OPTI-547: The Beam Propagation Method

Instructor: **Miroslav Kolesik**
Contact:
email: kolesik@optics.arizona.edu
office: Meinel Bldg. Room 538
office hours: TBD

OPTI-547, The Beam Propagation Method (3 credits).

Course description:

Wave equations for propagation in dielectric media, solutions using the beam propagation method based on spectral (Fourier, and Hankel transforms) and finite difference methods, with emphasis on thorough understanding of both the underlying physics and numerical simulation principles. Practical, hands-on approach with applications in various contexts, such as optical waveguides, free-space with optical elements, optical cavities, integrated optics and nonlinear optics. Provides a solid background for those interested in informed and efficient use of commercial simulation packages, and a firm basis for those interested in numerical modeling in optics in general.

Prerequisites:

Working knowledge of either Matlab or Mathematica (or a compiled programming language). Basic knowledge of electro-magnetic theory and Maxwell's equations, e.g. Opti 501, Opti 512, or Opti 546.

Expected learning outcomes:

After completion of this course, it is expected that students will have:
(i) developed a deeper understanding of of the connection between the Maxwell equations on one side and their numerical models on the other
(ii) developed a deeper understanding of numerical methods for partial differential equations in the context of beam propagation as well as in more general settings
(iii) gained experience in design, implementation, and testing of numerical algorithms
(iv) become comfortable in execution of numerical experiments and in assessment of the outcomes of simulations
(v) gained confidence to embark on projects that require significant numerical simulation and some software development.

These skills will be useful for PhD students, experimentalist and theorists alike, who need to include computer-aided modeling in their skill-sets.

Course outline

- Maxwell‘s equations in a dielectric medium.
  Maxwell‘s wave equation, scalar Helmholtz equation and its reduction to the

paraxial wave equation. Properties of simple wave-train solutions, notions of material and geometric dispersion, for plane-waves and propagation in idealized waveguides. Gaussian beam solution in free space.

- Free-space propagation.
  Solution of free-space propagation using Fourier transforms, relation to the Rayleigh-Somerfeld diffraction theory, special examples for comparison with numerics, diffraction by a planar object, Fresnel and Fraunhofer diffraction, Airy pattern, spot of Arago.

- Numerical beam propagation in 1D.
  Free space propagation in one transverse dimension, discretization in space, the discrete Fourier transform, sampling in k-space, periodic boundary condition and aliasing. Fast Fourier Transforms and general ideas underlying “fast” numerical algorithms. Sample 1D BPM code in Matlab for Gaussian beam propagation.

- Numerical beam propagation in 2D.
  Free-space propagation in two transverse dimensions, discretization in space, sampling in k-space, performing 2D FFT in Matlab. Example of Fraunhofer diffraction patterns, sample 2D BPM code in Matlab for Gaussian beam propagation, diffraction by a planar object.

- Numerical beam propagation in 2D, for radially symmetric problems.
  Hankel transform, numerical Hankel transforms and their application to propagation. Sampling in real and spectral spaces, understanding computational domain boundary issues. Comparison with the Fourier transform based methods. Sample implementation.

- Modeling other optical systems.
  Thin lenses and mirrors, optical interferometers, Fox and Li approach for optical resonators.

- Beam propagation in dielectric structures.
  Paraxial wave equation in an optical waveguide, example of a GRIN medium. Transverse mode solutions in 1D and 2D, TE modes of a 1D slab waveguide.

- Split-step Beam Propagation Method.
  Formal solution for propagation in dielectric structures, split-step BPM using FFT for numerical solution, alternating of free-space and phase-screen sections, accuracy of the method, numerical issues and sampling. Validation of the approach for mode excitation in a 1D GRIN, transverse mode beating for non-modal input conditions. Connection to other operator-splitting methods.

- Propagation in 1D and 2D waveguides.
  Simulation of 1D slab waveguides, apodized waveguide profiles, single-mode and multi-mode waveguides, transverse mode beating, radiation modes and absorbing boundary conditions, propagation in optical fibers, single-mode and multi-mode examples. Limitations of the Split-Step BPM in high index-contrast situations.

- Finite difference approaches to BPM.
  Simple scalar wave equation and its finite-difference representations. Basics of finite-difference schemes, appreciation of accuracy, sampling, and boundary treatment issues. Sample free-space propagation implementation and comparison to spectral methods.

- Finite difference approaches to BPM: material interfaces
  Material-interface boundary conditions for electromagnetic fields and their derivatives. Finite-difference representations, method of boundary derivative matching. Sample beam propagation implementation. Absorbing domain-boundary modeling, applications to leaky modes.

- Spatially varying structures.
  Examples of the BPM approach to non-uniform structures, tapered waveguides, directional couplers, scattering from refractive gratings

- Further generalizations: Time dimension and pulsed-beam propagation, numerical analogies analogies between space and time.

- Further generalizations: Inclusion of loss and gain, nonlinear propagation, self-focusing, nonlinear absorption.

Grading

The grade for this class will be based on the completion of a series of pre-set numerical modeling homework projects intended to give the student hands-on experience in writing and running simulation codes (mostly in Matlab), culminating in a final project.

Select lecture notes will be assigned for pre-class reading and annotation.

Course credit:
Final project: 30%
Homework: 60% (practical projects) + 10% (pre-class preparation)