Optics E-5730

Spring 2021

Lectures: Toni Laurila

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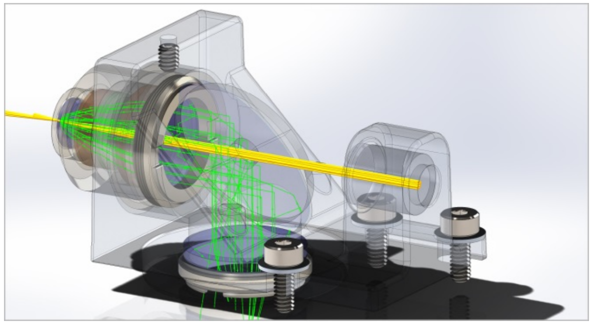
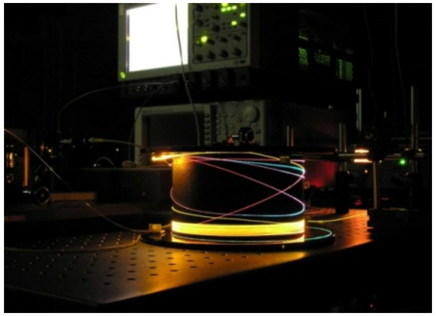
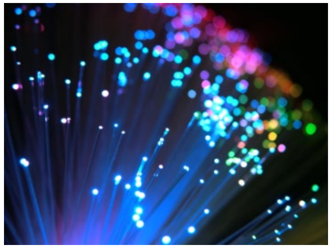
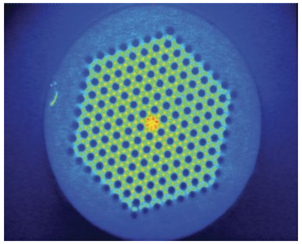
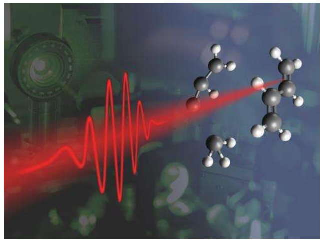



Course Contents

Geometrical optics and ray tracing
Wave optics
Radiometry
Coherence, interference and introduction to lasers
Diffraction
Optical fibres and optical telecommunication

Fundamentals of Optics, Spring 2021

ELEC E-5730

lectures online using Zoom at https://aalto.zoom.us/j/8453943170

exercises online using Zoom at https://aalto.zoom.us/j/5703080612

week	day	date	time	topic	
2	Mon	11.1.2021	8-10	Lecture 1: Geometrical optics 1	
	Fri	15.1.2021	8-10	Lecture 2: Geometrical optics 2	
3	Mon	18.1.2021	8-10	Lecture 3: Wave optics 1	
	Mon	18.1.2021	10-12	Exercise 1	
	Fri	22.1.2021	8-10	Lecture 4: Wave optics 2	
4	Mon	25.1.2021	8-10	Lecture 5: Coherence 1	
	Mon	25.1.2021	10-12	Exercise 2	
	Fri	29.1.2021	8-10	Lecture 6: Coherence 2	
5	Mon	1.2.2021	8-10	Lecture 7: Radiometry	
	Mon	1.2.2021	10-12	Exercise 3	
	Fri	5.2.2021	8-10	Lecture 8: Interferometry + 30 mins mid-term exam	
6	Mon	8.2.2021	8-10	Lecture 9: Fibre optics + Optical telecom	LAB WORKS PERIOD
	Mon	8.2.2021	10-12	Exercise 4	LAB WORKS PERIOD
	Fri	12.2.2021	8-10	Lecture 10: Diffraction 1	LAB WORKS PERIOD
7	Mon	15.2.2021	8-10	Lecture 11: Diffraction 2	LAB WORKS PERIOD
	Mon	15.2.2021	10-12	Exercise 5	LAB WORKS PERIOD
	Fri	19.2.2021	8-10	NO LECTURE	LAB WORKS PERIOD
8	Mon	22.2.2021	8-10	NO LECTURE	
	Mon	22.2.2021	10-12	Exercise 6	
	Fri	26.2.2021		Examination	

Optics E-5730

Information on Aalto MyCourses

- Exercises each week. Earn extra points for the exam by solving Home Work Questions in advance (3 questions each week).

- Voluntary mid-term exam with extra points on Friday February 5.

- Course book is available for purchase at the price of 10 euros

- Compulsory laboratory works will accomplished during two 3-hour laboratory sessions (see Course Schedule).

Optics E-5730

Exercises and Course Mark

E-5730 Optics

Exercise I January 18 2021

The exercises will be held on Mondays at 10-12 am. There will be six exercise sessions in total.

It is recommended that the students try to solve all the questions in advance. The demonstration questions (Q) will be discussed and solved together during the exercises.

Each question sheet also includes three Homework Questions (HQ) which the participating students are expected to solve in advance and return the written answers to the exercise supervisor before the beginning of the exercise session. The supervisor will mark the returned HQ solutions. By solving the Homework Questions one can earn maximum 9 extra points contributing to the total mark of the course. There will also be a 30-minute mid-term exam where it is possible to earn maximum 6 points.

The total mark of the course (max 45 points) is based on the following:

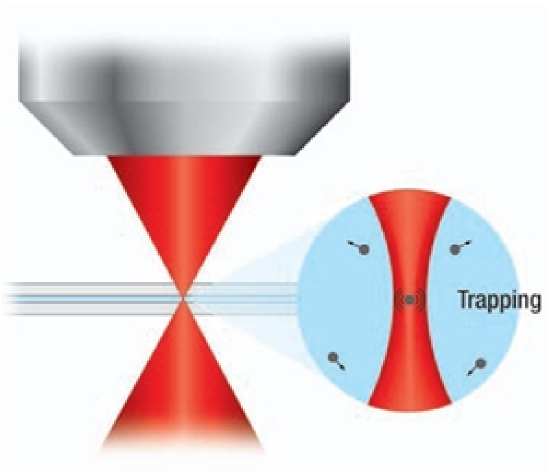
- written online exam (max 30 points)
- homework (HQ) questions (max 9 points)
- mid-term online exam (max 6 points)

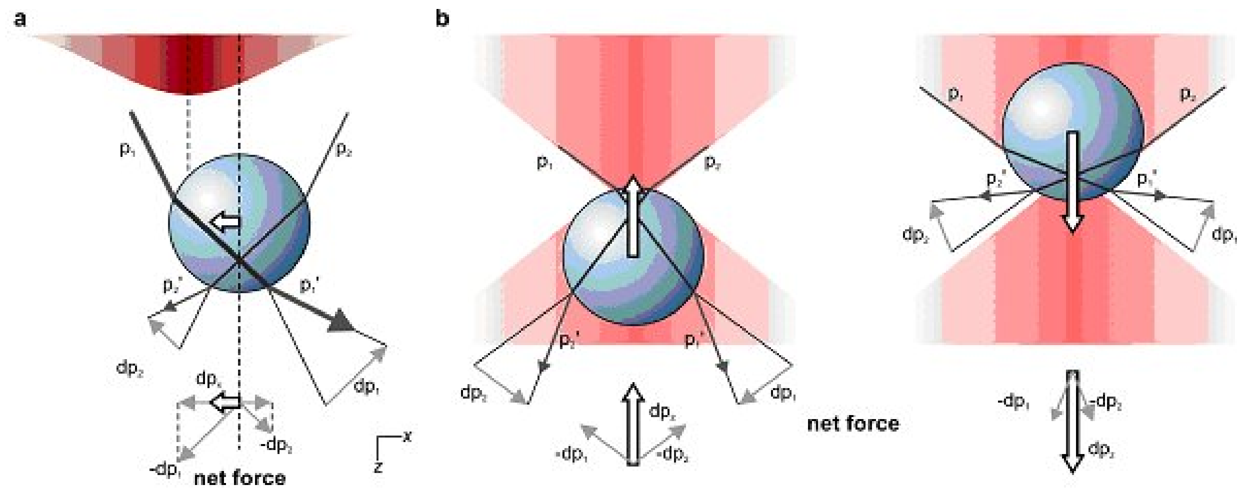
LIGO – **L**aser **I**nterferometer **G**ravitational-wave **O**bservatory
Detection of 10^{-19} m Length Changes

To detect gravitational waves, LIGO is able to measure a change in the arm length of about 10^{-19} m (10 000 times smaller than a proton). Achieving this degree of sensitivity requires a remarkable combination of precision lasers, vacuum technology and advanced optical and mechanical innovations.

Optical Tweezers

Holding and Manipulating Living Cells

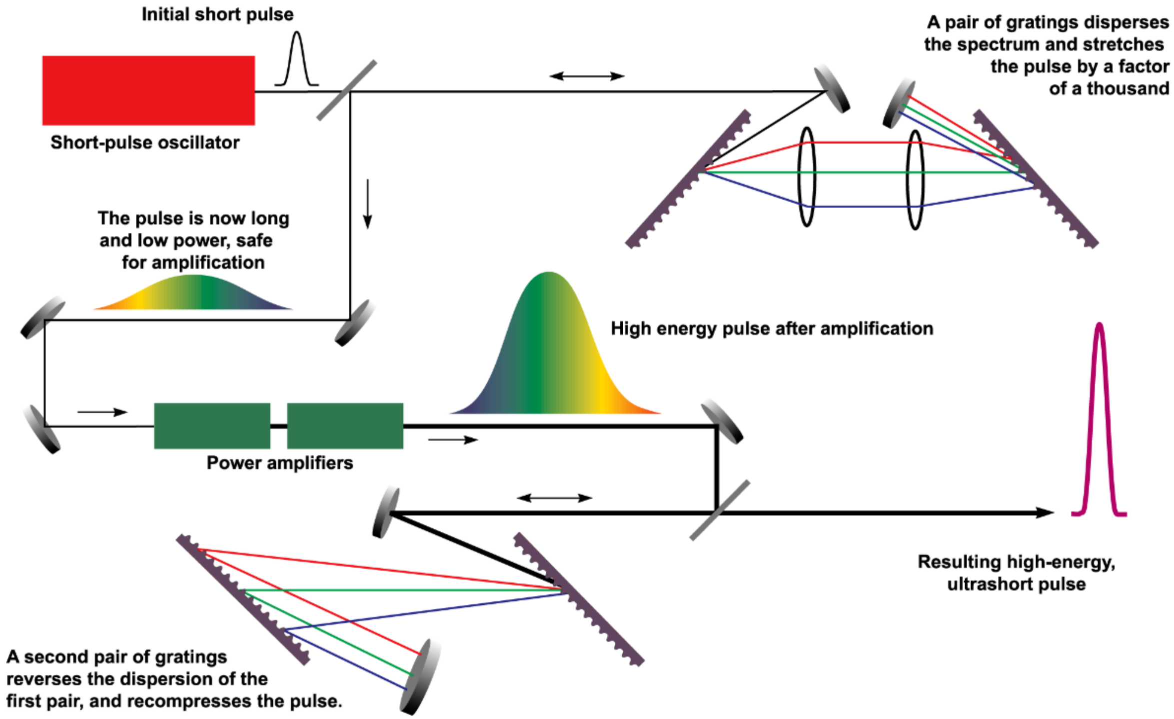


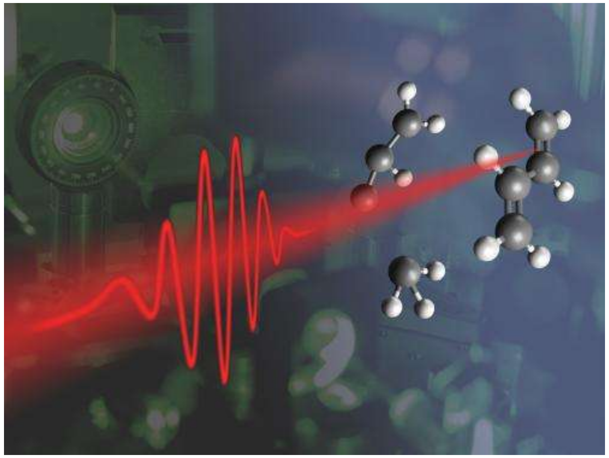


Tightly focused laser light is most intense at the centre of the trap, which means that if the object moves slightly away from the centre in a transverse direction, one part of the object will refract less light than the other. As a result, object refracts more light away from the centre of the trap than towards it.

Ultra-short Laser Pulses

Studying Light-Matter Interaction in 10^{-15} – 10^{-18} Seconds





Chemical reactions occur so quickly that it is impossible to observe their progress or control them using conventional methods. Chemical processes can be affected in a targeted manner using precise controlled ultra-short laser pulse, e.g., electrons can be extracted and collided again with the parent molecule.

Optics-related Nobel Prizes

Active Optics Research

- A. Ashkin, G. Mourou, D. Strickland – Physics 2018 (optical tweezers and ultra-short laser pulses)
- B.C. Barish, K.S. Thorne, R. Weiss – Physics 2017 (LIGO for detecting gravitational waves)
- S. Nakamura, T. Kajita, A.B. McDonald – Physics 2014 (blue LEDs)
- S. Hell, E. Betzig, W. Mörner - Chemistry 2014 (super-resolution microscopy)
- C. Kao (optical telecom), W. Boyle and G. Smith – Physics 2009 (CCD camera)
- W. Ketterle, E. Cornell, C. Wieman – Physics 2001 (BEC)
- 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

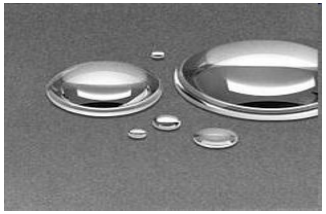
History of Optics

Role of Astronomy

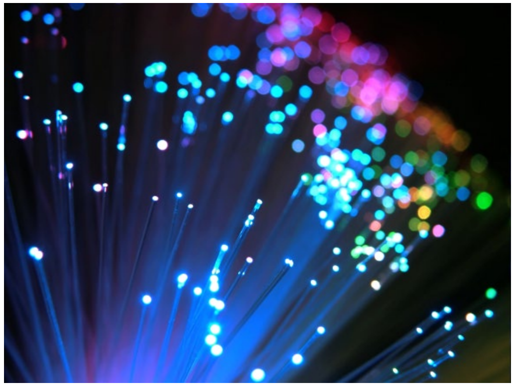
14th century painting

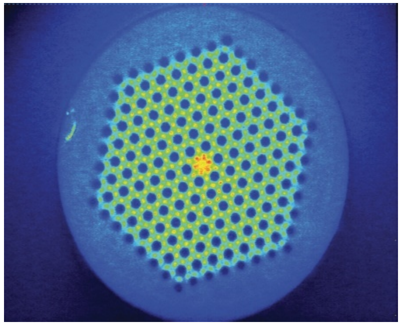
16-17th century

Examples on Modern Optics



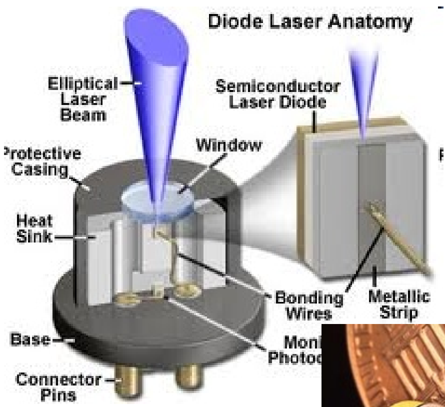
- semiconductor lasers
- metamaterials
    - negative refractive index
    - photonic crystals
- optical telecom
- metrology of time: optical clocks

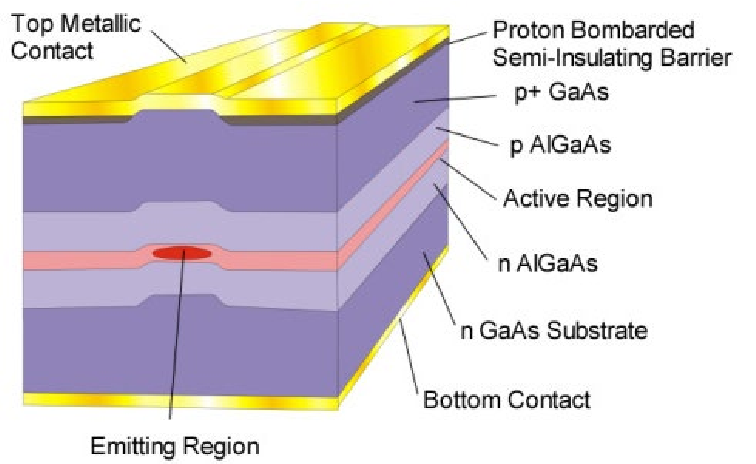


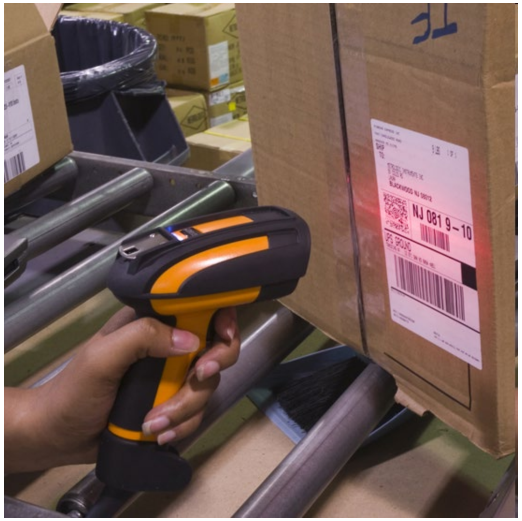


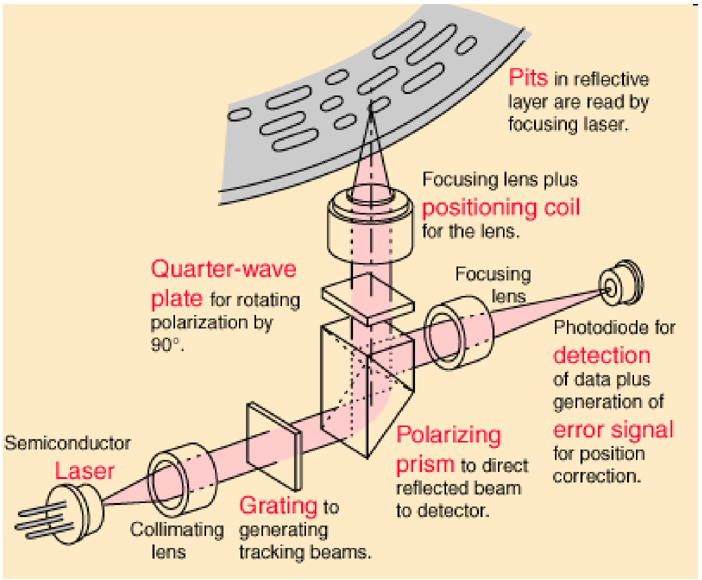
Semiconductor Light Sources

Light Emitting Diodes (LEDs) and Laser Diodes (LDs)

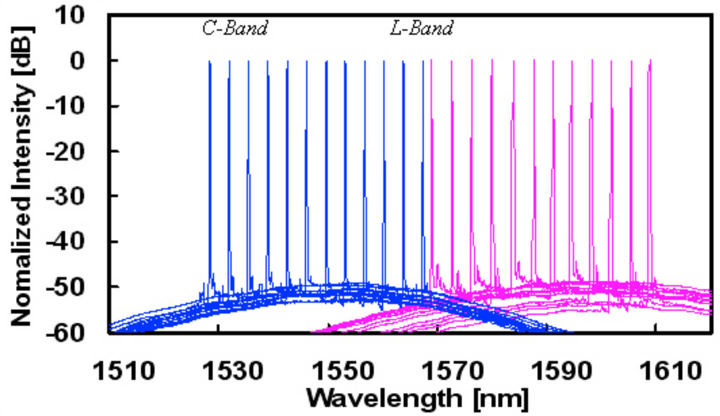




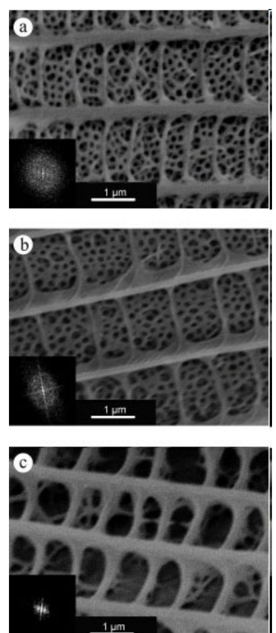


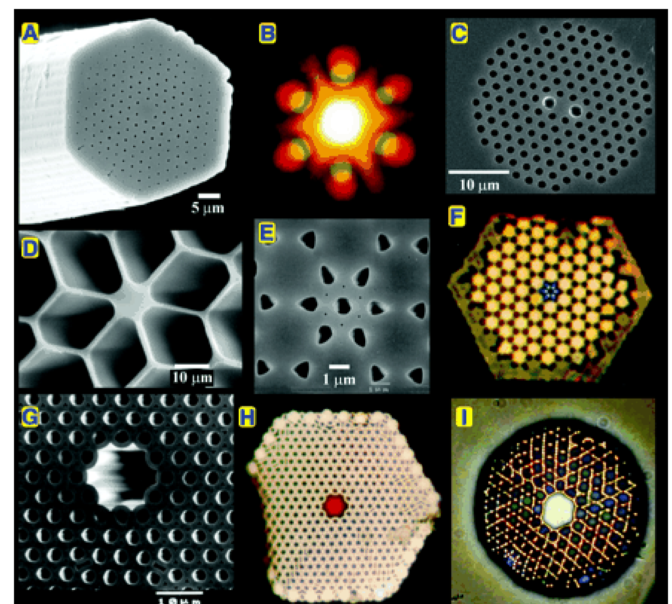


Optical Telecom & Internet



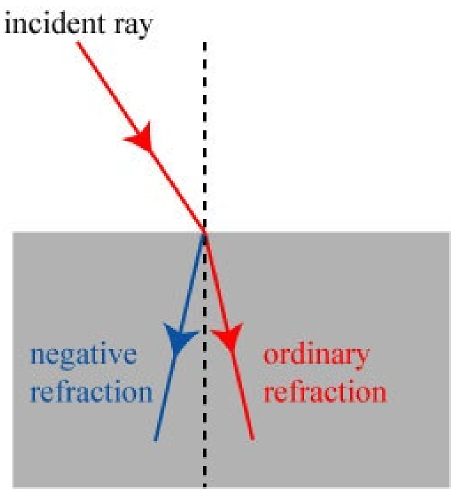
Biomimicing – Photonic Crystals

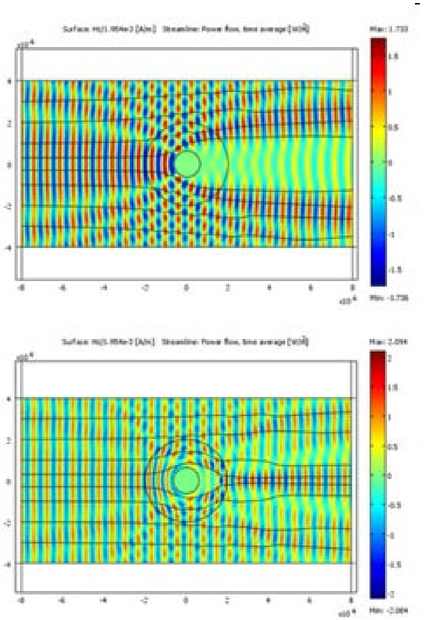




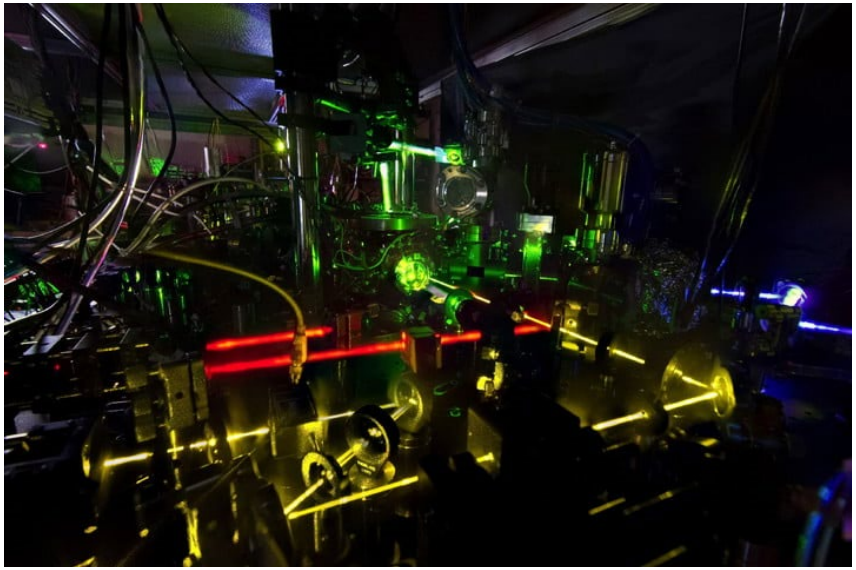
Negative Refractive Index

Metamaterials and Invisibility Cloaks





World's Most Accurate Clocks Are Optical
Losing One Second Every 14 Billion Years



National Institute of Standards and Technology (NIST), USA locks laser light onto a single ytterbium ion levitating in an ion trap:

- ion clock is a 'frequency generator with 18 decimals' ($f_0 \sim 5 \times 10^{14}$ Hz)
- can detect ~ 1 cm height changes on earth (theory of relativity)
- Centre for Metrology (VTT-MIKES) builds a clock based on a strontium ion

The Very Basics

What is Light?

• Light is **electromagnetic (EM) radiation** the energy of which can be observed e.g. as a) warming up of an illuminated target, b) electricity in photovoltaic cells or c) radiation pressure (very small)

• Light can be modelled both as

a) photons (particles or corpuscles), e.g., shadows

b) EM waves, e.g., interference, diffraction

• Quantum mechanical treatment combines these two formalisms (wave-particle dualism) – photons can be considered as ”wave packets”

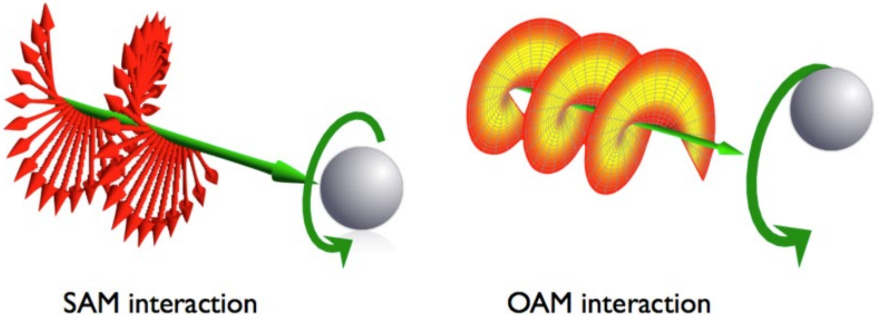
Quantum of Light = Photon

rest mass = 0
speed in vacuum $c_0 = 3.0 \times 10^8$ m/s

energy $E_p = h\nu = hc/\lambda$

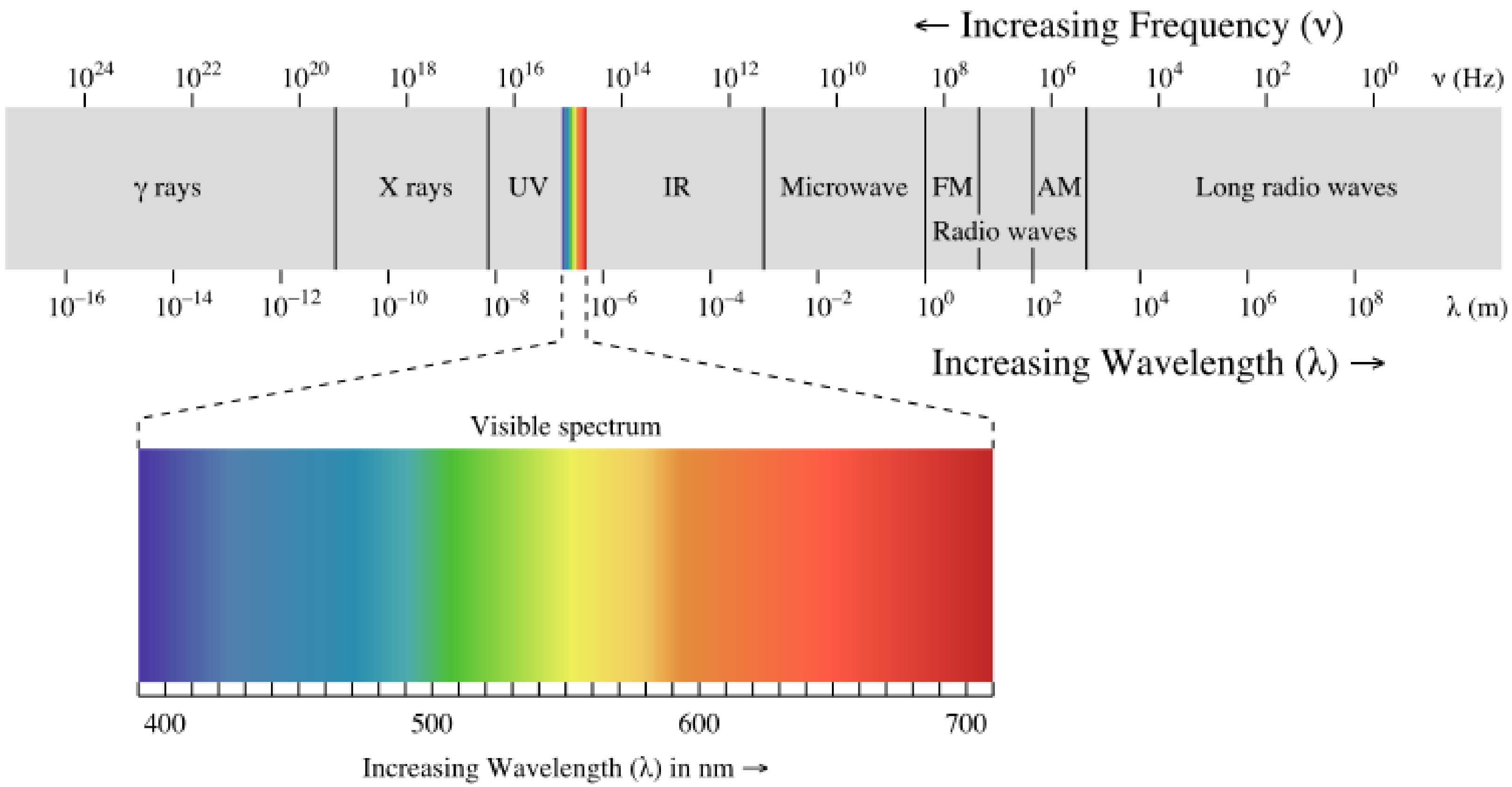
h is Planck's constant 6.626×10^{-23} Js
ν is the frequency of light
λ is the wavelenght of light

• according to the special theory of relativity, a particle having zero rest mass and travelling at the speed of light has non-zero linear momentum $p = E/c$
• interestingly, photons also exhibit angular momentum



SAM = spin angular momentum   OAM = orbital angular momentum

Electromagnetic (EM) Spectrum



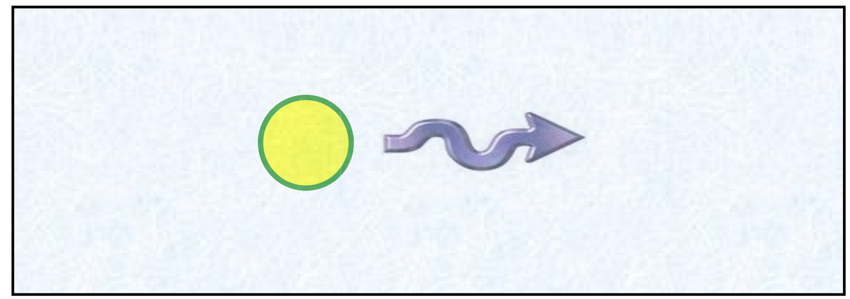
Interaction of Light with Optical Medium

light in a vacuum

speed $c_0 = 3 \times 10^8$ m/s

absorption coefficient $\alpha = 0$

light in a medium



speed $c = c_0/n$
where n is the refractive index
$n \geq 1 \rightarrow c \leq c_0$

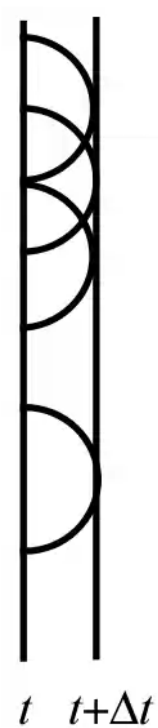
absorption coefficient $\alpha \neq 0$

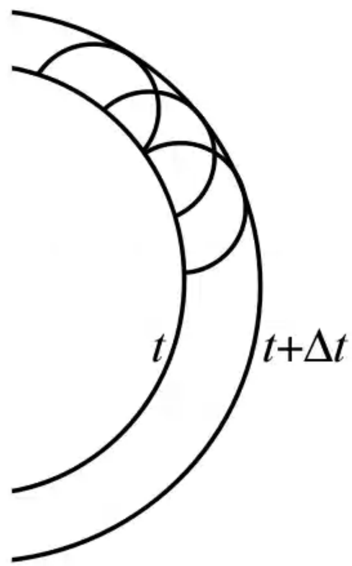
intensity $I(L) = I_0 \exp(-\alpha L)$

e.g. inside glass $n \approx 1.5$ and in an optical fibre $\alpha \approx 0.25$ dB/km = 0.06 km^{-1}

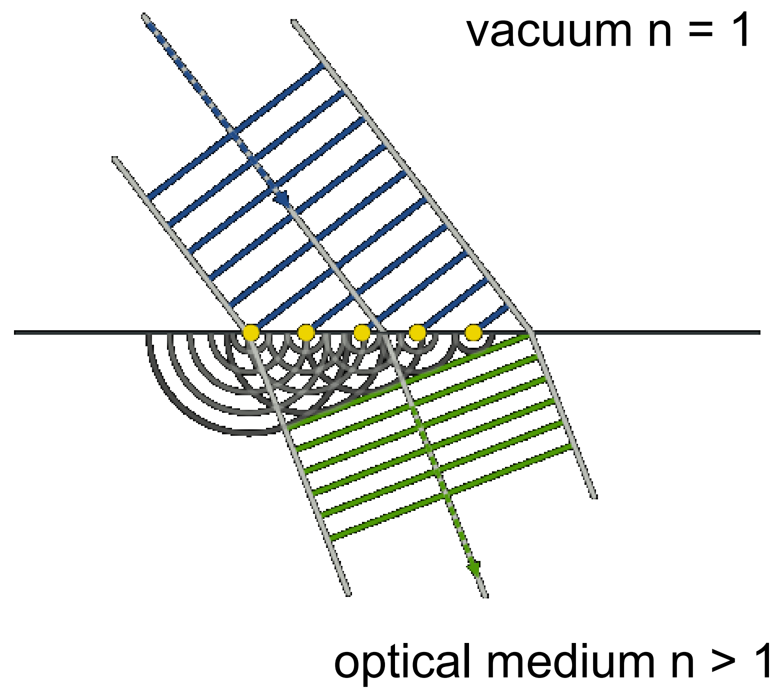
Huygens’ Principle

Every point of a wave front can be the origin of a new spherical wave (secondary wave). After a time Δt a new wave front can be formed as a tangent to all these spherical secondary waves.

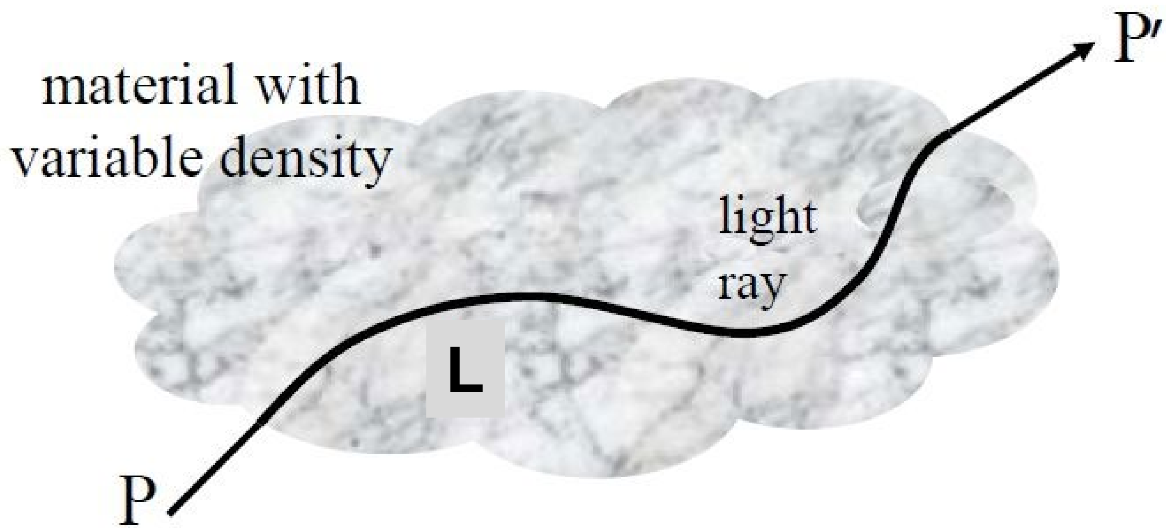




refraction



Fermat's Principle



The optical path length followed by light between two fixed points, **P** and **P'**, is an extremum ≈ the path that is traversed in the least time.

$$\partial L = \int_{P}^{P'} n ds$$

Linear Propagation of Light in a Homogenous Medium

In addition to the linear propagation of light,
following fundamental laws
can be derived from the Fermat’s principle:

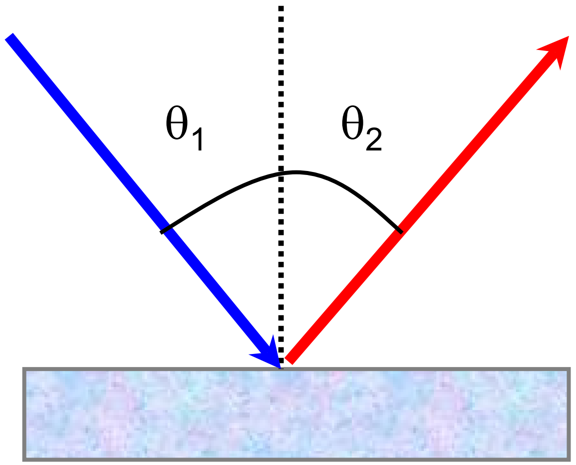
law of reflection

law of refraction

The derivation of these two
will be done in Excercise I.

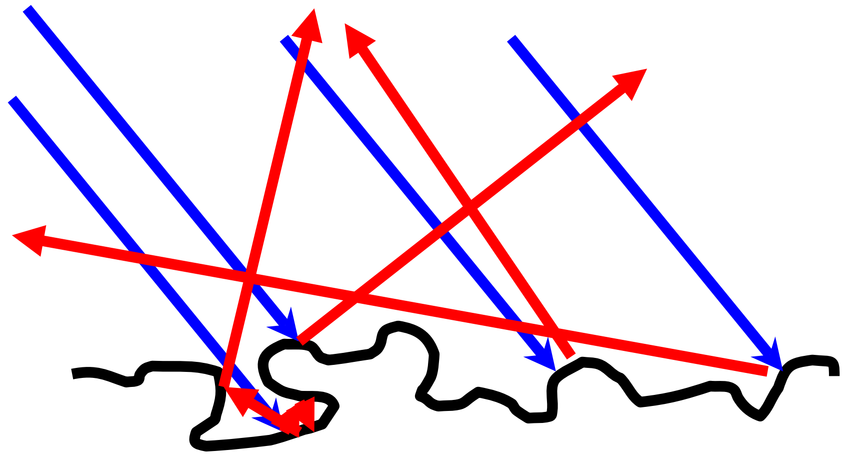
Reflection of Light

Specular reflection



ideal smooth surface
for example, well polished mirror surface

Diffuse reflection



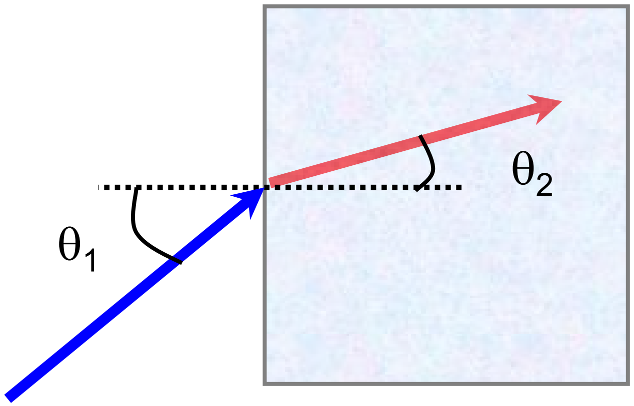
optically rough surface:
multiple reflections and
absorption losses
for example, wrinkled aluminium foil

law of reflection:
incident angle = reflection angle

Refraction of Light

from optically thin material into optically thick material

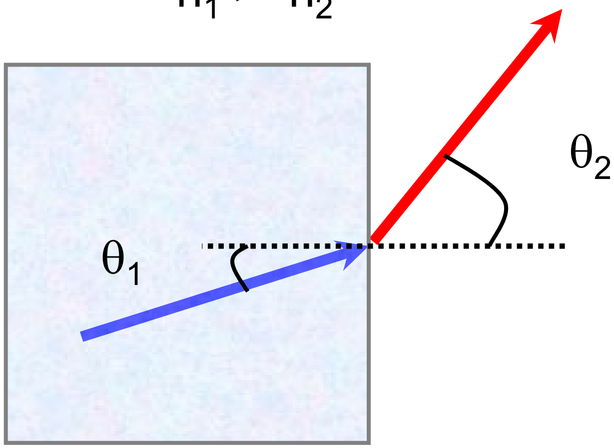
$n_1 < n_2$



refracted ray of light is closer to the normal of the interface

from optically thick material into optically thin material

$n_1 > n_2$

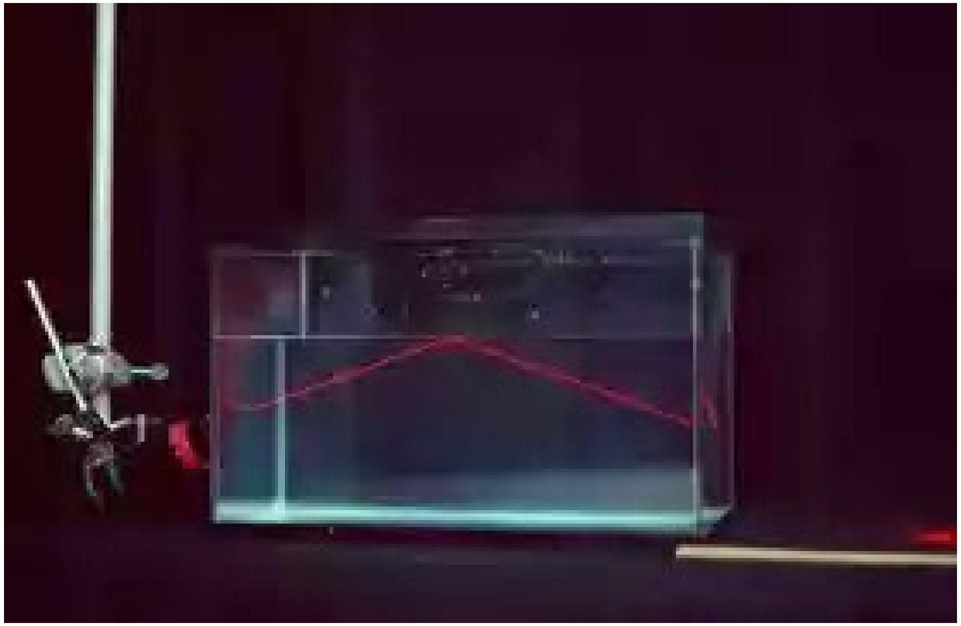


refracted ray of light is further away from the normal of the interface

Law of refraction or Snell's law: $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$

Total Internal Reflection (TIR)

Total Internal Reflection (TIR)



Total internal reflection is only possible upon moving from optically thicker material n_1 to optically thin material n_2 so that $n_1 > n_2$.