Lecture #26

Final Lecture

Lecture Outline

- Key points from course
- TE vs. TM
- Resonance hunting
- Photonic crystals fabricated by multi-photon direct laser writing
Key Points From Course

Key Steps in the Art of Computational EM

• Formulation of the method
  – Maxwell’s equations → numerical equations
• Implementation of the method
  – Numerical equations → computer code
• Using the modeling tool
  – Device → grid → extract data
  – Assumptions for model
• Reconciling the model with experimental results
  – Model → reality
Material Covered This Semester

• MATLAB
  – Basic commands
  – Graphics
  – Putting devices on grids
• 1D FDTD
  – Formulation: Yee grid, finite-differences, update equations, update coefficients
  – Implementation: PAB, TF/SF, Fourier transforms, transmittance and reflectance, grid resolution
  – Generalizations: loss, dispersion
• 2D FDTD
  – Formulation: boundary conditions, PML, update equations, update coefficients
  – Implementation: PML, TF/SF, Fourier transforms, transmittance, reflectance
  – Generalizations: stretched coordinate PML, alternate grid schemes, waveguides, metals, periodic devices

Other Key Points

• Rhythm of deriving update coefficients
• Order of code development
• Art of representing devices on grids
Questions for an In-Class Final Exam

• Write Maxwell’s equations
• Draw and label a 3D Yee cell
• Discuss the benefits and drawbacks of FDTD
• Rules of finite-difference equations
• Deriving an update equation from a simple finite-difference equation
• Outline the FDTD algorithm

TE vs. TM Modes in 2D Simulations
Reduction from 3D to 2D

Uniform Device

Effective Index Method

Two Distinct Modes in 2D

For 2D devices, \( \frac{d}{dz} = 0 \) and Maxwell's equations separate into two distinct modes.

- **Ez Mode**
  - \( \frac{\partial E_z}{\partial y} = \mu_y \frac{\partial H_y}{\partial z} \)
  - \( \frac{\partial E_z}{\partial x} = -\mu_x \frac{\partial H_x}{\partial z} \)
  - \( \frac{\partial E_z}{\partial t} = -\epsilon_z \frac{\partial E_z}{\partial t} \)

- **Hz Mode**
  - \( \frac{\partial H_z}{\partial y} = \epsilon_y \frac{\partial E_y}{\partial z} \)
  - \( \frac{\partial H_z}{\partial x} = -\epsilon_x \frac{\partial E_x}{\partial z} \)
  - \( \frac{\partial H_z}{\partial t} = \mu_z \frac{\partial H_z}{\partial t} \)
Framework #1 for the Definition of TE and TM

**E orientation relative to direction of propagation**

- For the $E_z$ mode, the electric field is always transverse to waves propagating in the $x$-$y$ plane.
  
  $E_z$ Mode = TE Mode

- For the $H_z$ mode, the magnetic field is always transverse to waves propagating in the $x$-$y$ plane.
  
  $H_z$ Mode = TM Mode

Framework #2 for the Definition of TE and TM

**E orientation relative to the plane of incidence**

- TE – the electric field is polarized perpendicular to the plane of incidence.
- TM – the electric field is polarized parallel to the plane of incidence.

In the limit as $\theta \to 90^\circ$, we have

- $E_z$ Mode = TM Mode
- $H_z$ Mode = TE Mode

This is exactly the opposite of Framework #1 when propagation is restricted to be in the $x$-$y$ plane.
Resonance Hunting

Device for This Example

Lecture 26 Slide 13

Lecture 26 Slide 14
Frequency-domain methods compute the field at one precise frequency from which transmittance and reflectance is calculated. If frequency points selected for the sweep are two widely spaced, narrow resonances are easily missed. Small frequency steps are very time consuming because many simulations have to be performed.

Time-domain methods typically excite devices with all frequencies over a broad range. If a resonance exists, a time-domain method will detect it in a single simulation. It may take many iterations to resolve how narrow the resonance is, but the method will detect it almost immediately.
Conclusions

- Time-domain methods are excellent for identifying the existence of resonances.
- Time-domain methods are poor for resolving the shape of narrow resonances.
- Frequency-domain scattering methods are not reliable for finding narrow resonances. Visualizing the fields during a sweep can help this.
- Frequency-domain methods are excellent for resolving the shape of resonances.

Photonic Crystals Fabricated by Multi-Photon Direct Laser Writing
Multi-Photon Direct Laser Writing

This is a scanning electron microscope image of a photonic crystal designed to operate in the infrared.

Fourier Transform Infrared Spectrometer

The cassegrain optics illuminates samples with a “hollow” Gaussian beam.

Reflected infrared power at near normal reflection angle is collected and measured.

Predicting Accurate Geometry

To predict the geometry of the photonic crystal more accurately, the DLW process was simulated in MATLAB.


Importance of Realistic Geometry

Metallo-Dielectric Photonic Crystals

Before copper plating  After copper plating


“State-of-the-Art” Simulation of Reflectance

Results obtained by Lumerical and Misawa’s research group.

A Better Simulation of Reflectance

Results obtained by UCF/Rumpf team...

Results obtained by UCF/Rumpf team...

Side-by-Side Comparison

Results obtained with Lumerical’s FDTD software

Results obtained by UCF/Rumpf


What May Have Been Their Mistake?

Below 10 μm (or so), this photonic crystal is a diffracting structure.

The optical configuration inside the FTIR cuts off the higher order modes. Essentially, it is only the zero-order diffracted mode that gets detected.