2.71/2.710 Optics
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Website: http://web.mit.edu/2.710/www

Units: 3-0-9, Prerequisites: 8.02, 18.03, 2.003
2.71: meets the Course 2 Restricted Elective requirement
2.710: H-Level, meets the MS requirement in Design
“gateway” subject for Doctoral Qualifying exam in Optics
Lectures: Mo 10-11, We 9-11
Classroom: 32-144
Class objectives

• Cover the fundamental properties of light propagation and interaction with matter under the approximations of geometrical optics and scalar wave optics, emphasizing
  – physical intuition and underlying mathematical tools
  – systems approach to analysis and design of optical systems
• Application of the physical concepts to topical engineering domains, chosen from
  – high-definition optical microscopy
  – optical switching and routing for data communications and computer interconnects
  – optical data storage
  – interface to human visual perception and learning
Imaging

Information sensing

Information display (projectors)

Information storage/recall

Lithography

Instrumentation / metrology

Optics in Engineering

Information transmission (telecom)

Materials/tissue processing
Topics

• Geometrical optics
  – Basic ray-tracing
  – Image formation and imaging systems
  – Optical system design
• Wave optics
  – Scalar linear wave propagation
  – Wave properties of light
  – Polarization
  – Interference and interferometers
  – Fourier/systems approach to light propagation
  – Spatial filtering, resolution, coherent & incoherent image formation, space-bandwidth product
  – Wavefront modulation, holography, diffractive optics
What you need

• Absolutely necessary
  – Euclidean geometry
  – calculus with complex variables
  – Taylor series approximation
  – MATLAB or other computation/visualization software
  – linear systems (2.003 level, we will extensively review)
• Helpful if you know but we will cover here
  – basic electrodynamics
  – basic wave propagation
  – Fourier analysis
Class compass

• Announcements, notes, assignments, solutions, links
  – http://web.mit.edu/2.710/www
• Broadcasts
  – 2.710@mit.edu
• Textbooks: “Optics” by E. Hecht, 4th edition (Addison-Wesley)
• Other recommended texts:
  – “Waves and fields in optoelectronics” by H. A. Haus
  – “Optics” by Klein and Furtak
  – “Fundamentals of photonics” by Saleh and Teich
  – “Fundamentals of optics” by Jenkins and White
  – “Modern Optical Engineering” by W. J. Smith
Administrative: 2.71

- Grade: 30% homeworks, 40% quiz, 30% final exam
- Ten homeworks
  - each due 1 week after post date (see syllabus)
  - see website for collaboration & late policies
  - mainly “comprehension” problems
- Occasional lab demonstrations (optional)
Administrative: 2.710

- Grade: 25% homeworks, 30% quizzes, 20% project, 25% final exam
- Ten homeworks
  - each due 1 week after post date (see syllabus)
  - see website for collaboration & late policies
  - both “comprehension” and “open-ended” problems
- Occasional lab demonstrations (optional)
- Project
  - teams of 5
  - selected among one of the application areas (topics soon TBA)
  - start on We. Nov. 2
  - weekly or so info meetings with instr/TA
  - oral presentation on Weds. Nov. 30
Applications / Projects

- Confocal microscopy
  - optical slicing
  - fluorescence
  - two-photon
  - real-time
  - holographic
  - spectroscopic
  - bio-imaging, imaging through turbulence
- Super-resolution
  - apodizing filters
  - hybrid (optics+signal processing) approaches
  - information-theoretic viewpoint
- Optical data storage
  - optical disks (CD’s, DVD’s, MO disks)
  - holographic memories
- Optical switching
  - optical MEMS
  - liquid crystals
  - thermo-optics
  - acousto-optics
- Statistical optics
  - Coherence imaging (van Cittert-Zernicke theorem, radio astronomy)
  - Optical coherence tomography
  - X-ray tomography (Slice Projection theorem, Radon transforms)
Administrative: both

- Two quizzes:
  - Quiz 1 on Wednesday Oct. 12, 9am (in class)
    - content: geometrical optics
  - Quiz 2 on Monday Nov. 28, 10am (in class)
    - content: wave (Fourier) optics
- Final exam:
  - scheduled by the Registrar
  - comprehensive on everything covered in class
- Practice problems will be posted before each quiz and the final
- Absence from quizzes/final: Institute policies apply
- Grading: Institute definitions apply
Administrative: both (cont.)

• TA Office hours: Tuesday 2-4pm
• Unlimited email access (broadcasts encouraged), best effort to reply within 24hrs.
• Recitations during scheduled class hours
  – *most* Mondays (some separate for 2.71 and 2.710)
  – broadcast by e-mail when not in syllabus
  – contents
    • example problems (usually before homeworks are due)
    • homework solutions (after homework due dates)
    • extended coverage of some special topics (e.g., optical design software; 2D Fourier transforms)
• suggestions welcome
Brief history of Optics

• Ancient Greeks (~5-3 century BC)
  – Pythagoras (rays emerge from the eyes)
  – Democritus (bodies emit “magic” substance, simulacra)
  – Plato (combination of both of the above)
  – Aristotle (motion transfer between object & eye)

• Middle Ages
  – Alkindi, Alhazen defeat emission hypothesis (~9-10 century AD)
  – Lens is invented by accident (northern Italy, ~12th century AD)
  – Della Porta, da Vinci, Descartes, Gallileo, Kepler formulate geometrical optics, explain lens behavior, construct optical instruments (~15th century AD)

• Beyond the middle ages:
  – Newton (1642-1726) and Huygens (1629-1695) fight over nature of light
Brief history of optics (cont’ed)

• 18th–19th centuries
  – Fresnel, Young experimentally observe diffraction, defeat Newton’s particle theory
  – Maxwell formulates electro-magnetic equations, Hertz verifies antenna emission principle (1899)

• 20th century
  – Quantum theory explains wave-particle duality
  – Invention of holography (1948)
  – Invention of laser (1956)
  – Optical applications proliferate
    • computing, communications, fundamental science, medicine, manufacturing, entertainment
Nobel Laureates in the field of Optics

• W. Ketterle (MIT), E. Cornell, C. Wieman – Physics 2001
• Z. Alferov, H. Kroemer, J. Kilby – Physics 2000
• A. Zewail – Chemistry 1999
• S. Chu, C. Cohen-Tannoudji, W. Phillips – Physics 1997
• E. Ruska – Physics 1986
• N. Bloembergen, A. Schawlaw, K. Siegbahn – Physics 1981
• A. Cormack, G. Housefield – Biology or Medicine 1979
• M. Ryle, A. Hewish – Physics 1974
• D. Gabor – Physics 1971
• A. Kastler – Physics 1966
• C. Townes (MIT), N. Basov, A. Prokhorov – Physics 1964
• F. Zernicke – Physics 1953
• C. Raman – Physics 1930
• W. H. Bragg, W. L. Bragg – Physics 1915
• G. Lippman – Physics 1908
• A. Michelson – Physics 1907
• J. W. Strutt (Lord Rayleigh) – Physics 1904
• H. Lorentz, P. Zeeman – Physics 1902
• W. Röntgen – Physics 1901
What is light?

• Light is a form of **electromagnetic energy** – detected through its effects, e.g. heating of illuminated objects, conversion of light to current, mechanical pressure (“Maxwell force”) etc.

• Light energy is conveyed through particles: “photons”
  – ballistic behavior, e.g. shadows

• Light energy is conveyed through waves
  – wave behavior, e.g. interference, diffraction

• Quantum mechanics reconciles the two points of view, through the “wave/particle duality” assertion
Particle properties of light

Photon = elementary light particle

Mass = 0
Speed \( c = 3 \times 10^8 \text{ m/sec} \)

(Equation) 
\[
E = hv
\]

\( h = \text{Planck’s constant} = 6.6262 \times 10^{-34} \text{ J sec} \)

\( \nu \) is the temporal oscillation frequency of the light waves

According to Special Relativity, a mass-less particle traveling at light speed can still carry energy (& momentum)!

relates the dual particle & wave nature of light;
Wave properties of light

\( \lambda: \) wavelength (spatial period)

\( k = \frac{2\pi}{\lambda} \)

wavenumber

\( \nu: \) temporal frequency

\( \omega = 2\pi\nu \)

angular frequency

\( E: \) electric field
Light propagation
Diffraction from an obscuration
Diffraction from a small obscuration
Diffraction from a periodic structure
Wave/particle duality for light

Photon = elementary light particle

Energy \( E = h\nu \)

\( h = \text{Planck's constant} \)
\( = 6.6262 \times 10^{-34} \text{ J sec} \)

\( \nu = \text{frequency (sec}^{-1}\text{)} \)
\( \lambda = \text{wavelength (m)} \)

\( c = \lambda \nu \)

“Dispersion relation”

(holds in vacuum only)
The light spectrum

Ultra-violet

Blue, $\lambda \sim 488\text{nm}; \nu \sim 6.1 \times 10^{14}\text{Hz}$

Green, $\lambda \sim 532\text{nm}; \nu \sim 5.5 \times 10^{14}\text{Hz}$

Red, $\lambda \sim 633\text{nm}; \nu \sim 4.8 \times 10^{14}\text{Hz}$

Infra-red

Visible spectrum

$\sim 0.4 \mu\text{m}$

$\sim 0.7 \mu\text{m}$
In homogeneous media, light propagates in rectilinear paths.
Light in vacuum: rays

In homogeneous media, light propagates in rectilinear paths
Polychromatic rays

In homogeneous media, light propagates in rectilinear paths.

Energy from pretty much all wavelengths propagates along the ray.

Wavefronts

$t=0$
(frozen)
Light in matter: refraction/absorption

Speed \( c = 3 \times 10^8 \) m/sec

Absorption coefficient 0

Speed \( c/n \)

\( n \) : refractive index (or index of refraction)

Absorption coefficient \( \alpha \)

Energy decay after distance \( L : e^{-2\alpha L} \)

E.g. glass has \( n \approx 1.5 \), glass fiber has \( \alpha \approx 0.25 \text{dB/km} = 0.0288/\text{km} \)
Molecular model of absorption

Incident photon sets molecule into vibrational motion ...

... resulting in energy dissipation
Light transmission through the atmosphere

Atmospheric transmission

human vision

\[ \lambda (\mu m) \]
Light in metals

light generates current $\Rightarrow$ energy dissipation

- Energy constant as it propagates
- Energy loss $\propto$ penetration depth

$\text{penetration depth} \propto \frac{1}{\text{(absorption coefficient)}}$

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Ideal metals

\[
\text{absorption coefficient } \quad \alpha = \infty \\
\Rightarrow \text{penetration depth} = 0
\]

Light never enters the ideal \Rightarrow all of it gets reflected

\[
\left( \frac{\text{Reflection coefficient}}{\text{Incident power}} \right) = \frac{\text{Reflected power}}{\text{Incident power}} = 1
\]
Non-ideal metals

absorption coefficient $\alpha$ is finite
$\Rightarrow$ penetration depth $> 0$

Vacuum -- Metal

Fraction of light energy that enters the metal is lost (converted to heat)

$$\left( \frac{\text{Reflection coefficient}}{\text{Incident power}} \right) = \frac{\text{Reflected power}}{\text{Incident power}} < 1$$
Thin metal films

Light is mostly reflected

Small fraction is still transmitted through the thin film

(typical film thickness \( \approx 10s \text{ of nm} \))
The law of reflection

oblique incidence

Minimum path principle
(aka Fermat’s principle)

a) Consider virtual source P” instead of P
b) Alternative path P”O”P’ is longer than P”OP’

c) Therefore, light follows the symmetric path POP’.

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Inversion upon reflection

green-purple-red form \textcolor{red}{right}\text{-handed} triplet

green-purple-red form \textcolor{blue}{left}\text{-handed} triplet

mirror
Specular vs diffuse reflection

**Specular**
- Flat (ideal) surface: orderly reflection
  - Clear image
  - (e.g. well-polished mirror)

**Diffuse**
- Rough surface: disorderly reflection
  - Diffuse image
  - Increased absorption due to multiple reflections
  - (e.g. aluminum foil)
Common dielectrics

- Air, \(n\) slightly higher than 1 (most commonly assumed \(\approx 1\) for all practical purposes)
- Water, \(n \approx 1.33\)
- Glass, \(n \approx 1.45-1.75\)
- Photorefractive crystals, e.g. lithium niobate \(n \approx 2.2-2.3\)
Light in air/glass interface

Incident light (speed $c$) 

Small fraction is reflected

Transmitted light (speed $c/n$) $n \approx 1.5$

absorption $\approx$ negligible
Transmission/reflection coefficients

Normal incidence only
(oblique incidence requires wave optics)

(Reflection coefficient) = \frac{\text{Reflected power}}{\text{Incident power}} = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2

(Transmission coefficient) = \frac{\text{Transmitted power}}{\text{Incident power}} = \left(\frac{2n_1}{n_2 + n_1}\right)^2

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Anti-reflection coatings

With proper design, the stack cancels the reflection for a wide range of incidence angles.
Incidence at dielectric interface

\[ \theta \]

incident

\[ n \quad n' \]
The minimum path principle

\[ \int_{\Gamma} n(x, y, z) \, dl \]

\( \Gamma \) is chosen to minimize this “path” integral, compared to alternative paths

(aka Fermat’s principle)

Consequences: law of reflection, law of refraction
The law of refraction

\[ n \sin \theta = n' \sin \theta' \]

Snell’s Law of Refraction
Two types of refraction

- From low to higher index (towards optically denser material):
  - Angle wrt normal decreases

- From high to lower index (towards optically less dense material):
  - Angle wrt normal increases