Nanophotonics: from fundamental principles to modern applications and devices
Open to all undergraduate students

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- *How does a laser work?*
- *How can we make solar cells more efficient?*
- *Can we perform mathematical operations using light on a photonic chip (instead of electricity in a transistor)?*
- *How can we transmit information across the globe at the speed of light reliably?*
- *Which concepts in optics and photonics can accelerate the development of augmented and virtual reality technologies?*

These are all the questions that you will be able to answer by taking this class. You will achieve this by bridging the gap between your practical and fundamental understanding of nanophotonics: our understanding of light-matter interactions at the nanoscale.

Description:

Nanophotonics underpins a wide array of modern technologies which billions of people are using on a daily basis: solar cells, lasers, light emitting devices (LEDs), displays, telecommunication networks, state-of-the-art LIDARs, augmented and virtual reality devices, and even some quantum computing architectures. The promise of nanophotonics is to realize devices that can control light on the nanoscale, and the way photons propagate, are absorbed, or emitted.

At the heart of these numerous important technologies lies many fundamental physical effects and advances in the modeling of light-matter interactions at the nanoscale. In many cases, the technologies that are now surrounding us found their origins in fundamental science whose main purpose was to understand the inner workings of how light interacts with matter.
The purpose of this course is to highlight connections between fundamental physics and practical applications in nanophotonic devices and modern technologies.

We will explore those connections in both ways. Our first approach will be following the path of many lab-based innovations: understanding fundamental optics, photonics, and physics to find their applications in modern technologies. The reverse approach will be example-based, and we will “reverse-engineer” ubiquitous technologies and devices from around us to understand their inner workings from a fundamental physics perspective.

Course goals:

The hybrid approach we adopt in this class is destined to develop a complementary set of skills at the intersection of physics, numerical modeling, and engineering:

1. *Fundamental optics, photonics, and physics*
- Use, interpret, and predict the behavior of abstract photonic, optics, and wave systems using theoretical tools in optics, photonics, and physics
- Contrast fundamental properties of electromagnetic waves, such as amplitude, polarization, frequency, wavelength, momentum
- Interpret physical concepts such as coherence, resonance, diffraction, interference

2. *Numerical modeling*
- Analyze fundamental challenges and techniques to model partial differential equations such as Maxwell's equations
- Contrast various types of solvers on simple examples based on their pros and cons

3. *Engineering*
- Identify engineering challenges in optics and photonics, based on current fabrication and technological capability. Examples include: spectral filters, polarization-sensitive devices, imaging devices.
- Use fundamental physical phenomena and theoretical understanding to solve engineering issues in a creative way
- Analyze existing photonic engineering solutions; justify their design and predict their performance using fundamental physics covered in this class

4. *General*
- Develop general scientific presentation skills (oral and written), such as result presentation and discussion, displaying and commenting equations and plots, building convincing arguments around assumptions and scientific conclusions.

Prerequisite:
Basic understanding of multivariate calculus and linear algebra is encouraged but not necessary.

PART I – COURSE STRUCTURE AND CONTENT

Course structure:
1. Fundamentals of photonics
2. Photonics in periodic media
3. Lasers, solar cells, and other important photonic devices
4. Contemporary topics in photonics

Unit 1: Fundamentals of photonics

Unit 2: Photonics in periodic media

Description:

In Unit 2, we are building upon the fundamentals of photonics that have been learned in Unit 1. can now describe the behavior of photonic systems in terms of the fundamental properties of light, and utilize general physical concepts to justify their predictions. This Unit is focused on a specific type of photonic media with many technological applications, fundamentally interesting physics, and numerical challenges in their modeling.

First, you will learn about the importance of geometrical feature size and periodicity in wave phenomena with various examples of wave propagation. will have to “unlearn” some of the results from Unit 1 which no longer hold in subwavelength, periodic media. The goal is for students to realize how some approximations used in Unit 1 break at the nanoscale and in periodic media. They will be exposed to a few examples where those properties behave in a very “original” manner compared to what they learned in Unit 1.

Second, derive the simplest analytical example of a photonic periodic medium (a multi-layer Bragg mirror). Through this simple example, students are exposed to general concepts to describe photonic in periodic media, such as eigenmodes, band structures, and symmetries/invariance.

Third, are introduced to more complex examples that generalize their learnings from the simple analytical example. They learn how to guess and derive properties of 2 and 3-dimensional periodic photonic structures in various cases.

Finally, are introduced to applications of photonic crystals and numerical challenges in their modeling with an example. Through that example, students calculate numerically the response of a photonic crystal in 2D and learn how they are integrated into useful devices in the real world.

Unit ILO:

1. *Fundamental optics, photonics, and physics*
- Use, interpret, and predict the behavior of wave systems in periodic media
- Use symmetries and invariance to predict the behavior of wave systems in periodic media with minimal derivations

2. *Numerical modeling*
- Analyze fundamental challenges and techniques to model nanoscale periodic photonic structures
- Identify the main components and variables of a numerical method in nanophotonics (e.g. finite-difference time-domain)

3. *Engineering*
- Identify engineering challenges in the fabrication of large-scale photonic crystals with lithographic techniques

Unit 3: Lasers, solar cells, and other important photonic devices

Unit 4: Contemporary topics in photonics

PART II - CLASS LOGISTICS AND GRADING

Problem Sets: There will be 6 problem sets. The problem sets will have a selection of problems ranging from simple (mathematical) problems, to longer design problems (where part of the assignment is to define the parameters of the problem). The objective is to develop a background for research.

Some problem sets will include numerical MATLAB and/or Python problems in order to build physical intuition and simple modeling skills. See MIT IST https://ist.mit.edu/software-hardware to get access to MATLAB licenses. Learning basic scientific computing skills is extremely useful in engineering, business, and research.

Some problem sets include design problems and research-like problems that require independent reading and thought. This differs from some undergraduate courses which have artificially simple problems that never occur in real science and engineering. Since some problems are complex, you should read the problem sets soon after they are handed out. Please attend office hours, since it is very difficult to answer complicated questions by email, and we tend to feel lonely when no one comes to visit us!

Quizzes: There will be two in-class written examinations covering approximately the first two-thirds of the course.

Term Paper: There is no final exam. A term paper and presentation will be required. The term paper will be on a selected special topic in nanophotonics and is intended to give you practice on independent study and allow you to investigate a topic that you are interested in. The term paper should be from 5 to 10 pages in length and will be due during the last week of classes. Details about the term presentation can be found below.

Summative assessment: Oral presentation

You have to prepare a 5-minute oral presentation and 3-minute Q&A where they present to the instructor one of three photonic devices/research results.

Two formative assessments will be created to make sure are continuously learning and working on that oral presentation:

- One ungraded quiz in class (multiple choice question with anonymous results shown live on a screen) on topics related to the examples they can pick for their oral presentation, and also a different example covered in class with the methodology they are supposed to use in their own assignment.

- A half-page summary of their main results and methodology, with feedback provided before the oral presentation

A. This assessment promotes the understanding of physics rather than the math-crunching behind it (the amount of equations used in the description is intentionally limited). It also promotes basic scientific presentation skills, an important ILO in the current academic world.
B. It is also meant to be authentic in picking examples from real-world light-based devices, whose functionality relies on fundamental physics covered in the class.
C. In order to be mindful of inequities, I will allow students to pick their own example, and will pre-assess whether the example can be a good fit for that assessment in one of the formative assessments. The formative assessments also allow me to gauge whether some students have inherent difficulties with oral presentation (by considering their writing assignments separately).

Example 1: Solar-cell concentrator

Example 2: Bragg-reflector in a laser cavity

Example 3: Photonic crystal polarization splitter to provide internal optical communication to the world

Example 4: Pick your own!

Examples for next years (to not always use the same examples: photonic crystal band gaps, quasi-periodic phase matching in nonlinear cavities, perfect transmission in lossy materials, enhanced scintillators for x-ray imaging, polarization imaging with metasurfaces, etc.)

(Only example 2 detailed below - would not appear in detailed syllabus but in handout later in the class)

Example 2: Bragg-reflector in a laser cavity

Lasers consist of a gain medium enclosed in a cavity providing optical feedback. Lasing occurs when the optical gain (created via optical or electrical pumping) is greater than the losses. Therefore, to realize lasers at low pumping powers, **it is very important to design good reflectors at select wavelengths.** Bragg reflectors appear in many different types of lasers and can be understood and developed in this class.

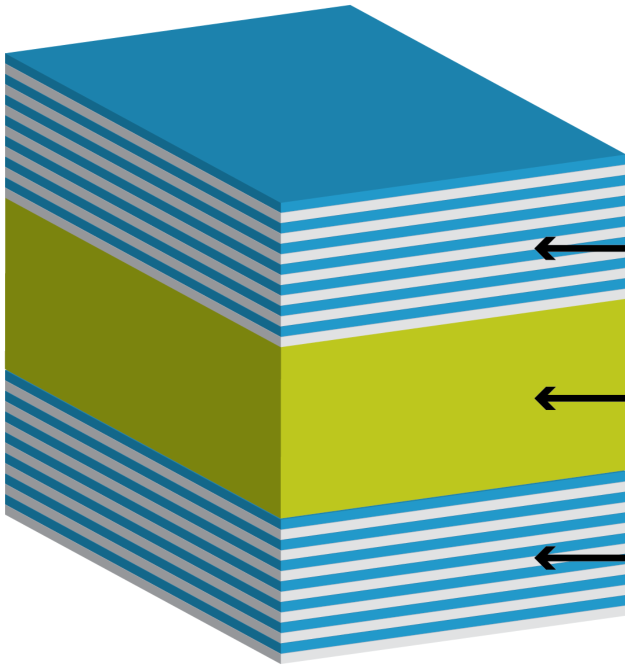

Figure: Schematic of a Bragg-reflector laser cavity. It comprises a gain medium "sandwiched" between two Bragg mirrors, consisting of alternating layers of two dielectric materials.

In this assignment, you have to explain to your instructors how a Bragg-reflector laser cavity works. You should focus on the functionality and physics of the Bragg reflector itself. You are expected to use concepts and linguo from the class, especially that pertaining to the description of photonics in periodic medium. Your presentation should include a presentation of the main physical parameters used to describe the physics of a Bragg mirror, and how it should be designed in conjunction with a given gain medium.

Before your oral presentation, you will have the opportunity to hand out a half-page written summary of your methodology (which should include between 1 and 3 equations), and some of the important concepts will be reviewed in a class quiz, where we will test our own *a priori* understanding of that device. Those two assignments will be ungraded and serve as a preparation for your **5-minute oral presentation, followed by a 3-minute Q&A session.**

Your oral presentation will be graded as follows:

- Clear, well-presented, and scientifically-sound delivery of the main physical concepts describing the device under study [50%]
- Use and interpretation of physical concepts from the class (band structure, reflection, transmission, coupling, wave propagation, coupled-mode theory, etc.) [30%]
- Contextualization of the physical device into a broader context [10%] (should be part of your introductory slide(s)).
- Respect of time constraints [10%]

Late Problem Sets: Late problem sets are not accepted because solutions are handed out the day problem sets are due. If you have completed part of the problem set, you should submit this (by the due date) for grading in order to receive partial credit. Not completing the full problem set is completely fine and should not be seen as a failure. Also, only your 5 best problem sets will count towards your final grade.

Collaboration: Collaboration on problem sets is strongly encouraged. However, you must list with whom you collaborated when you hand in your problem sets. Study groups may discuss the problems, strategies for solutions, etc. However, each person is expected to do all of the problems independently. You should not copy solutions from other members in your collaborative group. Evidence of copying will be considered cheating. To help you organize your team work, we will provide the following resources:

- **Study group assignment based on your background to diversify your experience in the class.** We believe that working with people from different backgrounds and all walks of life strongly supports deep and lifelong learning skills, beyond the scope of this class.
- **Multiple opportunities to work and think in class with your study group**, and to interact with other study groups. We will regularly have small quizzes in class where study groups have to come up with solutions to physical problems together and convince other groups of their own solutions.
- **Study group evenings supported by the department.** We do our best to secure funding from the department to fund one or two study group evenings by the department. You will be able to order dinner to work together on the class content with your study group, and the pizza is on us.

Academic Integrity: Please read the information on academic integrity: http://web.mit.edu/academicintegrity/. Some problem sets will require writing. Written assignments require original writing and should not be copied from other sources. Copying without citation is plagiarism and is considered unethical behavior.

PART III - ADDITIONAL REFERENCES

Most, if not all of the references below can be found online or borrowed via MIT library. If you cannot get your hands on a copy of one of those textbooks, we will make our own copies available in class for your own consideration.

Quantum electronics and photonics references:

1. Lasers, A.E. Siegman, University Science Books (1986)
2. Fundamentals of Photonics 2nd Edition, E.A. Saleh and M.C. Teich, Wiley (2007)
3. Photonics: Optical Electronics in Modern Communication, A. Yariv and P. Yeh, Oxford University Press (2007)
4. Principles of Lasers 5th Edition, O. Svelto, Springer (2010)
5. The Quantum Theory of Light, R. Loudon, Oxford University Press (2000)

6. Laser Physics, M. Sargent, M.O. Scully, and W.E. Lamb, Westview Press (1978)

Electromagnetics references:

1. Electromagnetic Wave Theory, J.A. Kong, EMW Publishers, Boston, MA (2000)
2. Waves and Fields in Optoelectronics, H.A. Haus, Prentice-Hall, NJ (1984)

General reference:

1. Mathematical Methods for Physicists, G.B. Arfkin, H.J. Weber and F.E. Harris, Academic Press (2012)