# EP118 Optics

**TOPIC 1**

**LIGHT**
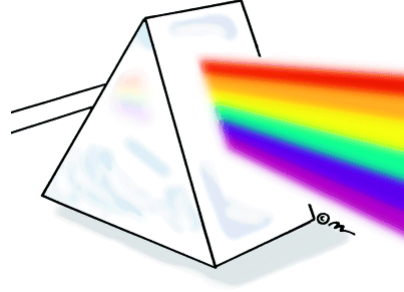


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**July 2011**

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# 1.1 History of Light

- Light is the portion of electromagnetic radiation that is visible to the human eye and is an energy propagating in space as photons.

- Optics is the branch of physics which involves the behavior and properties of light and interactions of light with matter such as
    - illumination
    - reflection
    - refraction
    - interference
    - diffraction
    - polarization
    - etc.



- Optics has many engineering applications such as the construction of instruments to use and detect the light.

| Time | Scientist | Description | Explains |
|------|-----------|-------------|----------|
| BC.300 | Euclid | Light travels in straight line | Reflection |
| 1200 | Ibn-i Haysem | Light is a ray | Reflection, Refraction |
| 1690 | Huygens | Ligth might be some sort of a wave motion | Reflection, Refraction |
| 1704 | Newton | Ligth consists of small particles called Corpuscular. | Reflection |
| 1800 | Young | The first clear demonstration of the wave nature of light | Interference |
| 1895 | Maxwell | Light is a form of high-frequency electromagnetic wave | Reflection, Refraction, Interference, Diffraction |
| 1901 | Planck | Light is a particle carrying energy called "photons" | Black body radiation |
| 1905 | Einstein | Light is a particle (photon) | Photo electric effect |
| 1923 | Compton | Light is a particle (photon) | Compton scattering |
| 1924 | De Broglie | Light and matter have both wave and particle duality | All |

# 1.2 Wave Nature of Light
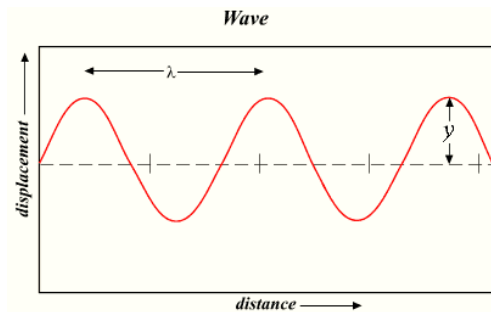

*Wave*

λ : wavelength

*f* : frequency (number of oscillations per second)

v : speed of the wave   $--> v = f\lambda$

For a light in vacuum $v = c = 3\text{x}10^8$ m/s   (*we'll see later*)
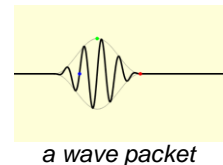
# 1.3 Quantum Theory of Light

Planck was used the idea that black bodies emit light (and other electromagnetic radiation) only as discrete packets of energy called **photons**.

Energy of photon is given by:

$$E = hf = \frac{hc}{\lambda}$$


*a wave packet*

*h* is the Planck's Constant ($h = 6.6 \times 10^{-34}$ J.s)
*c* is the speed of light  ($c = 3\text{x}10^8$ m/s)
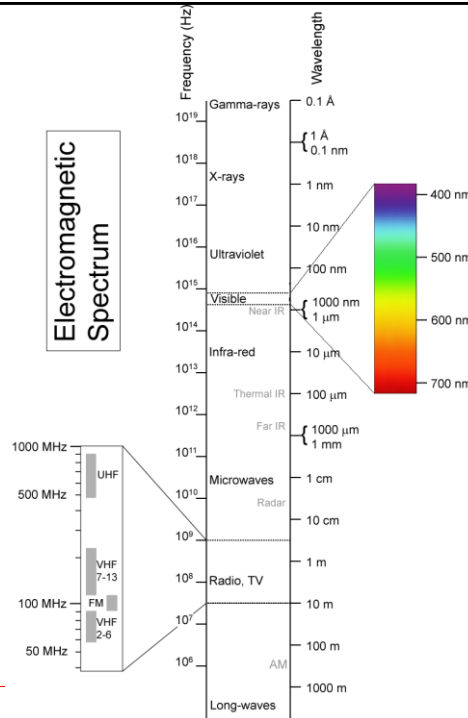
*The photon idea is later used by Einstein and Compton.*

# 1.4  EM Specturum

**The electromagnetic spectrum is the range of all possible frequencies of electromagnetic radiation.**

## Visible Radiation (light)

* have a wavelength ranging from 380 nm (**violet**) to 760 nm (**red**).
* is typically absorbed and emitted by electrons in molecules and atoms that move from one energy level to another.
* The sun and stars emit most of their radiation as visible light.



| Frequency (Hz) | | Wavelength |
|---|---|---|
| | Gamma-rays | 0.1 Å |
| $10^{19}$ | | |
| $10^{18}$ | | 1 Å / 0.1 nm |
| $10^{17}$ | X-rays | 1 nm |
| $10^{16}$ | | 10 nm |
| | Ultraviolet | 100 nm |
| $10^{15}$ | Visible | 1000 nm / 1 µm |
| $10^{14}$ | Near IR | |
| $10^{13}$ | Infra-red | 10 µm |
| $10^{12}$ | Thermal IR | 100 µm |
| | Far IR | 1000 µm / 1 mm |
| $10^{11}$ | Microwaves | 1 cm |
| $10^{10}$ | Radar | 10 cm |
| $10^{9}$ | | 1 m |
| $10^{8}$ | Radio, TV | 10 m |
| $10^{7}$ | | 100 m |
| $10^{6}$ | AM | 1000 m |
| | Long-waves | |

400 nm
500 nm
600 nm
700 nm

1000 MHz — UHF
500 MHz
VHF 7-13
100 MHz — FM
VHF 2-6
50 MHz

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## Radio waves

* have wavelengths ranging from ~ 100 m to about ~ 1 mm
* are generated by such electronic devices (such as LC oscillations)
* are utilized by antennas of appropriate size
* are used for transmission of data, via modulation.
  + *Radio, Television, Mobile Phones, Wireless Networking, Radar, …*

## Microwaves

* have wavelengths ranging from ~1 m to ~1 mm
* include both UHF and EHF.
* are generated by electronic devices
* are absorbed by molecules that have a dipole moment in liquids.
  + *In a microwave oven, this effect is used to heat food.*

## Infrared

* covers the wavelength range from roughly 1 mm to 750 nm
* hot objects can radiate strongly in this range
* is absorbed by molecular vibrations.
  + *The water in the Earth's atmosphere absorbs so strongly in this range that it renders the atmosphere effectively opaque*

Sayfa 8

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## Ultraviolet (UV)
* covers the wavelength range from roughly 10 nm to 400 nm
* can break chemical bonds.
* Sun emits a large amount of UV radiation.
  Earth absorbes most of them on the atmosphere's ozone ($O_3$) layer.
  + *Sunburn is caused by the disruptive effects of UV radiation*
    *on skin cells.*

## X-rays (Röntgen Radiation)
* have a wavelength in the range of 0.01 nm to 10 nm
* can penetrate solid objects
* can damage or destroy living tissues and organisms
* can be used to take images of the inside of objects
  + *Diagnostic radiography and crystallography.*
  + *Neutron stars and accretion disks around black holes emit*
    *X-rays, which enable us to study them.*

## Gamma-rays

* have a wavelength less than 10 pm

* are produced by sub-atomic particle interactions
  + *radioactive nuclei (such as $^{60}Co$ and $^{137}Cs$)*
  + *electron-positron annihilation*
  + *neutral pion decay*
  + *cosmic rays*
  + *fusion*
  + *fission*

* can highly penetrate solid objects
  + *irradiation of food and seed for sterilization*

* produce serious damage when absorbed by living tissues
* can also demage DNA of a cell
  + *radiation cancer therapy and*
    *some kinds of diagnostic imaging such as PET scans.*

## EXAMPLE 1

What is the energy in Joule and eV of
(a) a visible light of 500 nm and (b) a radio wave of 1 m of wavelength.

### SOLUTION

(a) $E = \dfrac{hc}{\lambda} = \dfrac{(6.6\times10^{-34}\text{ J.s})(3\times10^{8}\text{ m/s})}{500\times10^{-9}\text{ m}} = 3.96\times10^{-19}\text{ J}$

Since 1 eV = 1.6x10⁻¹⁹ J     $E = \dfrac{3.96\times10^{-19}\text{ J}}{1.6\times10^{-19}\text{ J/eV}} = 2.48\text{ eV}$

(b) $E = \dfrac{hc}{\lambda} = \dfrac{(6.6\times10^{-34}\text{ J.s})(3\times10^{8}\text{ m/s})}{1\,\text{m}} = 1.98\times10^{-25}\text{ J} = 1.24\times10^{-6}\text{ eV}$

## EXAMPLE 2

A half-wave antenna works on the principle that the optimum length of the antenna is half the wavelength of the radiation being received. What is the optimum length of a car antenna when it receives a signal of frequency 94.7 MHz?

### SOLUTION

*Wavelength is:*

$$\lambda = \frac{c}{f} = \frac{(3\times10^{8}\text{ m/s})}{94.7\times10^{6}\text{ Hz}} = 3.16\,\text{m}$$

*Thus, to operate most efficiently, the antenna should have a length of:*

$$L = \frac{3.16\,\text{m}}{2} = 1.58\,\text{m}$$

*For practical reasons, car antennas are usually one-quarter wavelength in size.*

# 1.5 Speed of Light

EM Theory tells us that the speed of light in a medium is given by:

$$v = \frac{1}{\sqrt{\mu\varepsilon}}$$

where

    μ is the permeability of the medium (related to magnetism)
    ε is the permittivity of the medium (related to electricity)

For free space (vacuum), in SI units:

    $\mu = \mu_0 = 4\pi \times 10^{-7}$ m.kg/C$^2$
    $\varepsilon = \varepsilon_0 = 8.85 \times 10^{-12}$   C$^2$.s$^2$/m$^3$.kg

Hence, the speed of light in vacuum represented by *c* is:

$$c = \frac{1}{\sqrt{\mu_0\varepsilon_0}} = \frac{1}{\sqrt{4\pi \times 10^{-7} \times 8.85 \times 10^{-12}}} \approx 3\times10^8 \text{ m/s}$$

A precise measurement yields:

$$c = 2.99792458 \times 10^8 \text{ m/s}$$

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*Some of the best measurements of c*

| Date | Author | Method | Result (km/s) | Error |
|------|--------|--------|---------------|-------|
| 1676 | Olaus Roemer | Jupiter's satellites | 214,000 | |
| 1726 | James Bradley | Stellar Aberration | 301,000 | |
| 1849 | Armand Fizeau | Toothed Wheel | 315,000 | |
| 1862 | Leon Foucault | Rotating Mirror | 298,000 | +-500 |
| 1879 | Albert Michelson | Rotating Mirror | 299,910 | +-50 |
| 1907 | Rosa, Dorsay | Electromagnetic constants | 299,788 | +-30 |
| 1926 | Albert Michelson | Rotating Mirror | 299,796 | +-4 |
| 1947 | Essen, Gorden-Smith | Cavity Resonator | 299,792 | +-3 |
| 1958 | K. D. Froome | Radio Interferometer | 299,792.5 | +-0.1 |
| 1973 | Evanson et al | Lasers | 299,792.4574 | +-0.001 |
| 1983 | | Adopted Value | 299,792.458 | |

Michelson Method
(Rotating Mirror)



- Light is reflected by face A of the rotating mirror (RM).
- Light then travels a distance, s, (a few kilometres) and returns to be reflected by face B.
- At a certain speed of rotation, the light reappears. This is because the time taken for light to go from face A to face B is the same as the time taken by the RM to rotate 1/8 of a revolution.
- If the RM completes *N* rotations per second then the time for one revolution is 1/*N*.
- The time taken for the light to cover the distance, *s* is given by $\Delta t = 1/8N$
- So, the speed of light is:

$$\boxed{c = 8Ns}$$

- Michelson found that *c* = (299796 +- 4) km/s

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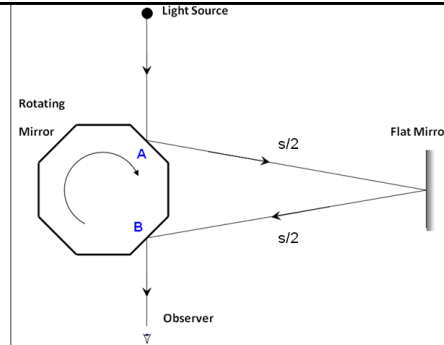
EXAMPLE 3

In the Michelson experiment for measuring the speed of light, total distance travelled by the light is given by *s* = 1000 m. To measure the true speed of light, determine the required angular speed in rad/s of the rotating mirror system.

SOLUTION

$$N = \frac{c}{8s} = \frac{(3\times10^8 \text{ m/s})}{(8)(1000\,\text{m})} = 3.75\times10^4 \text{ revolution/s}$$

*or*

$$N = \left(3.75\times10^4 \frac{\text{rev}}{\text{s}}\right)\left(\frac{60\,\text{s}}{1\,\text{min}}\right) = 2.25\times10^6 \text{ rev/min} = 2.25\times10^6 \text{ rpm}$$

*Angular speed is*

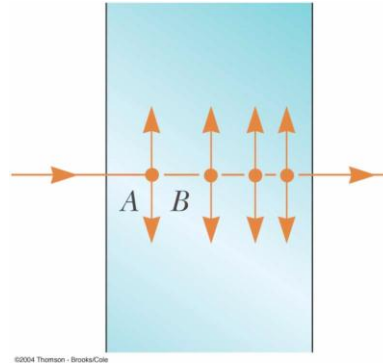$$\omega = \left(3.75\times10^4 \frac{\text{rev}}{\text{s}}\right)\left(\frac{2\pi\,\text{rad}}{1\,\text{rev}}\right) = 2.36\times10^5 \text{ rad/s}$$

# 1.6  Light in a Medium

- The light enters from the left

- The light may encounter an electron

- The electron may absorb the light, oscillate, and reradiate the light

- The absorption and radiation cause the average speed of the light moving through the material to decrease



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*Light passing from one atom to another in a medium. The dots are electrons, and the vertical arrows represent their oscillations.*

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# 1.7  Refraction Index

- The speed of light in any material is less than its speed in vacuum.

- The index of refraction, *n*, of a medium can be defined as

$$n \equiv \frac{\text{speed of light in a vacuum}}{\text{speed of light in a medium}} = \frac{c}{v}$$

- For a vacuum:     n = 1
  For other media:   n > 1
  For air:        n = 1.00029 ≈ 1
  For water:       n = 1.333

| Indices of Refraction[a] | | | |
|---|---|---|---|
| Substance | Index of Refraction | Substance | Index of Refraction |
| *Solids at 20°C* | | *Liquids at 20°C* | |
| Cubic zirconia | 2.20 | Benzene | 1.501 |
| Diamond (C) | 2.419 | Carbon disulfide | 1.628 |
| Fluorite ($CaF_2$) | 1.434 | Carbon tetrachloride | 1.461 |
| Fused quartz ($SiO_2$) | 1.458 | Ethyl alcohol | 1.361 |
| Gallium phosphide | 3.50 | Glycerin | 1.473 |
| Glass, crown | 1.52 | Water | 1.333 |
| Glass, flint | 1.66 | | |
| Ice ($H_2O$) | 1.309 | *Gases at 0°C, 1 atm* | |
| Polystyrene | 1.49 | Air | 1.000 293 |
| Sodium chloride (NaCl) | 1.544 | Carbon dioxide | 1.000 45 |

[a] All values are for light having a wavelength of 589 nm in vacuum.

See also: **http://refractiveindex.info**

- As light travels from one medium to another, its frequency does not change

- Both the wave speed and the wavelength do change

- The wavefronts do not pile up, nor are created or destroyed at the boundary, so $f$ must stay the same.
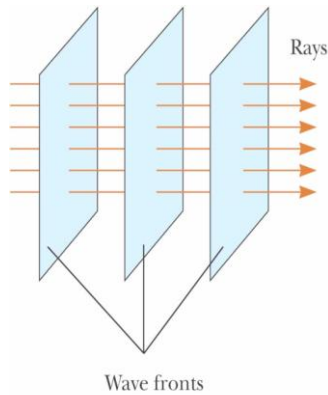
- $v = f\lambda$ on both sides

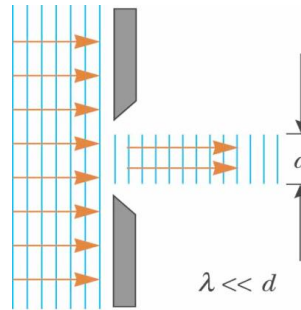$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$



wavefront

$n_1 = \dfrac{c}{v_1}$

$\lambda_1$

$A$

$1$

$v_1$

$2$

$\lambda_2$

$v_2$

$B$

$n_2 = \dfrac{c}{v_2}$
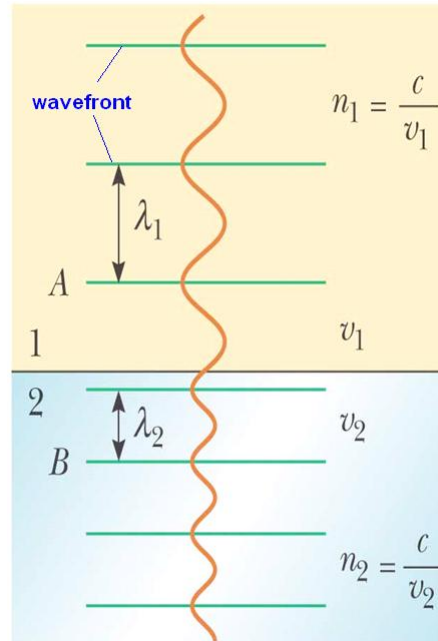
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# 1.8   Ray and Wave Approximations



Rays

Wave fronts
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The rays are straight lines perpendicular to the wave fronts



$d$

$\lambda \ll d$
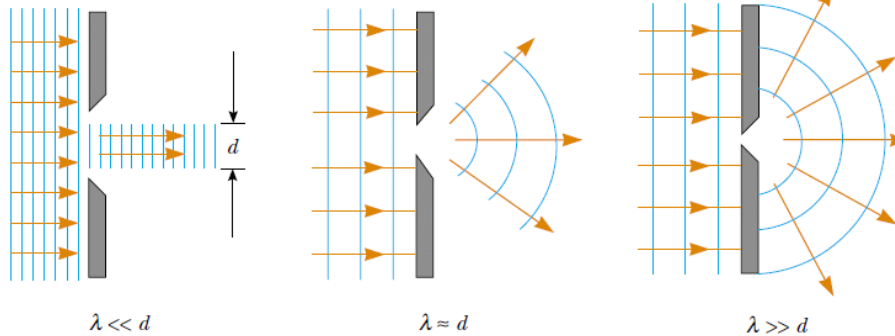
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If a wave meets a barrier and if λ<<d  then the light behaves like a ray.
*This approximation is good for the study of mirrors, lenses, prisms, etc.*

$\lambda \ll d$          $\lambda \approx d$          $\lambda \gg d$

$d$

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if λ ~ *d*  or λ >> *d* then we cannot use the ray approximation
since the light can make interference or diffraction.

# 1.9  Exercises

1. What is the speed, energy (in eV) and frequency of a γ-ray of 1 pm wavelength (a) in air and (b) in water?

2. A laser in a compact disc player generates light that has a wavelength of 780 nm in air. (a) Find the speed of this light once it enters the plastic of a compact disc (n = 1.55) (b) What is the wavelength of this light in the plastic?

3. Assume that a 1kW-oven gives all of its energy as microwave radiation. How long does it take to boil a glass (200 ml) of water if its initial temperature is 20 °C?

4. Explain why frequency of the light does not change as it travels from one medium to another.

5. 10% energy of total energy from a 100 W ligth-bulb is radiated as photons. Calcuate number of violet (λ = 400 nm) photons leaving from the bulb in 10 sec.

6. In the Michelson experiment for measuring the speed of light, octagonal mirror rotates at 3000 rpm. To measure the true speed of light, determine the required distance between rotating mirror and flat mirror.

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7. A green light of wavelength 580 nm is incident on a slit of width *d*. For which of the following value of *d* is the ray approximation valid?
   (a) 10 μm    (b) 1 μm    (c) 0.1 μm    (d) 1 nm

8. Which of the following em-radiations can be absorbed by molecular vibrations?
   (a) gamma-ray   (b) x-ray   (c) microwave  (d) radio waves

9. Which of the following em-radiations can be produced by sub-atomic particle interactions?
   (a) gamma-ray  (b) x-ray  (c) microwave  (d) radio waves

10. Which of the following em-radiations can be used in transmission of data?
    (a) gamma-ray   (b) x-ray   (c) microwave  (d) radio waves

11. Which of the following em-radiations can be used to heat food?
    (a) gamma-ray   (b) x-ray   (c) microwave  (d) radio waves

12. Which of the following em-radiations can be used in radiography?
    (a) gamma-ray   (b) x-ray   (c) microwave  (d) radio waves

13. In many kitchens, a microwave oven is used to cook food. The frequency of the microwaves is on the order of $10^{10}$ Hz. The wavelengths of these microwaves are on the order of
    (a) kilometers    (b) meters    (c) centimeters   (d) micrometers

# 1.10  References

1.  Serway, Beichner, **Physics for Scientists and Engineers** 6th ed, Brooks/Cole

2.  http://en.wikipedia.org/wiki/Light

3.  http://en.wikipedia.org/wiki/Electromagnetic_spectrum

4.  http://www.phys.ncku.edu.tw/mirrors/physicsfaq/Relativity/SpeedOfLight/measure_c.html

5.  http://www.saburchill.com/physics/chapters3/0007.html