Introduction

Optics is the discipline that looks into the nature, generation, manipulation, transmission and detection of light, and the light–matter interaction and its application.

Shunping Zhang（张顺平）
School of Physics and Technology, WHU

Office: Physics Room 5-211
Tel: 027-68752219
E-mail: spzhang@whu.edu.cn

群名称:钟级男生创建的群

INTERNATIONAL
YEAR OF LIGHT
2015

QQ

18-物弘-张三

群名称:钟级男生创建的群

Course introduction

- **Determination of the final grade**
  - **Attendance 5% + Homework 15%**
  - **Mimi scientific report 20%**
  - **Final exam 60%**

- **Reference**
  - Optics, 5th Edition, Eugene Hecht, Publishing house of electronics industry, 2017.
  - 光学，游璞，于国萍，高等教育出版社，2003
  - 光学，赵凯华，钟锡华，北京大学出版社，1984
  - Principles of Optics (7th edition)，M. Born, E. Wolf，世界图书出版社，2001

Course introduction

- Lots of concepts.
- **The superposition principle** is the main line linking those content from different chapters.

Course Design

- The main course follows the *Optics* by You & Yu, taking into account some of the contents from *Optics* by Hecht.
- **Extracurricular reading**.
- Add super-resolution fluorescence microscopy and SNOM.
- Add frontiers：Nanophotonics and more?

§ 1.1 Brief History

- As early as 4,000 years ago in ancient Egypt and about 3,000 years ago in China, people had precedents to use optical phenomena. Such as bronze mirror, concave mirror to take fire （《周礼•考工记》，周朝） and so on.

- 4 0 0 years BC, people knew about the relationships between light and the shadow, and pinhole imaging in our country. （《墨经》，《经下》：“景到，在午有端，与景长，说在端。”）；

- In the Northern Song Dynasty, early optical experiments concerning convex and spherical mirrors were recorded（沈括《梦溪笔谈》，宋朝）.

墨翟，春秋末期战国初期时期，约公元前476~390年，宋国人

《墨经》光学八条

周礼·考工记

……段氏为镈器．桃氏为刃．金有六齐．六分其金而锡居一．谓之钟鼎之齐．五分其金而锡居一．谓之斧斤之齐．四分其金而锡居一．谓之戈戟之齐．参分其金而锡居一．谓之大刃之齐．五分其金而锡居二．谓之削杀矢之齐．金锡半．谓之鉴燧之齐．

筑氏为削．长尺博寸．合六而成规．欲新而无穷．敝尽而无恶．……

阳燧：向日取火的凹镜　　**鉴燧之齐：铸造铜镜与阳燧的合金。**

What is the light?

Earlier — Late 17^{th}/early 18^{th} C

- **Emission (corpuscular) theory**： R. Descartes (笛卡尔) and I. Newton（牛顿）
  - Light is a tiny particle emitted by a luminescent object. These particles can move in a straight line at great speed in a vacuum or transparent medium.
  - It can explain the rectilinear propagation of light and the reflection of light. If assuming $v_{\text{water}} > v_{\text{air}}$, it also can explain the refraction of light barginly.
  - Can not explain the interference, diffraction and polarization of light.

What is the light?

Late 17^{th} C — First half 19^{th} C

- **Wave theory**: raised by R. Hooke（胡克）and C. Huygens（惠更斯）
  - Light is a kind of wave motion. The propagation of light is not the movement of particles, but the movement of energy in the form of waves.
  - can simply explain the **reflection** and **refraction**.
  - **Limitations**: It regards light as some kind of mechanical elastic wave. Therefore, there must be a special elastic medium (aether, 以太) that pervades the space.

- Newton's too famous, almost no one believed the wave theory.
- Early 19th C, the wave theory explained nicely the **interference**, **diffraction** and **polarization** of light, by Thomas Young (托马斯•杨）、A. J. Fresnel（菲涅尔）et al.

What is the light?

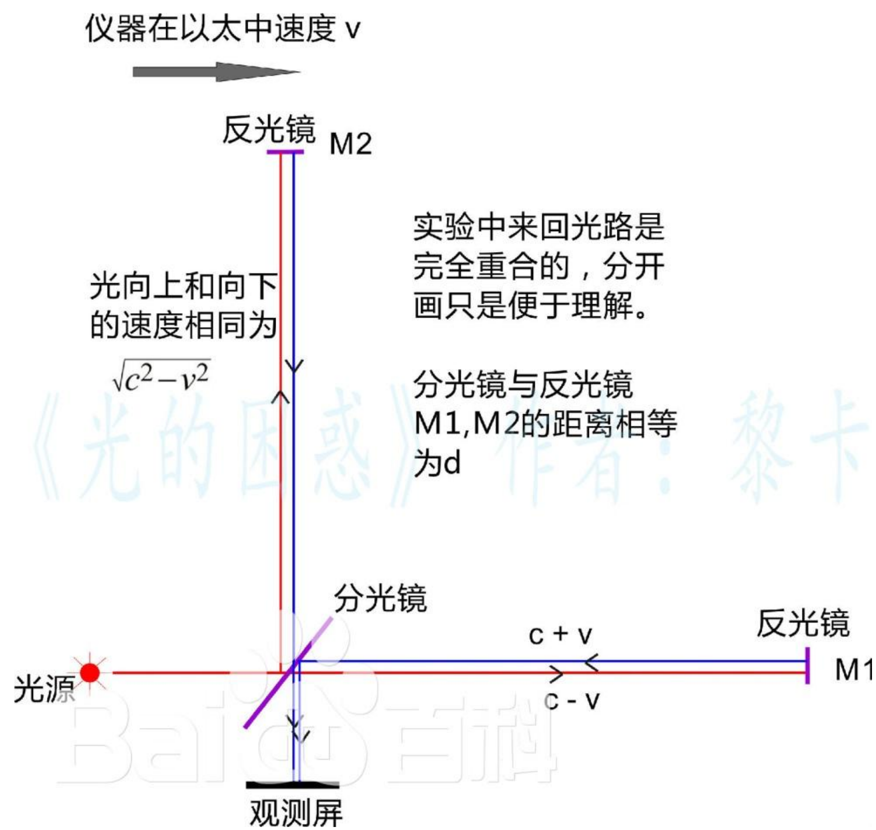
- **Aether is ridiculous.**
  - Density $\rho_{aether} << \rho_{air}$, its elastic shear modulus far larger than steel.
  - The mechanical wave can only occur and propagate in the medium. The light is a transverse wave, and a transverse mechanical wave can only be generated in the solid.

$$v_{\mathrm{e}} = \left(E_{\|} / \rho_{\mathrm{e}} \right)^{1/2}$$

  - The properties of aether is different in different materials, since light travels at different speeds in different media.
  - The aether fills the entire universe, and all stars move without drag in the aether.

What is the light?

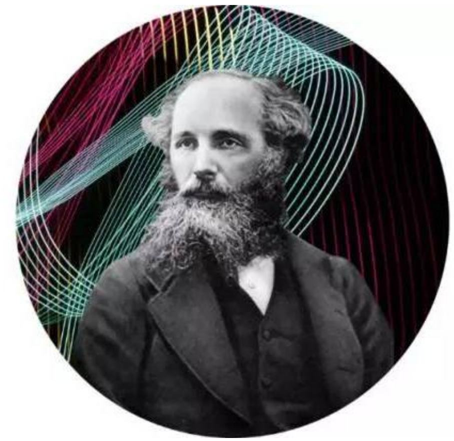
- In 1887，Michelson-Morley （迈克尔逊-莫雷）measured the earth's motion speed with aether optically and denied the existence of aether.
  - It appears from all that precedes reasonably certain that if there be any relative motion between the earth and the luminiferous aether, it much be small; quite small enough entirely to refute Fresnel's explanation of aberration.



What is the light?

- 19^{th} C 60s，James Clerk Maxwell（麦克斯韦）Summarizes a set of equations that describe the changing laws of electromagnetic fields.

- In 1888，Heinrich R. Hertz（赫兹）proved the existence of electromagnetic waves and it had the same propagation speed as light, $v = c_0$.
  - Light is an electromagnetic wave.
  - The wave nature of light is perfectly described by Maxwell's equations.
  - Wave theory reach its peak.



Maxwell，1831~1879，Scotland

Hertz，1857~1894，Germany

What is the light?

- But in early 20th C, the wave theory can't explain **blackbody radiation**, **photoelectric effects**, **Compton scattering**, and the **spectral lines of atoms**.

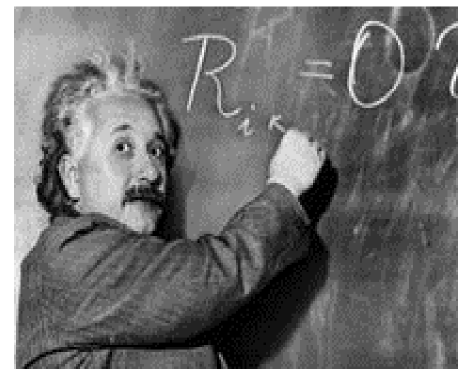
APPENDIX B.

NINETEENTH CENTURY CLOUDS OVER THE DYNAMICAL THEORY OF HEAT AND LIGHT*.

(Friday evening Lecture, Royal Institution, April 27, 1900.)

§ 2. CLOUD I.—RELATIVE MOTION OF ETHER AND PONDERABLE BODIES; such as movable bodies at the earth's surface, stones, metals, liquids, gases; the atmosphere surrounding the earth; the earth itself as a whole; meteorites, the moon, the sun,

* *Journal of the Royal Institution.* Also *Phil. Mag.* July, 1901.

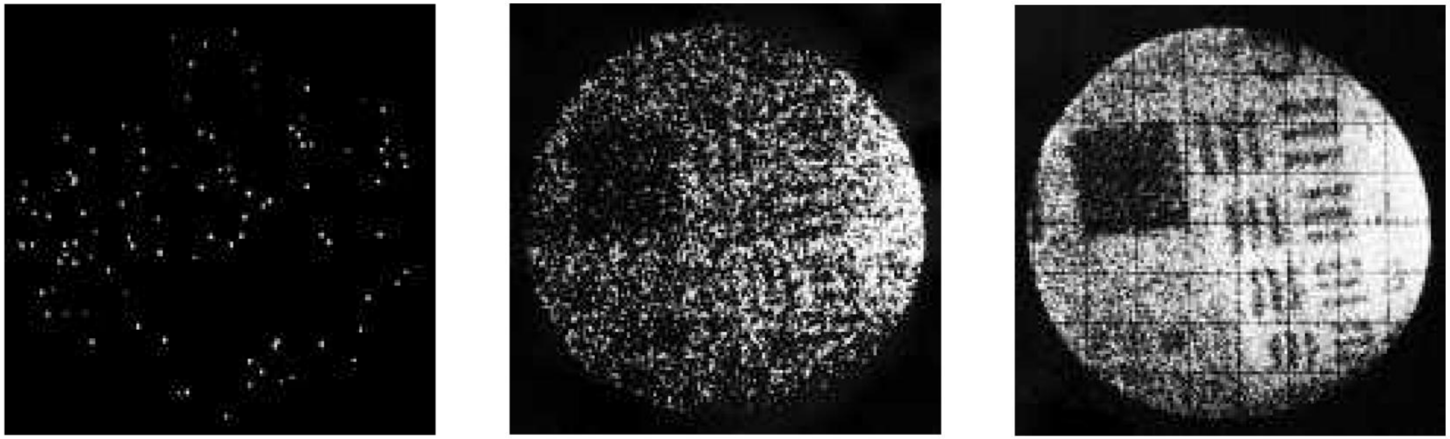


Einstein, 1879~1955
Germany

- In 1905, A. Einstein（爱因斯坦）proposed a new form of corpuscular theory that light is consisted of 'particles' of energy, called photon later.

What is the light?

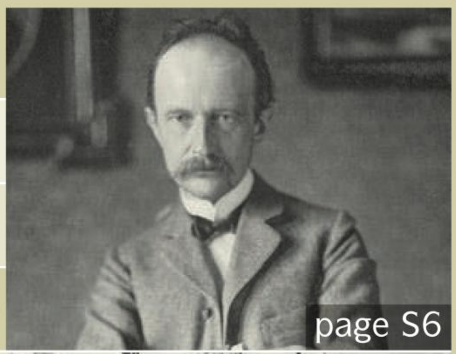
- **Wave-particle duality**. In the **propagation**, the wave nature of light is obvious. The particle nature of light is significant in the **light-matter interaction**.



- In 1930s, QED gave a reasonable explanation of the wave-particle duality of light. Classical wave optics applies in the limit of large number of photons.

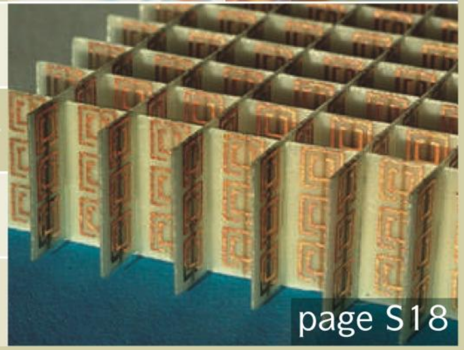
Memorabilia for optics

MILESTONES TIMELINE	
1600s–1800s	Debate on the character of light (Milestone 1)
1861	Maxwell's equations (Milestone 2)
1900	Planck's theory of black-body radiation (Milestone 3)
1905	Special relativity and Photoelectric effect equation (Milestone 4)
1923	Compton effect (Milestone 5)
1947	Quantum electrodynamics (Milestone 6)
1948	Holograms (Milestone 7)
1954	Solar cells (Milestone 8)
1960	The laser (Milestone 9)
1961	Nonlinear optics (Milestone 10)
1963	Quantum optics (Milestone 11)



Memorabilia for optics

1964	Bell inequality (Milestone 12)
1966	Optical fibres (Milestone 13)
1970	CCD cameras (Milestone 14)
	Semiconductor lasers (Milestone 15)
1981	High-resolution laser spectroscopy and frequency metrology (Milestone 16)
1982–1985	Quantum information (Milestone 17)
1987	Photonic crystals (Milestone 18)
1993	Blue light-emitting diodes (Milestone 19)
1998	Plasmonics (Milestone 20)
2000	Metamaterials (Milestone 21)
2001	Attosecond science (Milestone 22)
2006	Cavity optomechanics (Milestone 23)



Memorabilia for optical microscope

1595	Invention of the microscope (Milestone 1)
1858	First histological stain (Milestone 2)
1871	Synthesis of fluorescein (Milestone 2)
1873	Diffraction limit theory (Milestone 3)
1911	First fluorescence microscopy (Milestone 4)
1929	First epifluorescence microscope (Milestone 4)
1935	Phase contrast microscopy (Milestone 5)
1939	Polarization microscopy (Milestone 6)
1942	Immunofluorescence (Milestone 7)
1955	Differential interference contrast (Milestone 8)
1961	Concept of confocal microscopy (Milestone 9)
1967	The dichroic mirror (Milestone 4)
1972	Fluorescence correlation spectroscopy (Milestone 10)
1976	FRAP (Milestone 10)
	FRET (Milestone 11)
1980	Calcium probes (Milestone 12)

Frits Zernikel
1888 ~ 1966

Observed unstained cells that survived and transparent cytoplasm（1935 ）\1953 Nobel Prize in physics

1981	Video-enhancement differential interference contrast (Milestone 8)
	TIRF microscopy (Milestone 13)
1983	Deconvolution microscopy (Milestone 14)
1987	Realization of confocal microscopy (Milestone 9)
1990	Two-photon microscopy (Milestone 15)
1993	Light sheet microscopy (Milestone 16)
	Single molecule microscopy (Milestone 17)
1994	GFP (Milestone 18)
1997	Fluorescent protein-based biosensors (Milestone 19)
1999	Red fluorescent proteins (Milestone 20)
2000	Breaking the diffraction limit: STED (Milestone 21)
2002	Photoactivatable fluorescent proteins (Milestone 20)
2006	Breaking the diffraction limit: PALM/STORM (Milestone 21)

E. Betzig (PALM), Stefan W. Hell (STED), William E. Moerner share Nobel Prize in Chemistry (2014)

Optics for human being

- The invention of the laser in the 1960s, largely extended the area that people can do in optical communications, holography, nonlinear optics, and optical information processing.
- The invention of optical fiber, charge coupled device (CCD), LED etc. affect significantly in our daily life.

Laser
Scientific revolution

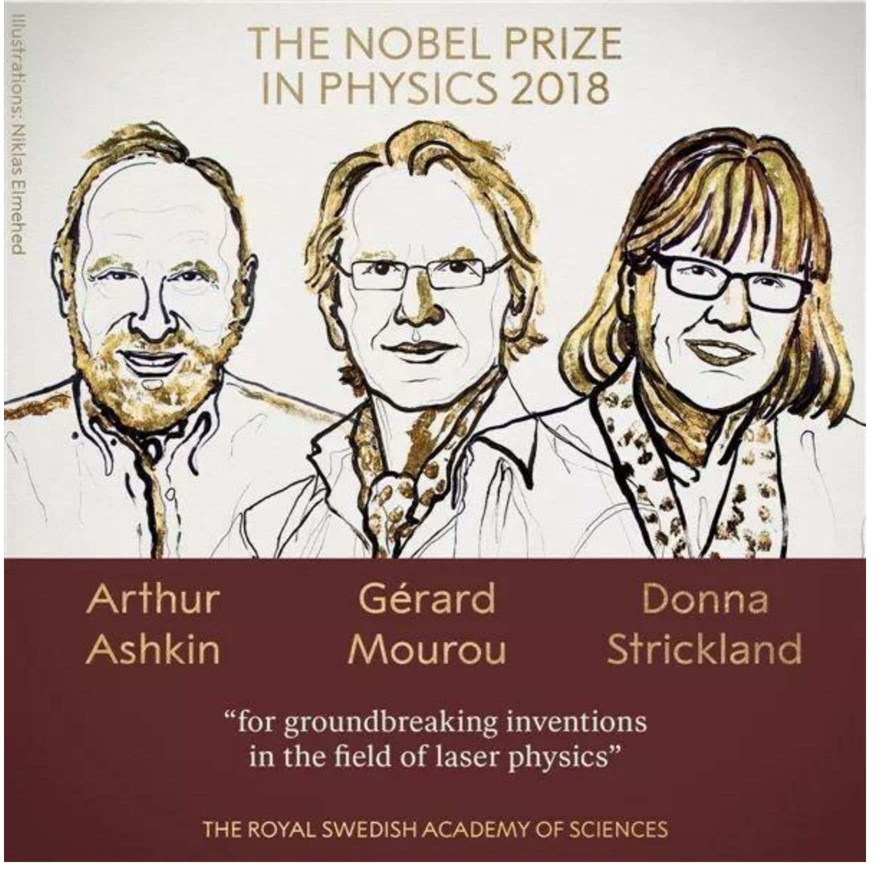
Optical fiber
Information era

LED
Energy revolution

Optics for human being

The Nobel Prize in Physics 2018 was awarded "for groundbreaking inventions in the field of laser physics" .

- Arthur Ashkin "for the optical tweezers and their application to biological systems"
- Gérard Mourou and Donna Strickland "for their method of generating high-intensity, ultra-short optical pulses."



Optics for human being

Nobel Prizes in recent years

Laser cooling 1997 Nobel Prize in physics

fs spectroscopy reveals chemical reaction, 1999 Nobel Prize in chemistry

Laser precision spectroscopy, 2005 Nobel Prize in physics

Optical fiber/ CCD, 2009 Nobel Prize in physics

Super Resolution Imaging 2014 Nobel Prize in chemistry

Blue LED 2014 Nobel Prize in physics

LIGO, 2017 Nobel Prize in physics

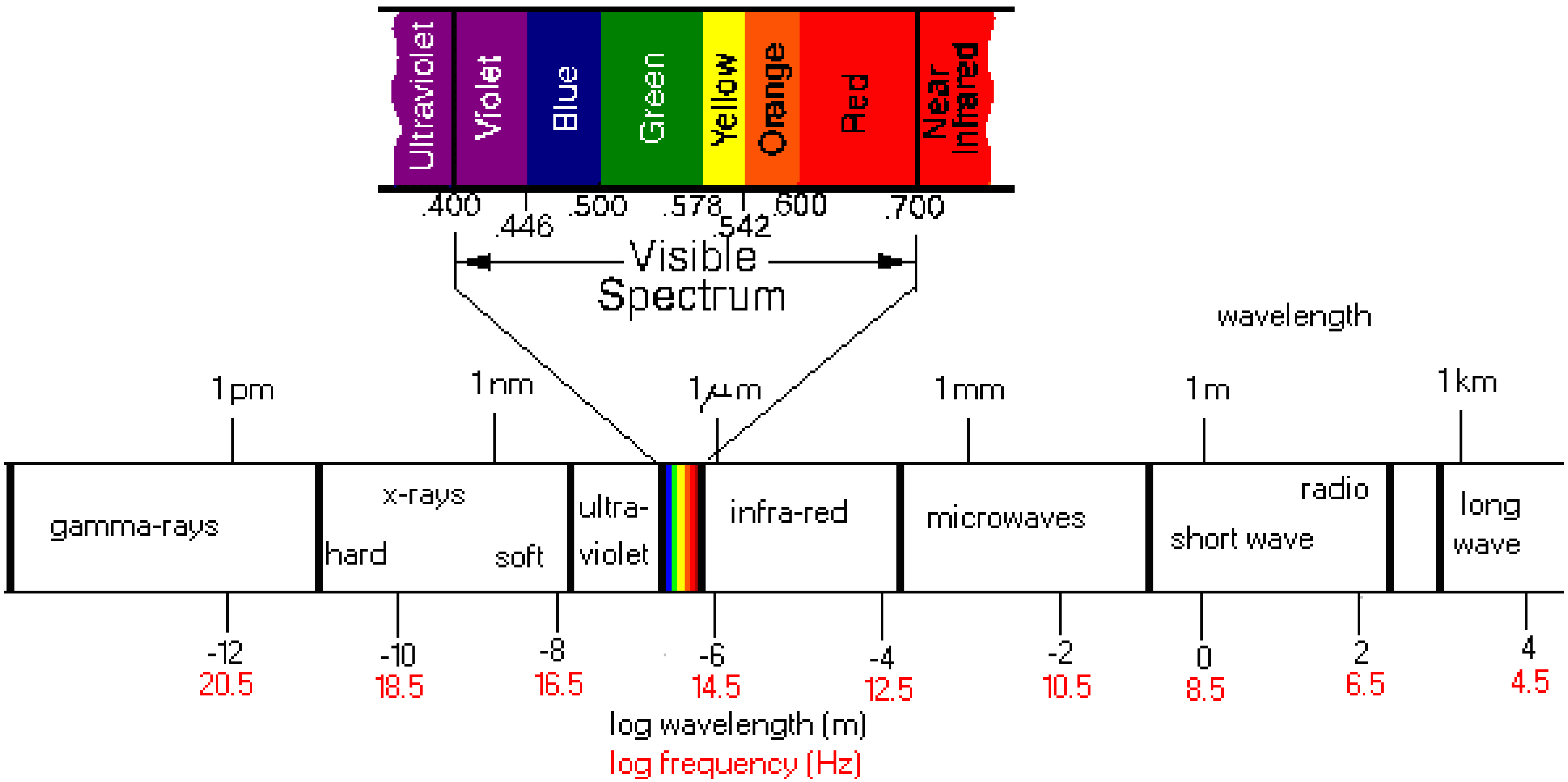
Laser physics, 2018

- On Feb. 12, 2016, LIGO (laser interferometer gravitational wave observatory) announced the detection of gravitational waves.
- On Aug. 16, 2016, the Quantum Satellite "**Mozi**" was launched.

Humans have never stopped exploring the light!

§ 1.2 Basic parameters of light

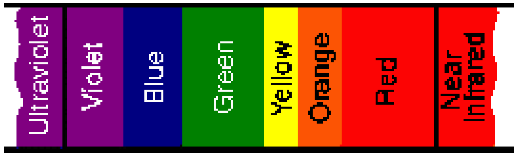
- Light is an electromagnetic wave.



Wavelength

- Visible light, wavelength range is about 400 nm ~ 760 nm.
- Different wavelengths correspond to different color in vision. The human eye is most sensitive to yellow-green light at 555 nm.
- Red、orange、yellow、green、blue、violet： /nm

red	630 ~ 760	**orange**	600 ~ 630
yellow	550 ~ 600	**green**	480 ~ 550
blue	450 ~ 480	**violet**	400 ~ 450



- Monochromatic light, containing a single frequency, exists only in theory.
- A light source always contains a certain range of wavelength. - quasi-monochromatic light.

Velocity

- Velocity in vacuum:

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = 2.997\,924\,58 \times 10^8 \text{ m/s}$$

$$\varepsilon_0 = 8.85 \times 10^{-12} \text{ F/m}, \quad \mu_0 = 4\pi \times 10^{-7} \text{ H/m}$$

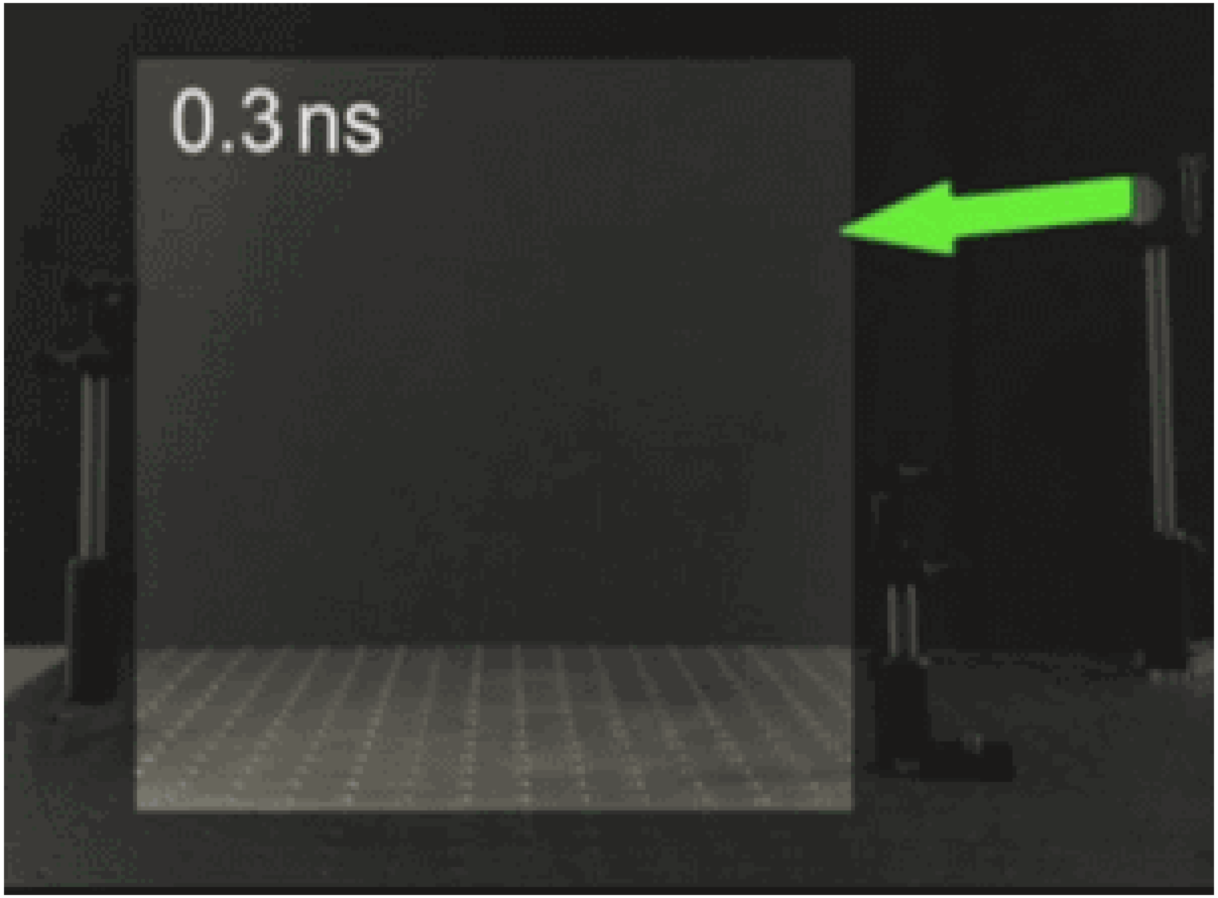
- In medium:

$$v = \frac{1}{\sqrt{\varepsilon_0 \varepsilon_r \mu_0 \mu_r}} = \frac{c}{\sqrt{\varepsilon_r \mu_r}} \equiv \frac{c}{n} < c$$

  - Refractive index : $n = c/v$
  - When light passes through different linear medium, the frequency does not change.
  - λ in vacuum and medium $\lambda_0 = \dfrac{c}{\nu}$ $\quad \lambda = \dfrac{v}{\nu}$

Velocity

- Snapped by high speed camera:



Energy and momentum

Wave

wavelength λ wave vector $\mathbf{k}$ frequency ν

temporal period T angular frequency ω velocity v

$$\mathbf{k} = \frac{2\pi}{\lambda}\hat{\mathbf{k}} \quad v = \frac{\lambda}{T} = \lambda\nu \quad \omega = 2\pi\nu = \frac{2\pi}{T} = \frac{2\pi}{\lambda}v = kv = k_0 c$$

Particle

Energy $E = h\nu = \hbar\omega$

Momentum $\mathbf{p} = \hbar\mathbf{k} = \frac{h}{\lambda}\hat{\mathbf{k}}$

Plank constant

$h = 6.626\times10^{-34}\ \mathrm{J\cdot s}$

$\hbar = h/2\pi$

- Wave-particle duality. In the propagation, the wave nature of light is obvious. The particle nature of light is significant in the light-matter interaction.

Comparison: Photon and Electron

- Photons and electrons differ quite a lot.

	electron	photon
Rest mass	m_0	0
Motion mass	m	$h\nu/c^2$
Motion velocity	$< c$	c
Spin	1/2	1
Distribution law	Fermion	Boson

- Both have the wave–particle duality:

$$E = h\nu \qquad p = h/\lambda$$

- Both can carry information.