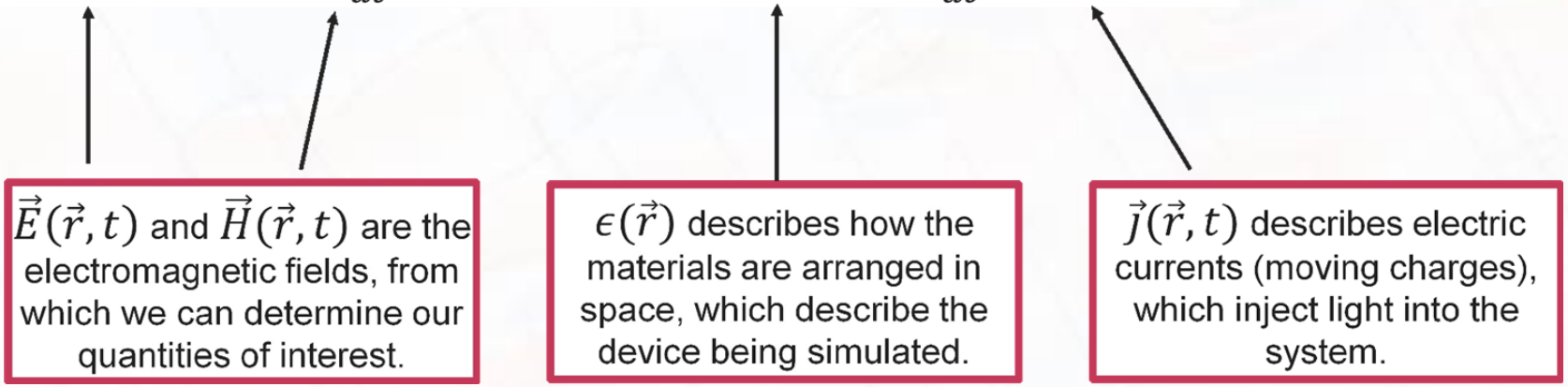
Metasurface



MAXWELL'S EQUATIONS

- In the absence of free charges, electromagnetic phenomena is described by

$$\nabla \times \vec{E}(\vec{r},t) = -\mu_0 \frac{\partial \vec{H}(\vec{r},t)}{dt} \qquad \nabla \times \vec{H}(\vec{r},t) = \epsilon(\vec{r})\epsilon_0 \frac{\partial \vec{E}(\vec{r},t)}{dt} + \vec{j}(\vec{r},t)$$



$\vec{E}(\vec{r},t)$ and $\vec{H}(\vec{r},t)$ are the electromagnetic fields, from which we can determine our quantities of interest.

$\epsilon(\vec{r})$ describes how the materials are arranged in space, which describe the device being simulated.

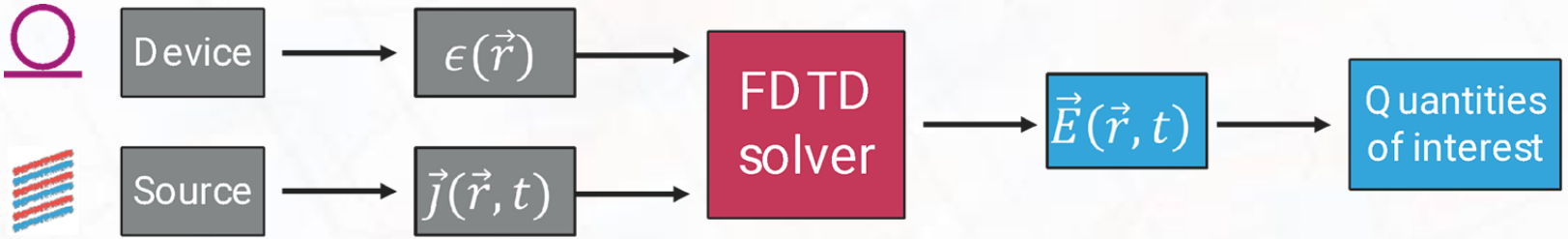
$\vec{j}(\vec{r},t)$ describes electric currents (moving charges), which inject light into the system.

SOLVING MAXWELL'S EQUATIONS

- Goal of EM simulations is to solve these equations for ***E*** and ***H*** given ε and ***J***.

$$\nabla \times \vec{E}(\vec{r},t) = -\mu_0 \frac{\vec{H}(\vec{r},t)}{dt} \qquad \nabla \times \vec{H}(\vec{r},t) = \epsilon(\vec{r})\epsilon_0 \frac{d\vec{E}(\vec{r},t)}{dt} + \vec{j}(\vec{r},t)$$

- Given some device ε and an incident field or current source ***J***.



HOW TO SOLVE MAXWELL'S EQUATIONS

- Analytical / semi-analytical solutions
  - Uniform space, thin films
  - Spheres with Mie theory



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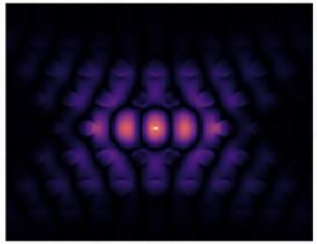
- General-purpose: space discretization into generic basis functions
  - Fourier modal basis (RCWA)
  - Finite-element methods
  - Finite-difference methods
  - ……



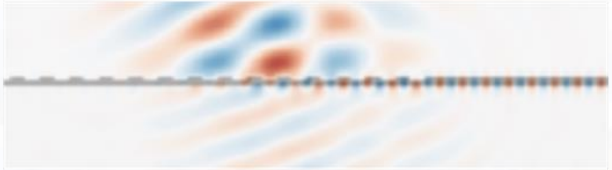
FINITE-DIFFERENCE TIME-DOMAIN (FDTD)

- Most widely used method:
  - Easy to setup simulations
  - Let's you simulate a wide range of phenomena in photonics: nonlinear, dispersive, space-time modulation
  - Accurate, robust, and highly scalable

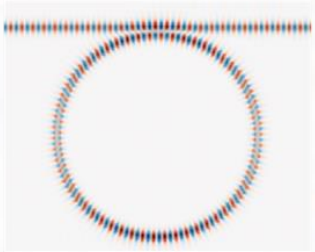
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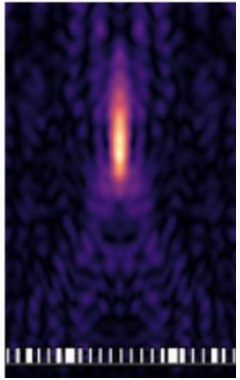
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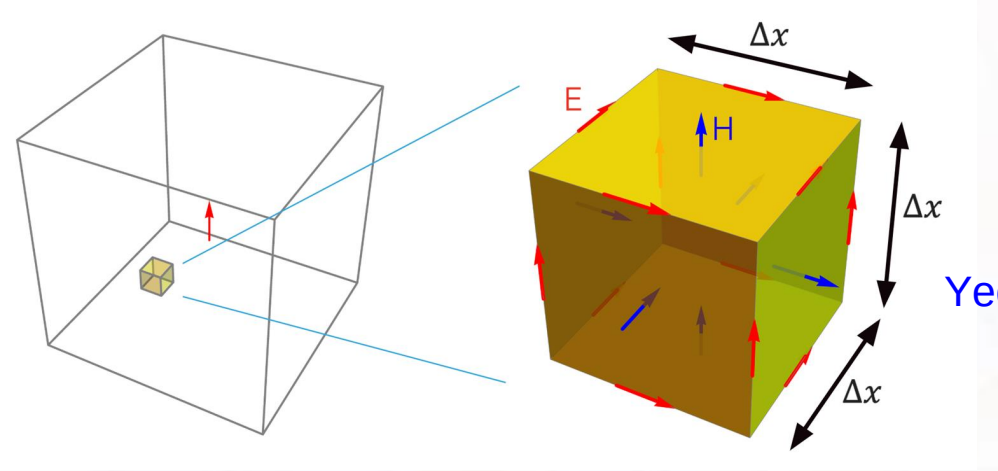


Metasurface



FDTD METHODS

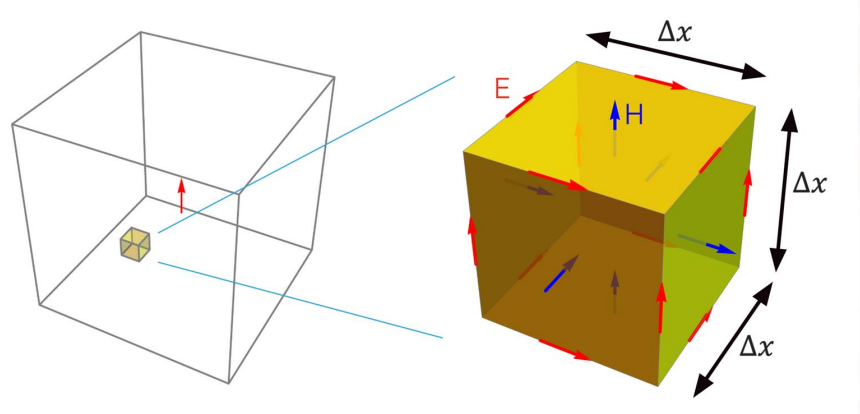
- Staggered rectangular grid: Yee lattice
  - Easy and general-purpose
- Explicit time stepping
  - Scalable to simulate large devices



FDTD METHODS

If the time-domain fields decay by the end of the simulation, their Fourier transform is exactly equivalent to the steady-state harmonic field solution

A single simulation allows us to determine the response over the entire bandwidth



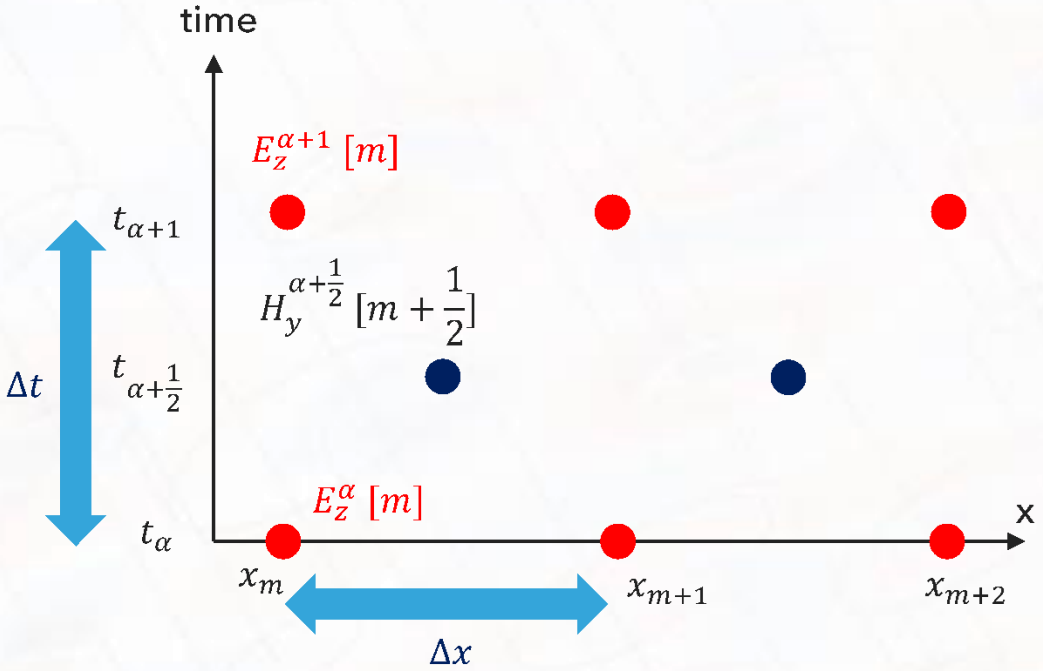
YEE GRID IN 1D

Maxwell's equation in 1D:

$$\varepsilon \frac{\partial E_z}{\partial t} = \frac{\partial H_y}{\partial x}$$
$$\mu \frac{\partial H_y}{\partial t} = \frac{\partial E_z}{\partial x}$$

Discretization:

- Spatial step size: Δx
- Temporal step size: Δt
- Staggered ***E*** and ***H*** in space and time



YEE GRID IN 1D

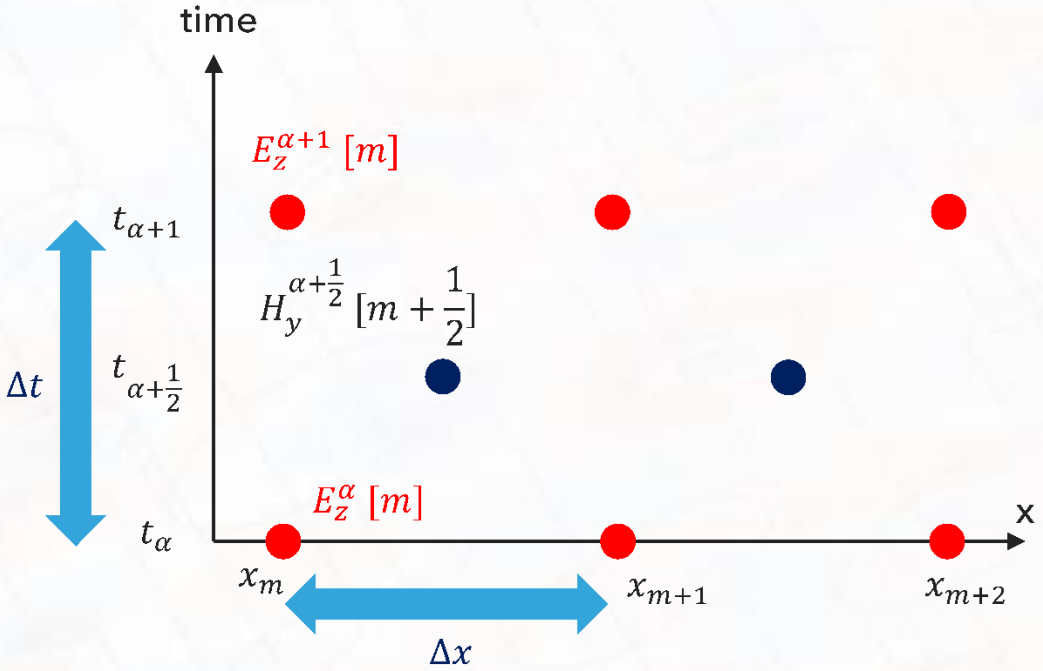
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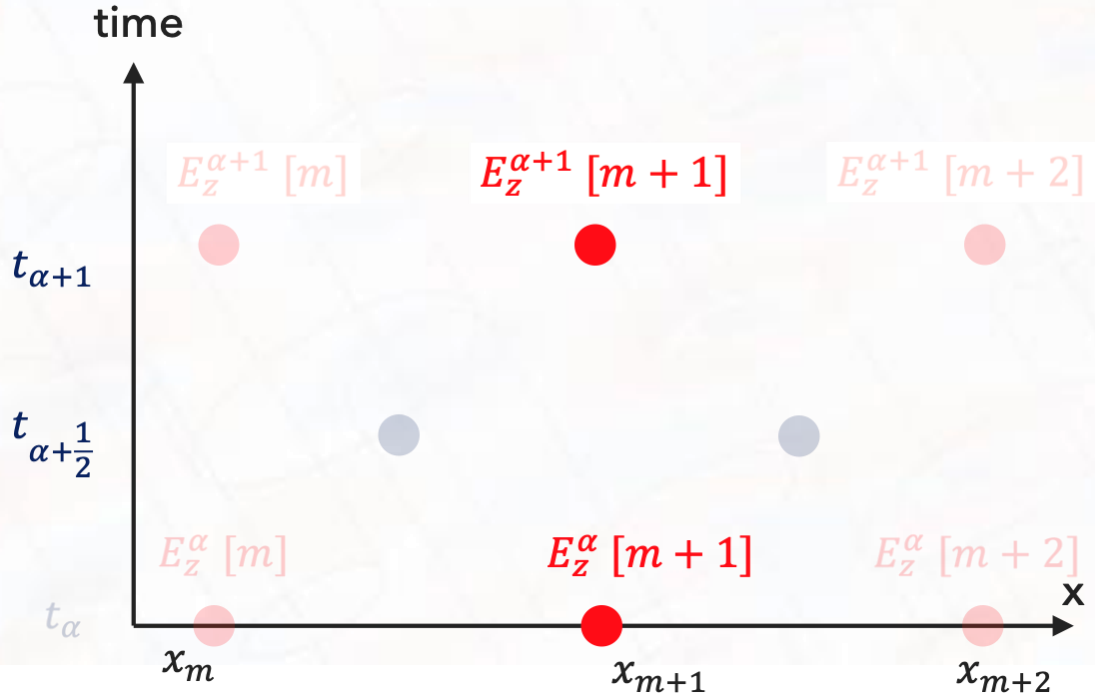
TIME UPDATE FOR E

Finite difference in time:

$$\varepsilon \frac{\partial E_z}{\partial t} = \frac{\partial H_y}{\partial x}$$

Finite difference operator

$$\frac{\partial E_z}{\partial t} \approx \frac{E_z^{\alpha+1} - E_z^{\alpha}}{\Delta t}$$



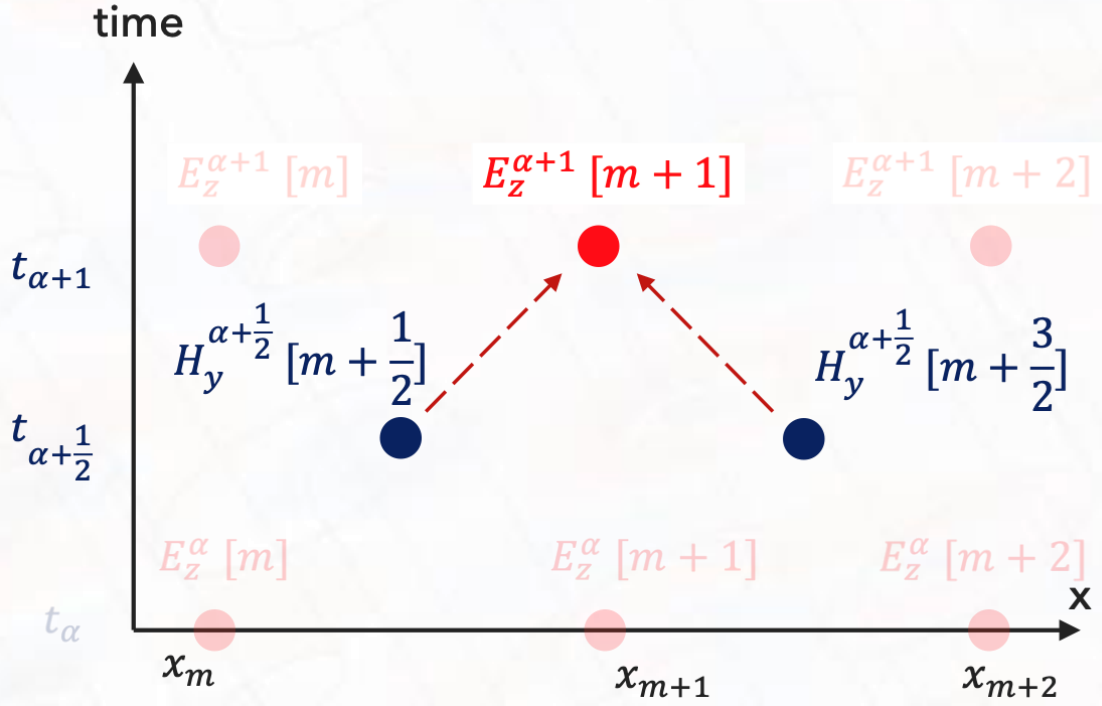
TIME UPDATE FOR E

Finite difference in space:

$$\varepsilon \frac{\partial E_z}{\partial t} = \frac{\partial H_y}{\partial x}$$

Finite difference operator

$$\frac{\partial H_y}{\partial x} \approx \frac{H_y[m+\frac{3}{2}] - H_y[m+\frac{1}{2}]}{\Delta x}$$



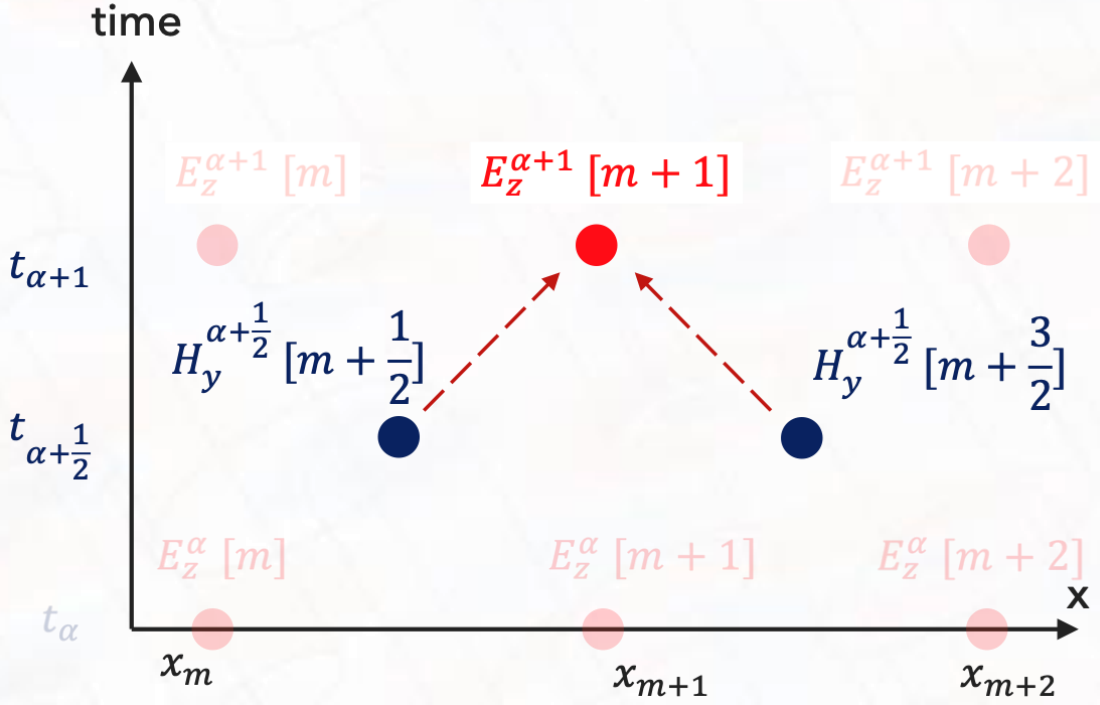
YEE GRID IN 1D

Time update for $\boldsymbol{E}_z$:

$$\varepsilon \frac{\partial E_z}{\partial t} = \frac{\partial H_y}{\partial x}$$

Center difference in both space and time:

- 2nd order accuracy!

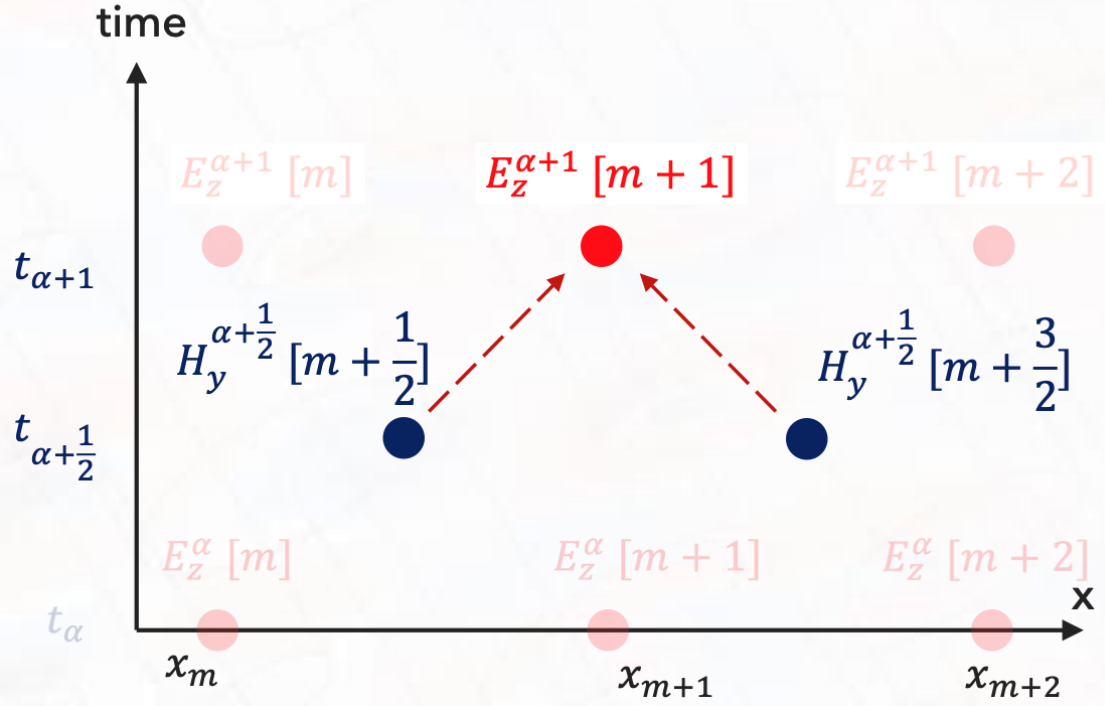


YEE GRID IN 1D

Time update for $\boldsymbol{E}_z$:

$$\varepsilon \frac{\partial E_z}{\partial t} = \frac{\partial H_y}{\partial x}$$

$$E_z^{\alpha+1}[m+1] = E_z^{\alpha}[m+1] + \frac{\Delta t}{\varepsilon \Delta x}\left(H_y^{\alpha+\frac{1}{2}}\left[m+\frac{3}{2}\right] - H_y^{\alpha+\frac{1}{2}}\left[m+\frac{1}{2}\right]\right)$$

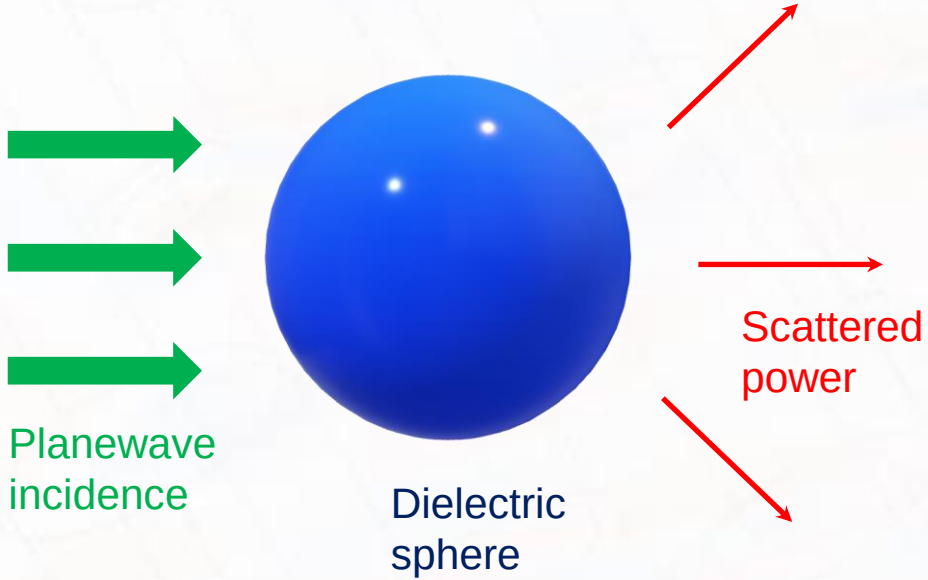


OTHER CONCEPTS IN FDTD METHODS

- Space and time discretization
- Boundary truncation with Perfectly matched layers (PML)
- Source injection: Gaussian pulse
- Total-field scattered-field (TFSF)
- ……

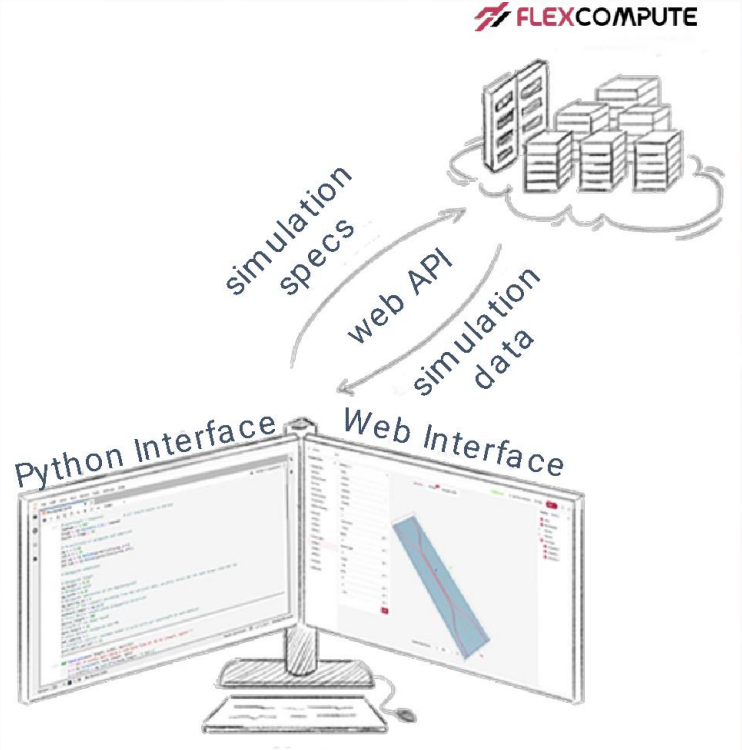
EXAMPLE: SPHERE SCATTERING

- Goal: compute total scattered power in a range of frequencies.
- Benchmark against theory: Mie scattering



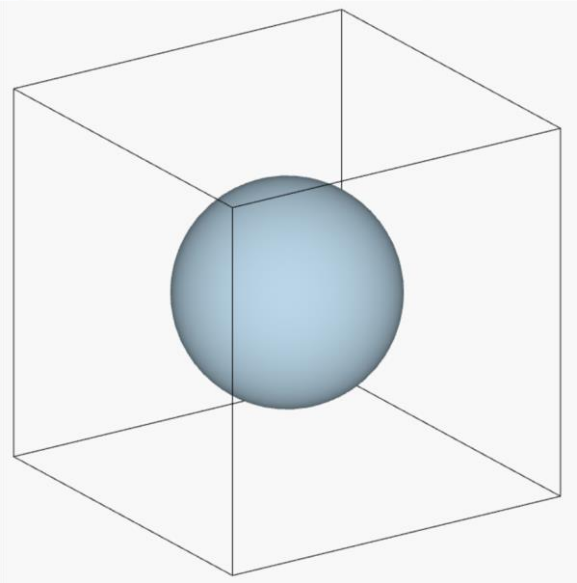
RUNNING Tidy3D SIMULATIONS

- How to setup and run simulations:
  - Open source, python package.
  - Browser-based GUI.



DEVICE DEFINITION

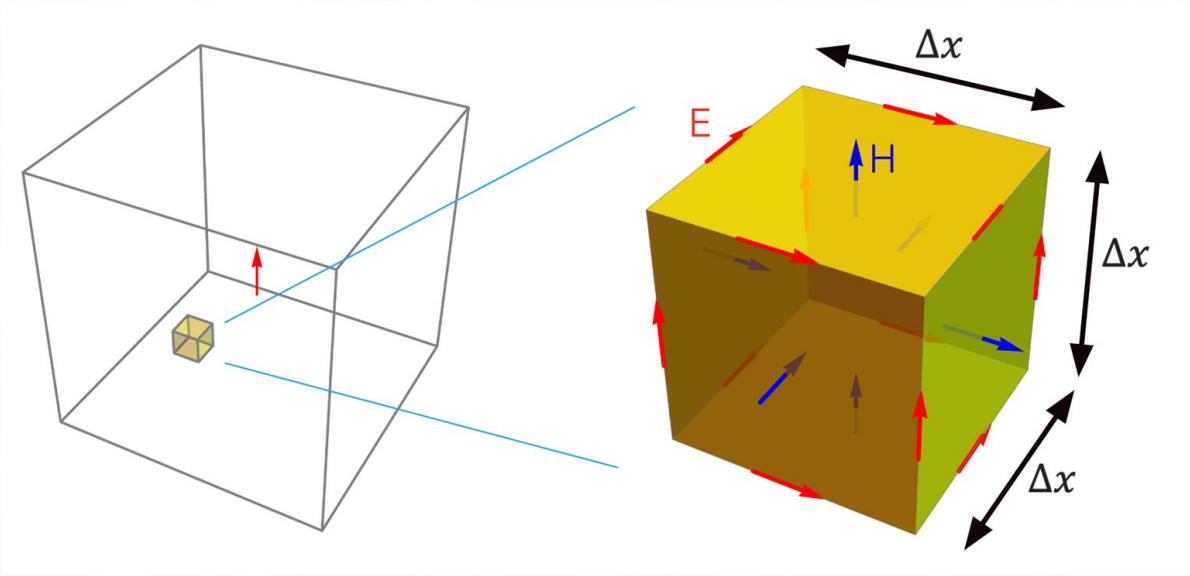
- Radius: 0.15 μm
- Material: refractive index 3.48



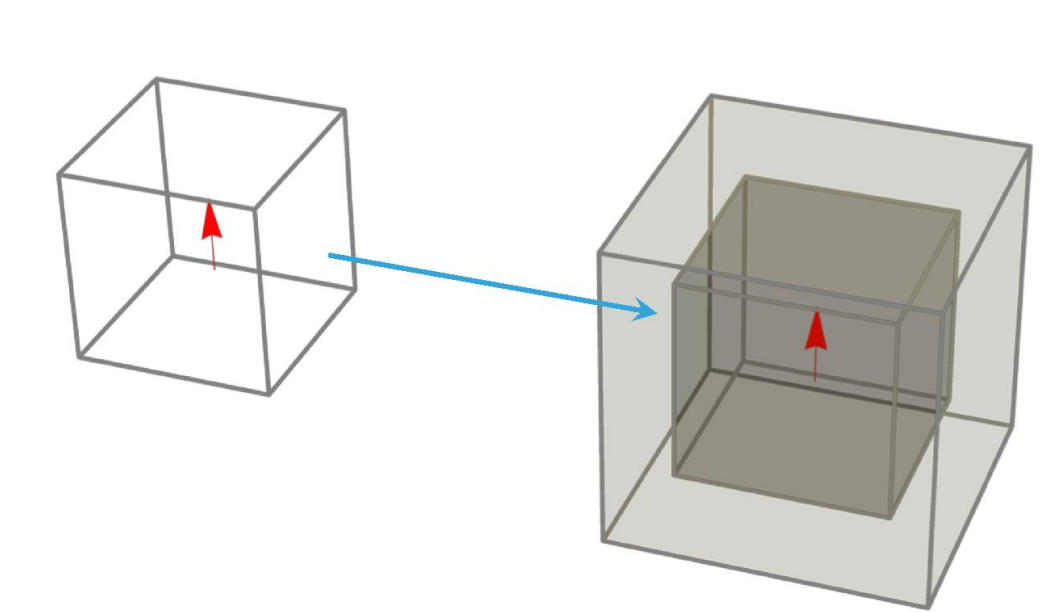
Dielectric sphere

DISCRETIZATION

- Typical choice: $\Delta x = \lambda/20$
- Time step size: CFL condition



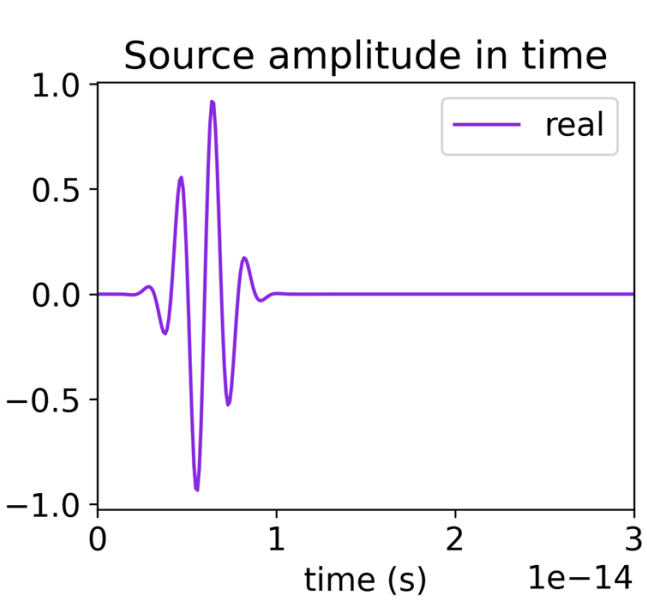
BOUNDARY CONDITIONS

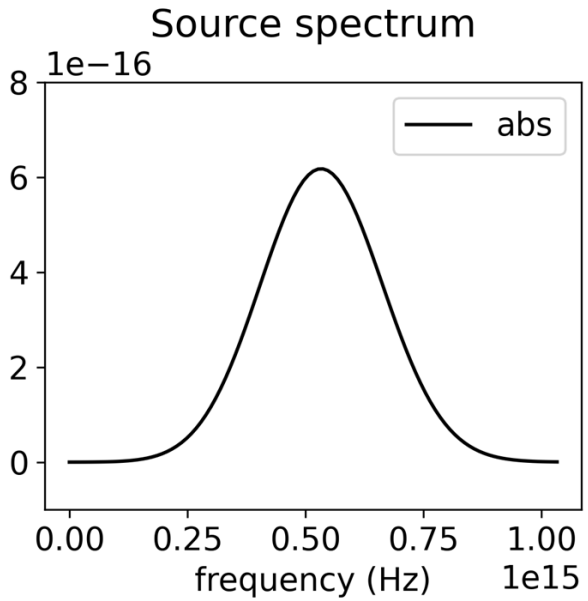


Computational domain surrounded by Perfectly Matched Layers (PML), with a thickness of typically 10 Yee cells

SOURCE INJECTION: TEMPORAL PROFILE

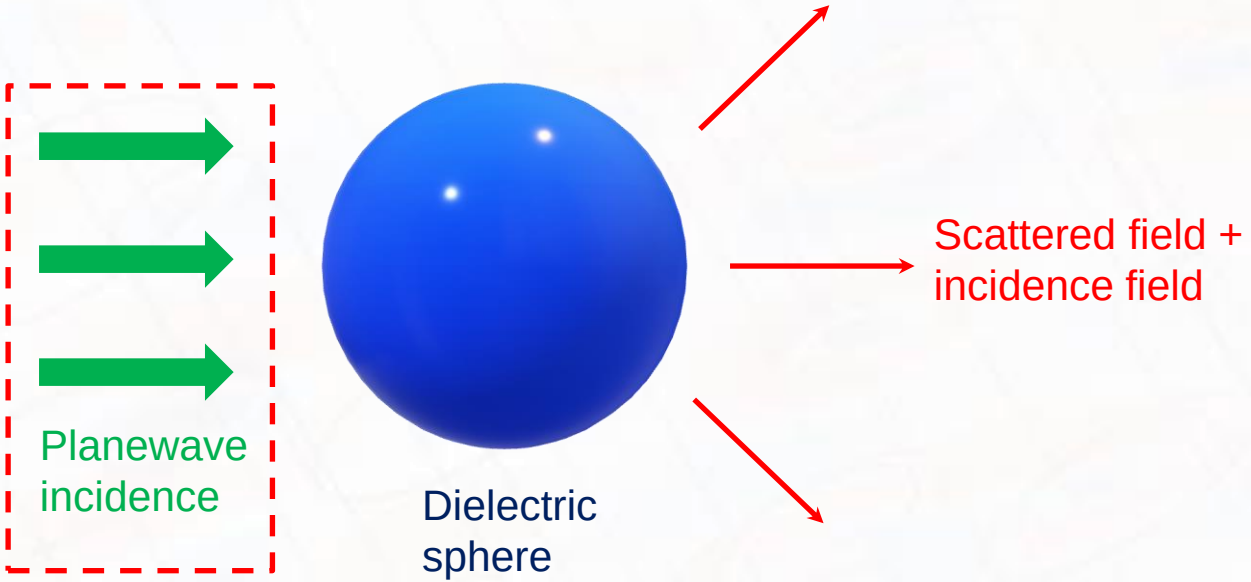
- Pulsed source: broadband input



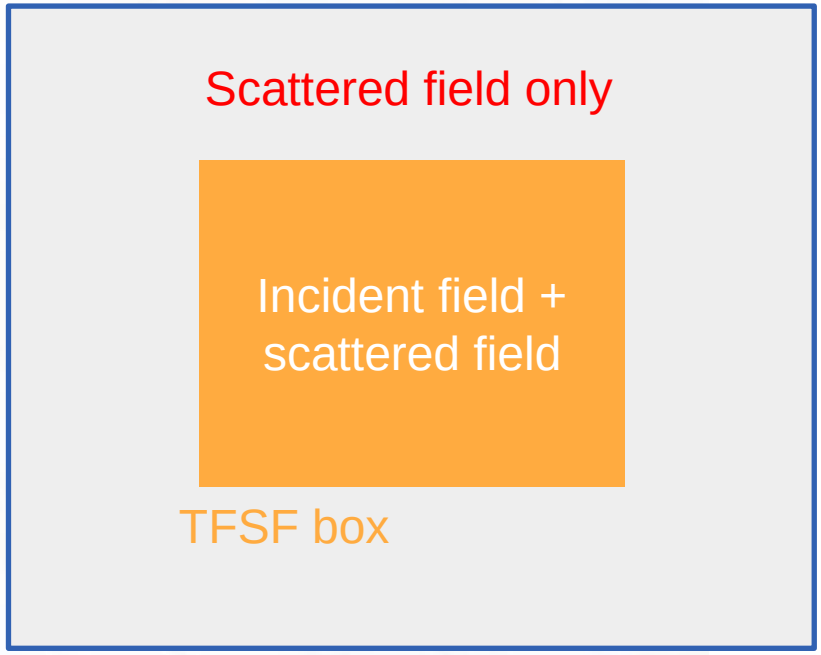


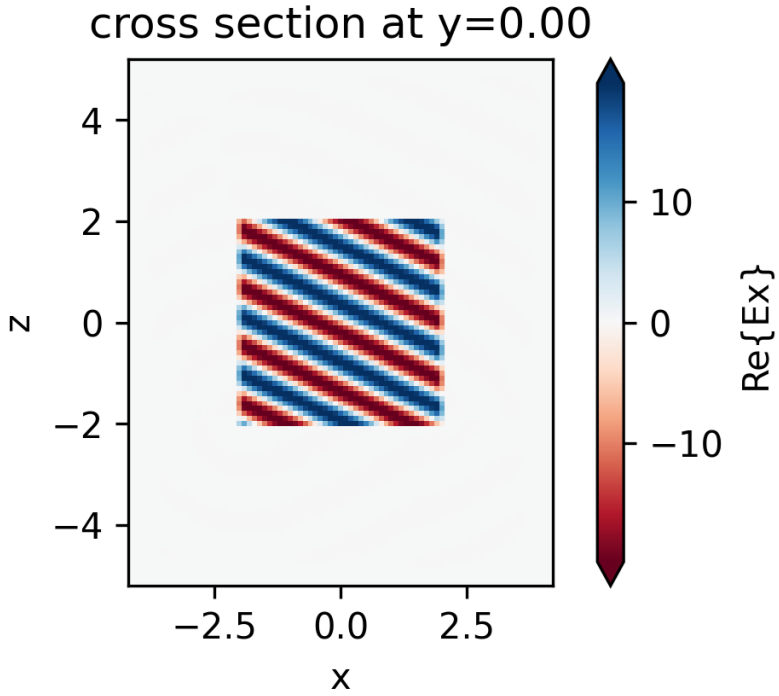
SOURCE INJECTION: SPATIAL PROFILE

- How to obtain scattered field to compute scattered power?
- One approach: run a reference simulation without sphere to obtain incidence field



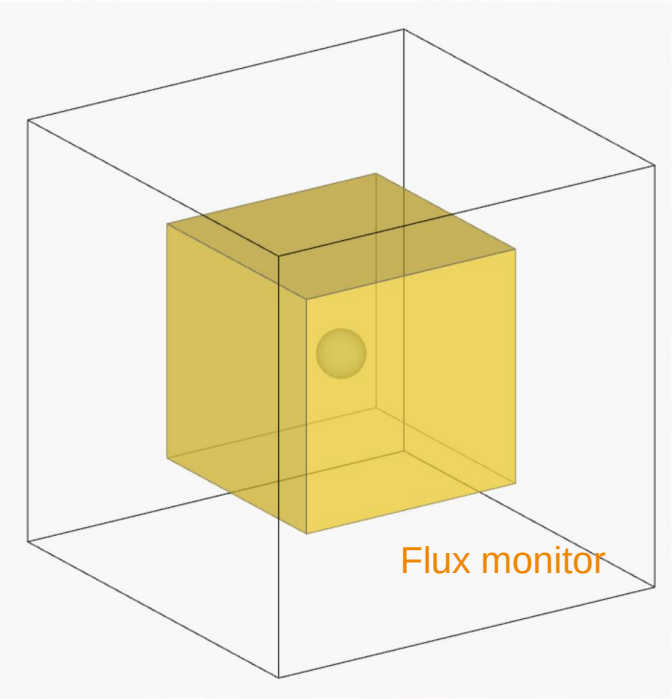
TOTAL-FIELD SCATTERED-FIELD (TFSF)





FLUX MONITORS

- Integrate Poynting flux over the surfaces to compute total scattered power
- Defined at multiple frequencies





Dr. Weiliang Jin
Sr. Research Scientist
Ph.D. Princeton, Post-Doc Stanford

What We Learned Today

- Insight into how FDTD works: Yee grids
- FDTD is a general-purpose method, scalable to simulate a very large device
- How to simulate scattering efficiency of a dielectric sphere: TFSF, PML, flux monitors…

For more questions please contact:

support@flexcompute.com, marjon@flexcompute.com

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Fridays • 1-2pm CT



The FDTD Method
Feb 9 Dr. Weiliang Jin • *Princeton, Stanford*



Multimode Photonics Design
Feb 16 Dr. Lucas Gabrielli • *Cornell*



Designing Filters + Reflectors
Feb 23 Dr. Tom Chen • *Stony Brook*



Photonic Crystal Slabs
Mar 1 Dr. Momchil Minkov • *EPFL, Stanford*



Inverse Design in Photonics
Mar 8 Dr. Tyler Hughes • *Stanford*

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Today's Session

Tidy3D iOptics OPTICA

Two-Part Session

- Theory
- Example Walkthrough

Questions

- **Chat is open for Qs!** Ask anytime.
- We will respond to as many as possible.
- Some questions will be read live to Dr. Jin.
- Responses to answered questions via email.

Emails

Tidy3D iOptics OPTICA

Pre-Session Emails

- Reminder for upcoming session
- Recording from previous session
- Optional pre-session homework

Post-Session Emails

- Slides
- Session example with solution
- Exercise without solution
- Very important for Level 3

Perks

Tidy3D iOptics OPTICA

Live Attendance

- 10 FlexCredits to all live attendees.
- **Code of the week** to be shared via email.

Certificate of Achievement

- It’s a surprise… 🤫
- Revealed during **Session 2**



Today's Speaker

Tidy3D iOptics OPTICA

Dr. Weiliang Jin

Senior Scientist, Tidy3D

Bachelor's @ Peking University

Physics

Ph.D. @ Princeton University

Electrical & Electronics Engineering

Post-Doc @ Stanford University (Fan Lab)

Photonics Design, Thermal Management, Laser Cooling