ECE 6006 Numerical Methods in Photonics

Administrivia

What: Numerical Methods in Photonics
*ECE 6006*

Who: Dr. Robert McLeod
ECE 1B47
(73)5-0997
robert.mcleod@colorado.edu

Where: KOBL 375

When: Tu/Th 12:30 – 1:45 PM

Text: None – we will read classic papers

Reserve: [http://libraries.colorado.edu/search/p?SEARCH=mcleod](http://libraries.colorado.edu/search/p?SEARCH=mcleod)

Grading: Numerical projects (6) 75%
Individual project 25%

Website: [http://ece.colorado.edu/~mcleod](http://ece.colorado.edu/~mcleod)
Why numerical methods?

• Maxwell + constitutive relationships cover most optics problems.

• Numerics complements
  – Theory:
    • Explore complex problem
    • Discover simpler description
    • Validate hypothesis
  – Experiment:
    • Do impossible experiments
    • Measure/visualize results
    • Easily change conditions

• Opens door to automated design
Teaching goals

Subject area

At the end of the class, you should:

• know of a **broad range of computational tools** and be able to select the best for any particular application,
• be able to rapidly write your own tools specific to your needs,
• **understand the limits** of various methods in order to make best use of your own or commercial packages,
• be able to couple numerical methods to **optimization** to create powerful design tools,
• have a **better understanding of optics** in general by simulating and visualizing a number of relevant optical phenomenon.

This is not a course for those who wish to research on numerical methods but instead for those that wish to use them. This will tilt the lectures towards concept and implementation but not, for example, proofs of stability.
Teaching goals
Beyond subject area

- **Design** is the fundamental skill of engineering, but is almost never taught in engineering curricula.

- Numerical methods are particularly powerful for design, if harnessed intelligently. The contraposition is also true.

- Thus, all projects in this class will be phrased as design challenges.

- How is this different than HW?
  - Problem statement is incomplete.
  - Problem statement may be contradictory.
  - No single right answer.
  - You must define “best”.
  - You must choose solution domain.
Design challenges

• Will be posted on website, often with supplementary materials.
• Are often incomplete or vague. That is, you may need to choose reasonable parameters, select the overall structure of the code, find and code up validation problems, etc. Welcome to the real world.
• Are open-ended. Don’t just do the minimum.
• Are due when they are due. This is a 6000 level class and the workload is appropriate. If you get behind, you’re toast. So don’t.
• Are to be turned in electronically including:
  1. Your source code(s) with good internal documentation including at least your name and the method implemented. Include any subfunctions you created so that the code can run stand-alone.
  2. A report documenting your result in MS Word or PDF in IEEE letter format (on the website). These don’t have to be long, but should be complete, particularly in demonstrating the code does what it should and showing any unique things you did. Write these in journal style. That is, pretend that you are the first person to have ever applied the numerical method to this kind of design problem. DO NOT write a “lab report”. Hint: write in present tense. Your reports should generally cover
     • Description of the method – you can be brief, refer to the literature etc.
     • Capability of your implementation – what can the code do or not do?
     • Validation – Show test results. Quantify accuracy. Best way is to run the code on a simple, known theoretical problem. Internal consistency checks may also be valuable.
     • Design results – state your merit criteria, the domain representation and solution found. Trade-offs or other knowledge gleaned are valuable additions.
• Make these professional in appearance and writing style – it’s not that much more work and is hugely important to your future success.
• Rubric (out of 12.5 pts)
  – 1.5 Code: internal documentation, neatness, clarity—this is the equivalent of your lab notebook for an experimental class.
  – 3 Report: Writing is professional, figures are clear. Just like always, graphs need axes (in physical units, not array indices) captions etc.
  – 2 Function: Your code works, as demonstrated in validation problems or checks.
  – 1 Application: You used the code correctly (proper parameters, sampling density, etc). This is an often overlooked pitfall.
  – 5 Design results. Difficulty of problem attacked, creativity in approach, capability of results.
Individual investigations

• Goals:
  – To allow (force?) you to look in-depth at a method that is relevant to your own research interests.
  – To broaden the spectrum of techniques covered beyond the “basic” methods I will teach.
  – To have you teach each other.
  – To do (potentially) publishable work
  – These do not have to be “design” oriented, but can be if you wish.

• What to do:
  – By the end of September (HARD DEADLINE)
    • Work with me or select on your own a variant or totally different numerical method not covered in class.
    • Find one or two good fundamental papers that describe the technique. Send these in electronic form to me for posting on the class website.
  – Finals week:
    • Give a 20 minute presentation on your results
    • Turn in your presentation (Adobe PDF or MS Word) and code as a normal HW assignment.
Advice on coding

• For your first assignment, create a documentation style that you can copy for the rest of the semester.
  – Header with name of code, modification history, reference to literature, dictionary of passed variables, notes on implementation, example call
  – Variable dictionary at top of code including units
  – Section breakouts to make visually simple
• Comment first, code second. That is, insert section breakouts describing the flow, then go back and code in the holes.
• Don’t write monster codes with 3000 lines, bits you comment in and out, etc. You will pay for this bad habit. I will too.
• Do break code into subroutines to make it simpler and so you can re-use bits.
  – Every time you need a new kind of plot, stop and write a routine to do that plot with all the bells and whistles (axis labels, readable fonts, legends etc), then just call it again next time. Add to it as you find new features you need.
  – For each HW, I strongly recommend that you write each method as a subroutine call and then call that with the different parameters to generate the different results. You will then be able to use this code in the future.
• Proceed methodically, plotting or examining everything you can to verify that each step is working before going on to the next. Write validation checks directly into the code (e.g. conservation of energy). Include test problems with known results and plot your results vs the expected. “It looks right” is not good enough. If something doesn’t quite check, stop and figure out why.
Survey

Please send me an email before the end of Wednesday with:

1. Several best times for office hours.
2. Several worst times for office hours
3. Optics courses you have already taken
4. Reason for taking this class
Syllabus

Topic

- Organization and adminstrivia
- Maxwell’s equations
- Optimization methods

1 Finite Difference Time Domain (FDTD)
   - The use of finite differences to solve differential equations
   - Effect of sampling
   - FD applied to the time-domain Maxwell’s equations – the Yee method
   - Boundary conditions
   - Sources
   - Including materials
   - Stability, consistency and convergence

- Ray tracing and Gaussian beam superposition

2 Eigensolution in semi-infinite Cartesian space (homogeneous)
   - Spectral domain in infinite Cartesian space
   - Booker quartic
   - Fourier propagation
   - Time and space domain
   - Relationship to Green’s function formalism

3 Born approximation and k-space (weakly inhomogeneous)
   - Optical Diffraction Tomography

4 Beam propagation method (numerical strongly homogeneous)
   - FFT split step algorithm and its properties
   - Extensions
   - FD based

5 Waveguides (waveguide mode eigensolution)

- Periodic media (Bloch mode eigensolution)

6 Coupled modes (analytic strongly inhomogeneous)

7 Student projects

#’s indicate homework assignments.
Conceptual map of course

Maxwell’s equations

Finite differences

FDTD

Radiation BCs
Scattered/total
Material interactions

Eikonal

FD of eikonal Paraxial ray matrices

Complex rays for GBs Gaussian beams

Gaussian superposition

Mode solvers

Variational Single-layer slabs Multi-layer slabs

Bloch modes

Eigenmode expansion

Bidirectional propagation

Optimization

Wave equation

1-way wave equation

\( \infty \) space solution

\( \infty \) half-space solution (Booker quartic)

Snell’s Walk-off/group V
TIR Diffraction/dispersion

Fourier propagation

Fresnel diffraction

K-space

Bragg selectivity/degneracy

Coupled modes

Beam propagation

Guided modes ABCs Solitons

Tomography
Phase retrieval
Most important concepts

- **Optimizers**: deterministic and nondeterministic
- **FDTD**: FDs, Yee grid, magic time step, numerical dispersion, stability, radiation BCs
- **Ray tracing**: eikonal, Gaussian beams a complex rays
- **Fourier optics**: spatial frequency, Snell’s law, Booker quartic, TIR, propagation equation, diffraction & dispersion
- **K-space**: undepleted, graphical tool, object as $\Sigma$ of gratings
- **Diffraction tomography**: Scattering yields curved slice of object FT
- **Phase retrieval**: Measure I at two planes separated by diffraction, iteratively solve for amplitude and phase
- **BPM**: depleted pump, split diffraction (Fourier) and refraction, conserves $E$, ABCs, solitons, guided mode properties, spatio-temporal propagation, non-Cartesian coordinates
- **Mode solvers**: Variational, single-layer slabs, multi-layer slabs
- **Bloch modes** of periodic structures: Floquet theorem, connection with Fourier propagation
- **Eigenmode expansion**: Orthogonality of modes, bidirectional, unidirectional, connection with Fourier propagation
- **Coupled modes**: Derivation from K-space, coupling constant, phase-mismatch, coupled guides, plane-waves in volume hologram, FD solution
- **K-space BPM**: Derivation from coupled modes, concept of object as superposition of thin gratings