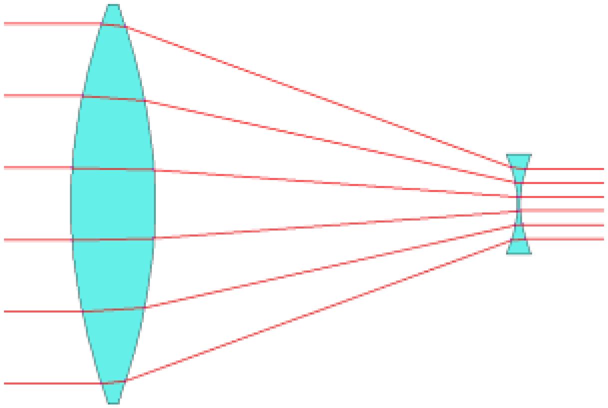
EP 324
Applied Optics

Topic 1

The Light



Department of

Engineering of Physics

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Sep 2015

PART I

THE LIGHT

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	Light might be some sort of a wave motion	Reflection, Refraction
1704	Newton	Light 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

Wave Particle Duality

Depending on the experiment you make,
the light can exhibit two behaviors:

- Wave-like behavior

- Particle-like behavior

Note that:

Particles (electrons, protons, etc) can also exhibit both particle-like or wave-like behaviors.

Wave is a *disturbance* that travels through space

Mechanical Waves

sound

water

string waves …

Electromagnetic Waves

Light

Radio waves

X-ray …

Wave

Quantum Mechanical Waves

to describe the probability density of a particle!

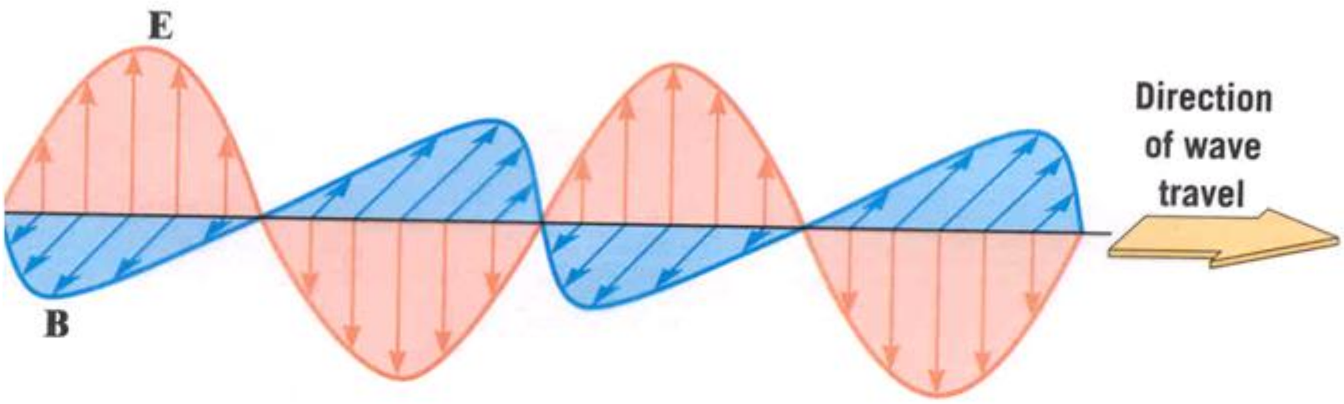
Gravitational Waves

disturbances in the curvature of space-time! (Not observed).

Electromagnetic Waves

EMW is a form of energy exhibiting wave-like behavior as it travels through space. EMW has both electric field (**E**) and magnetic field (**B**) components, which

* oscillate in *phase*
* perpendicular to each other and
* perpendicular to the direction of energy propagation



***** James Clerk Maxwell first theoretically postulated EMWs (in 1862).

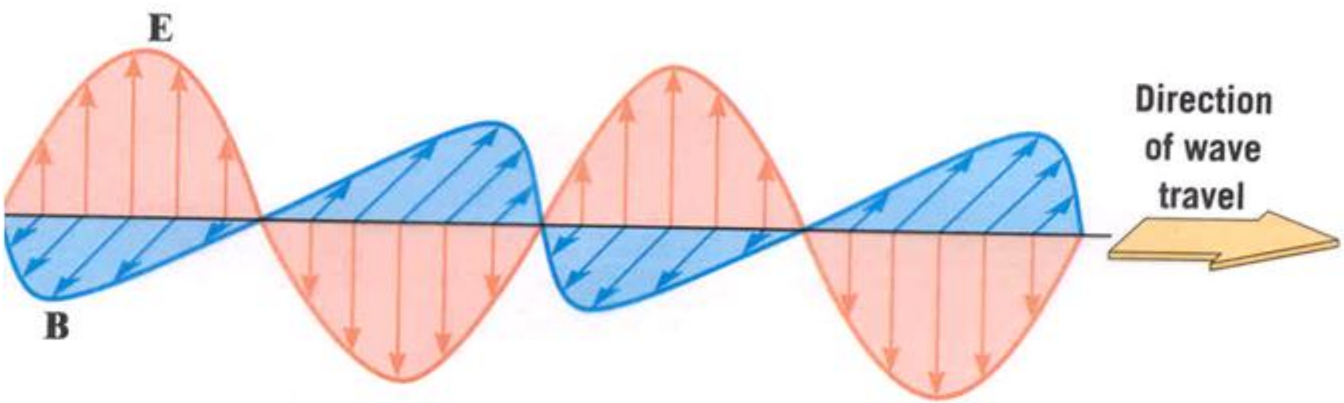
***** These were confirmed by Heinrich Hertz experimentally (in 1886).

Maxwell's Equations

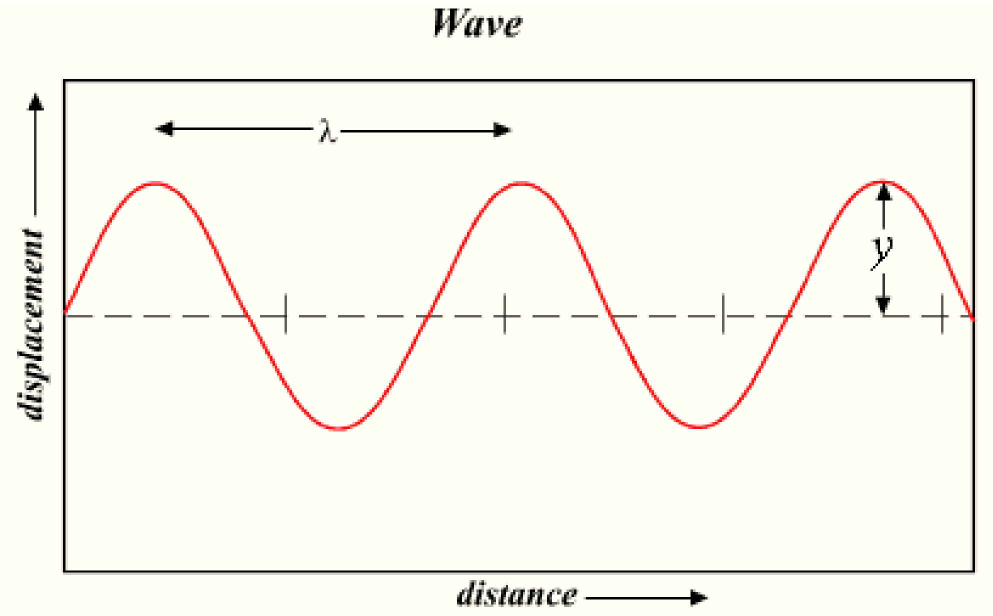
The set of equations that form the foundation of :

** classical electrodynamics*
** classical optics*
** electric circuits.*

Name	Differential equations
Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$



Wave Nature of Light



λ : wavelength

f : frequency (number of oscillations per second)

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

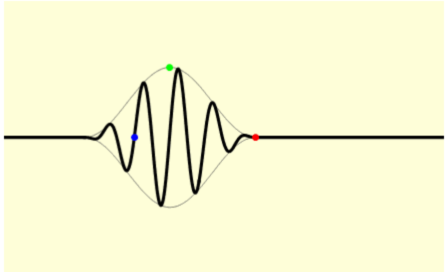
For a light in vacuum $v = c = 3 \times 10^8$ m/s (*we'll see later*)

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

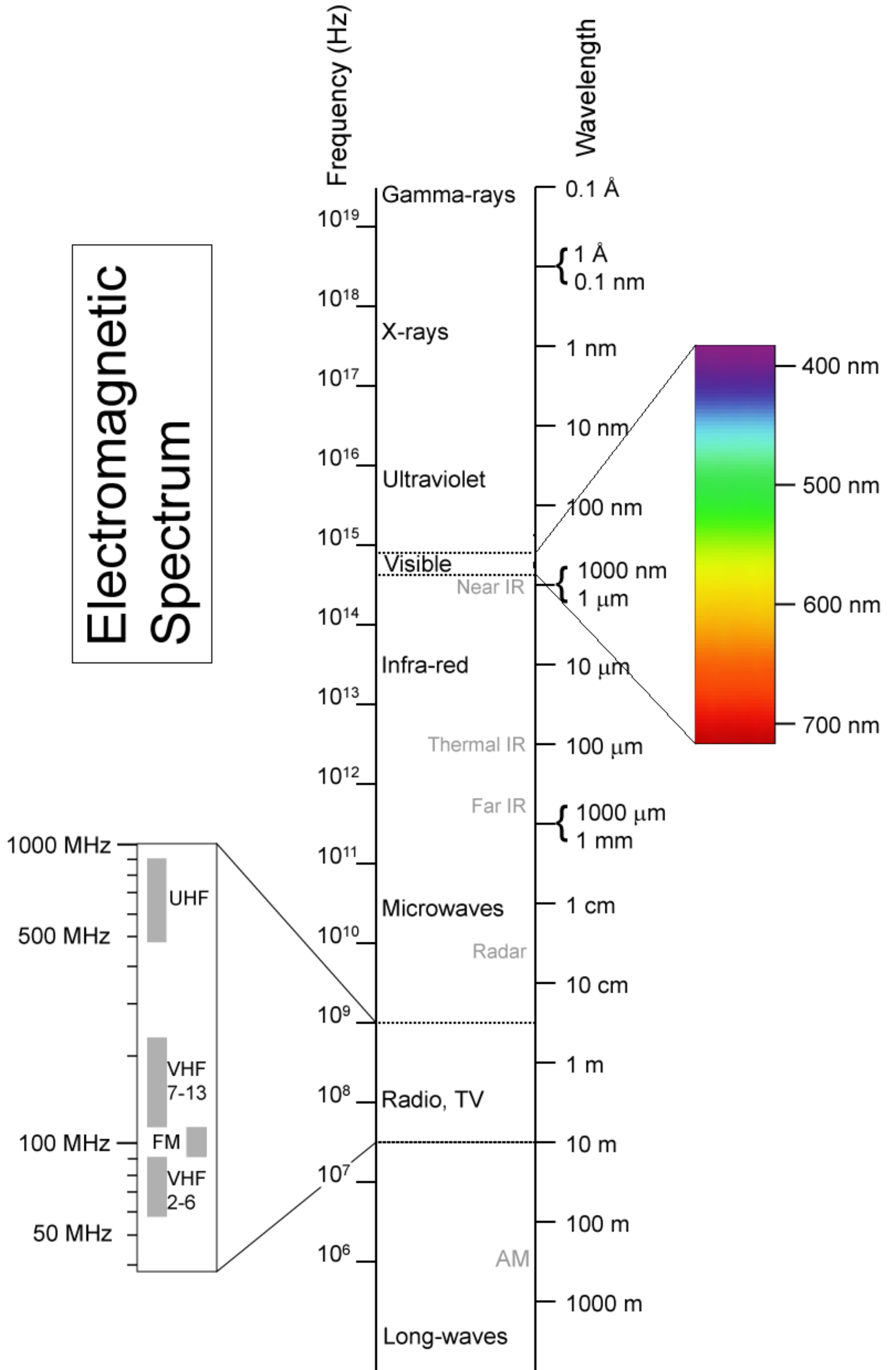
h is the Planck's Constant (h = 6.6 x 10^{-34} J.s)
c is the speed of light (c = 3×10^8 m/s)

The photon idea is later used by Einstein and Compton.

http://phet.colorado.edu/en/simulation/photoelectric
http://www.youtube.com/watch?v=4p47RBPiOCo

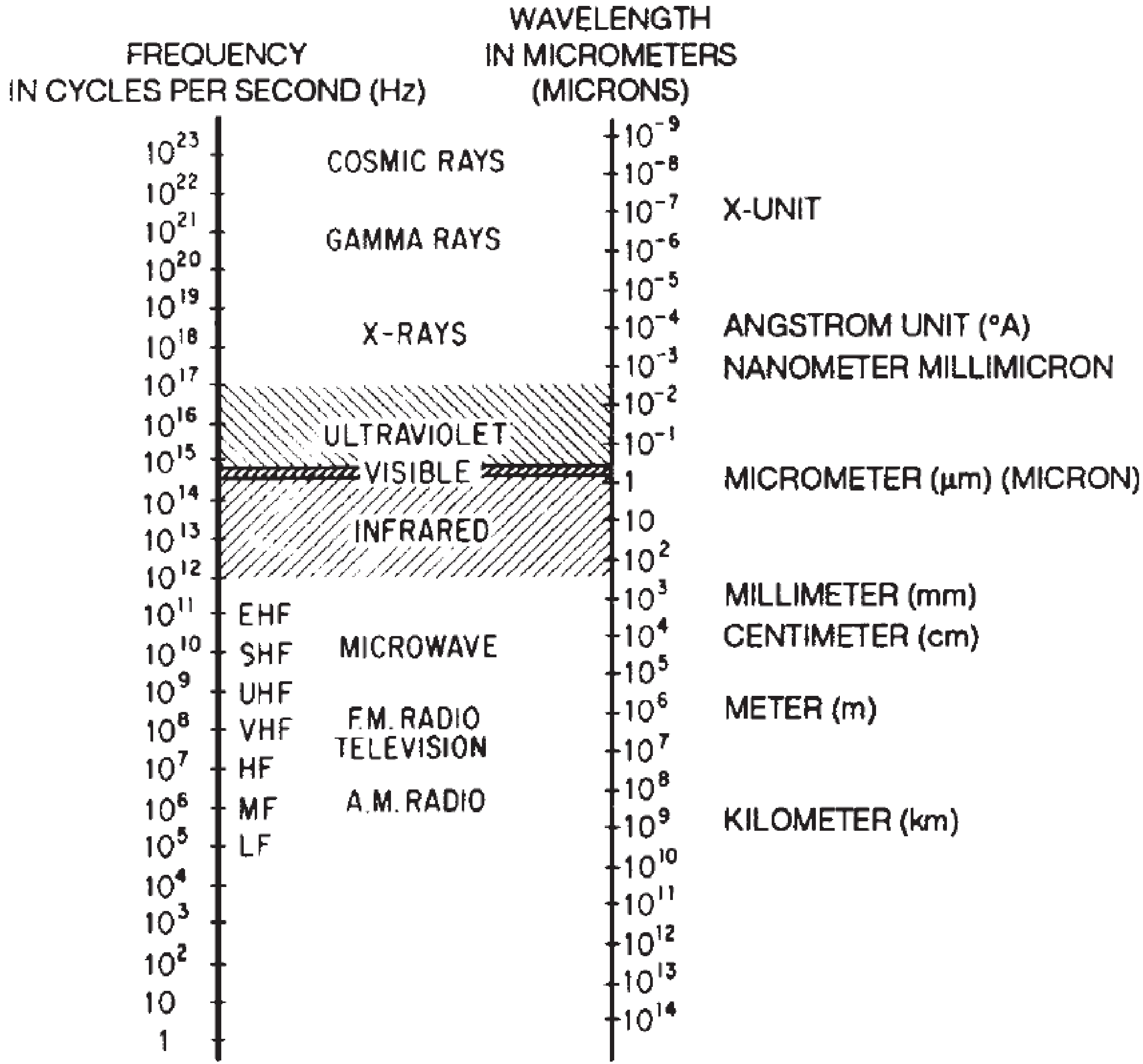
EM Specturum

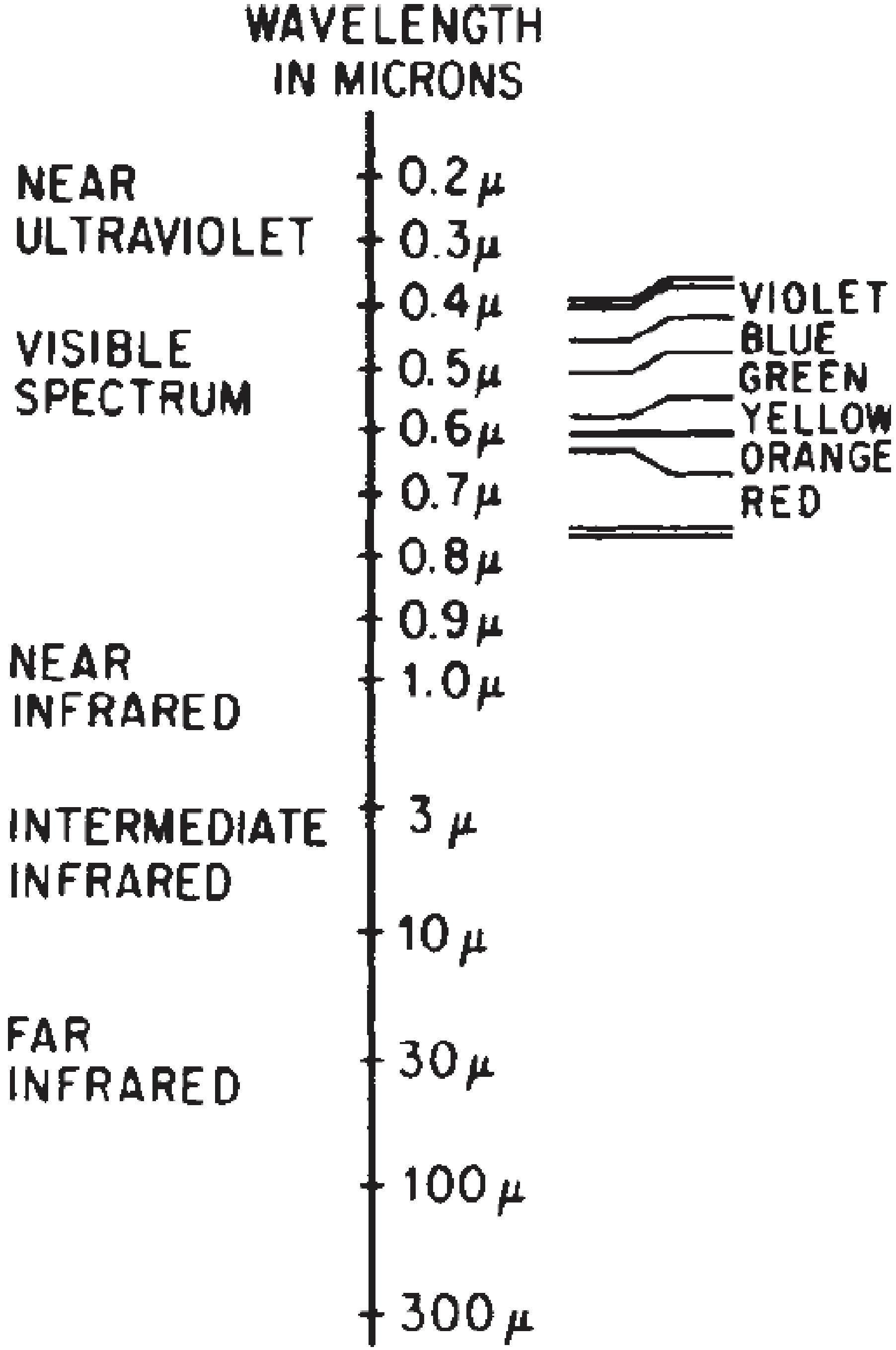
The electromagnetic spectrum is the range of all possible frequencies of electromagnetic radiation.



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
IN CYCLES PER SECOND (Hz)
WAVELENGTH
IN MICROMETERS
(MICRONS)
COSMIC RAYS
GAMMA RAYS
X-RAYS
ULTRAVIOLET
VISIBLE
INFRARED
EHF
SHF
UHF
VHF
HF
MF
LF
MICROWAVE
F.M. RADIO
TELEVISION
A.M. RADIO
X-UNIT
ANGSTROM UNIT (°A)
NANOMETER MILLIMICRON
MICROMETER (μm) (MICRON)
MILLIMETER (mm)
CENTIMETER (cm)
METER (m)
KILOMETER (km)


WAVELENGTH
IN MICRONS
NEAR
ULTRAVIOLET
VISIBLE
SPECTRUM
NEAR
INFRARED
INTERMEDIATE
INFRARED
FAR
INFRARED
0.2 μ
0.3 μ
0.4 μ
0.5 μ
0.6 μ
0.7 μ
0.8 μ
0.9 μ
1.0 μ
3 μ
10 μ
30 μ
100 μ
300 μ
VIOLET
BLUE
GREEN
YELLOW
ORANGE
RED

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*

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

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

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

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

EXAMPLE

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:

$$\lambda = \frac{c}{f} = \frac{(3 \times 10^8 \text{ m/s})}{94.7 \times 10^6 \text{ Hz}} = 3.16 \text{ m}$$

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.

Speed of Light

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

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

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:

$$c = \frac{1}{\sqrt{\mu_0\varepsilon_0}} = \frac{1}{\sqrt{4\pi\times10^{-7}\times8.85\times10^{-12}}} \approx 3\times10^{8}\ \mathrm{m/s}$$

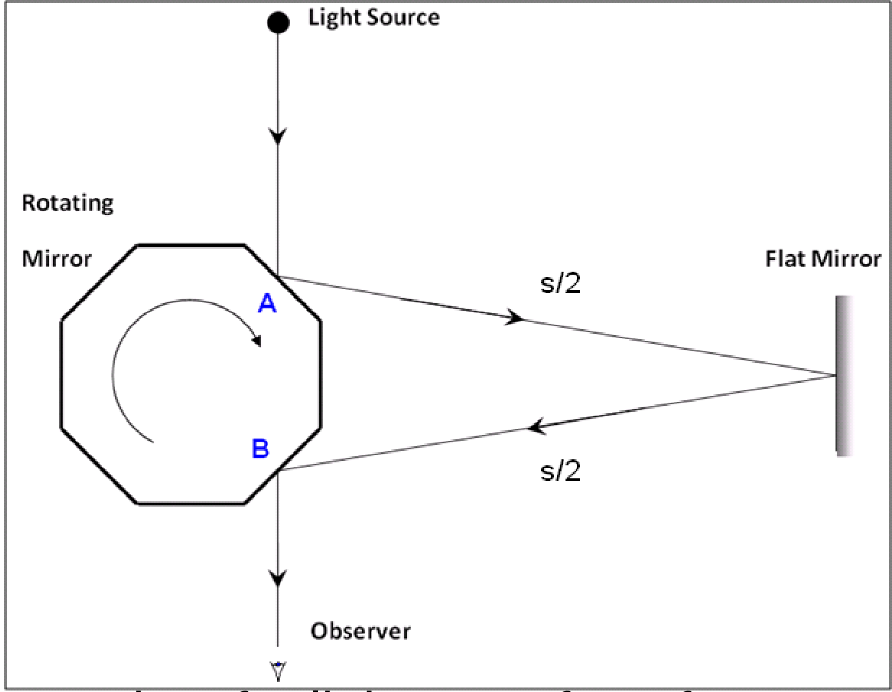
A precise measurement yields:

$$c = 2.99792458\times10^{8}\ \mathrm{m/s}$$

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 kilometers) 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

EXAMPLE

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

$$N = \frac{c}{8s} = \frac{(3\times 10^{8}\ \text{m/s})}{(8)(1000\ \text{m})} = 3.75\times 10^{4}\ \text{revolution /s}$$

or

$$N = \left(3.75\times 10^{4}\ \frac{\text{rev}}{\text{s}}\right)\left(\frac{60\ \text{s}}{1\ \text{min}}\right) = 2.25\times 10^{6}\ \text{rev/min} = 2.25\times 10^{6}\ \text{rpm}$$

Angular speed is

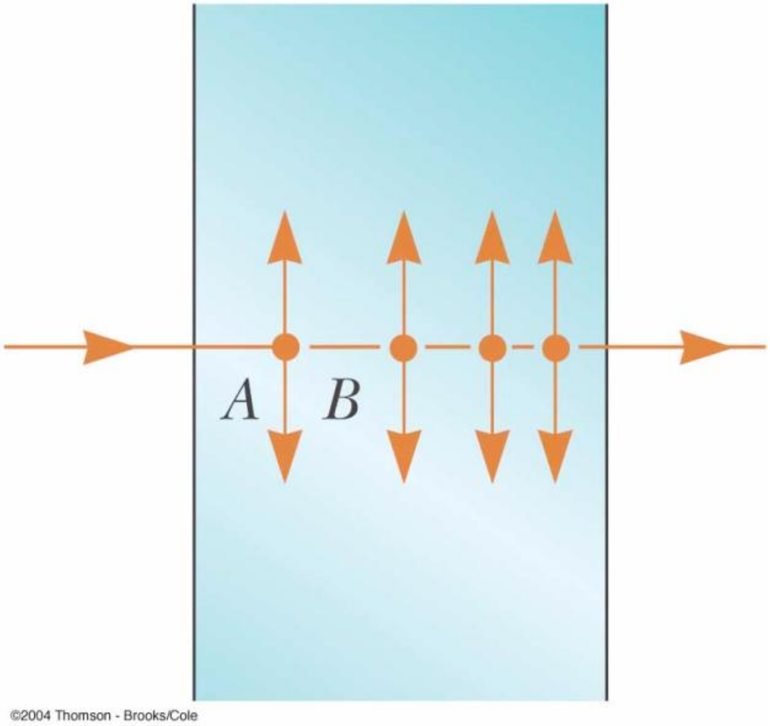
$$\omega = \left(3.75\times 10^{4}\ \frac{\text{rev}}{\text{s}}\right)\left(\frac{2\pi\ \text{rad}}{1\ \text{rev}}\right) = 2.36\times 10^{5}\ \text{rad/s}$$

PART II

THE INDEX OF REFRACTION

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



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

Index of Refraction

- 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: $n = 1.000293 \approx 1$
  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**

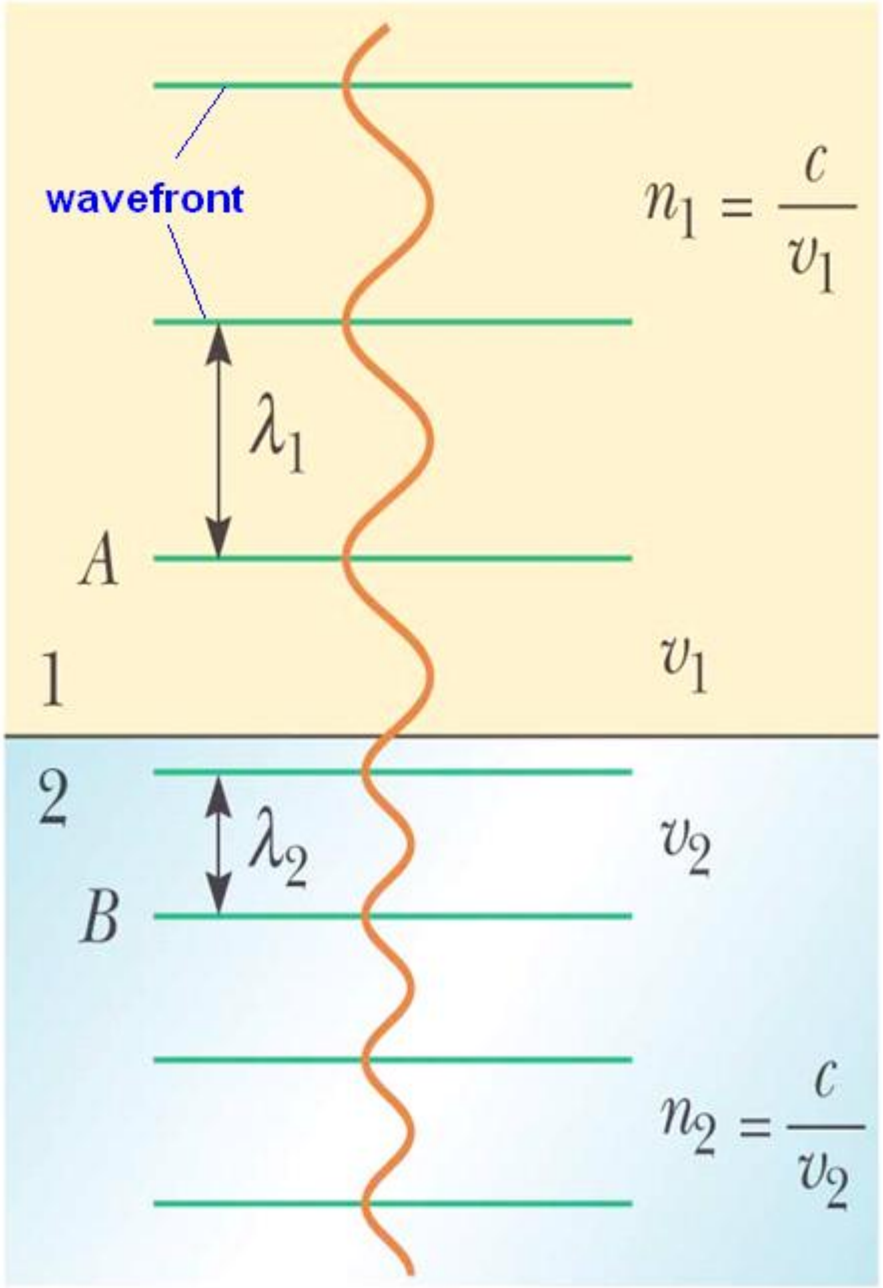
- As light travels from one medium to another, its frequency <u>does not</u> change

- Both the wave speed and the wavelength <u>do</u> 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

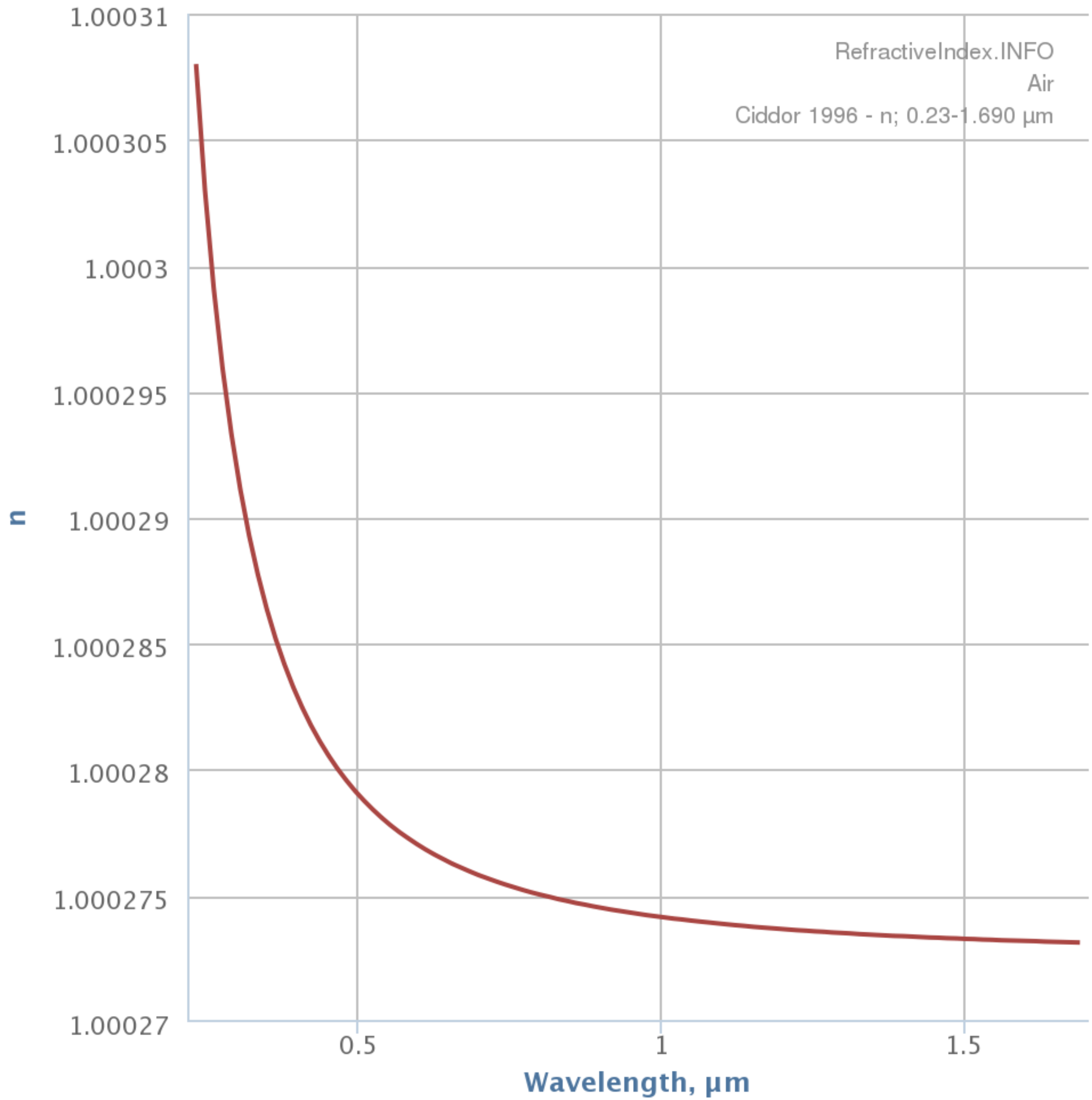
$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$



Dispersion

n depends on wavelength.

n = f(λ)



http://refractiveindex.info

Dispersion

- Actual index of refraction for air at 15 oC is:

$$(n-1)\times 10^{8} = 8342.1 + \frac{2,406,030}{130-q^{2}} + \frac{15,996}{38.9-q^{2}}$$

where q = 1/λ (λ is the wavelength in microns).

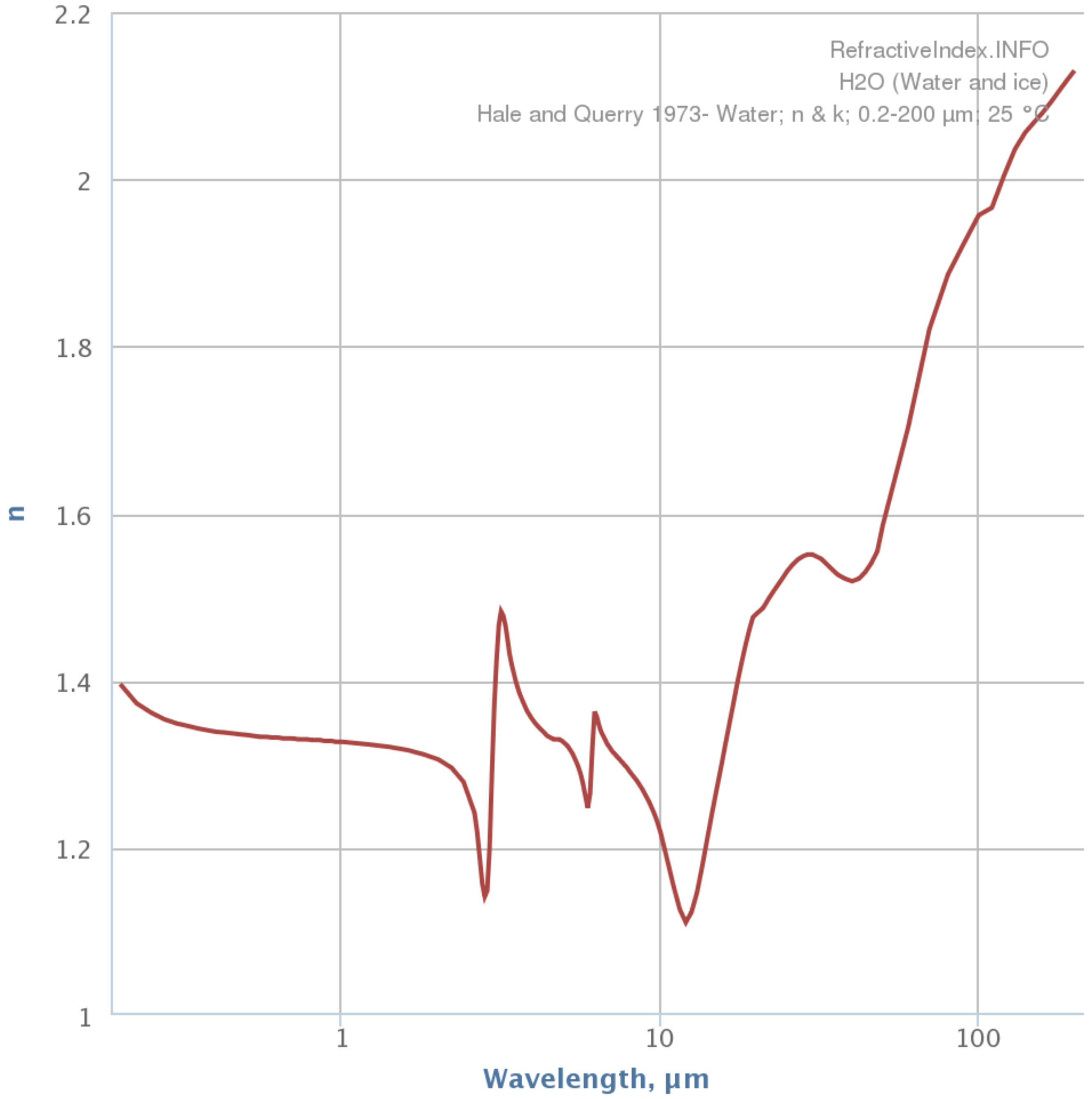
- At other temperatures (t in oC): $$n_t - 1 = \frac{1.0549\,(n_{15}-1)}{1+0.00366\,t}$$

- The change in index with air pressure is:
  0.0003 per 15 lb/in^2 or 0.00002/psi

Note:
1 lb = 4.448222 N
1 in = 2.54 cm
1 Pa = 1 N/m^2
1 psi = 6.8948 x 10^3 Pa
1 bar = 10^5 Pa
1 atm = 1.01325 x 10^5 Pa

n depends on wavelength.

n = f(λ)



http://refractiveindex.info

n depends on wavelength.

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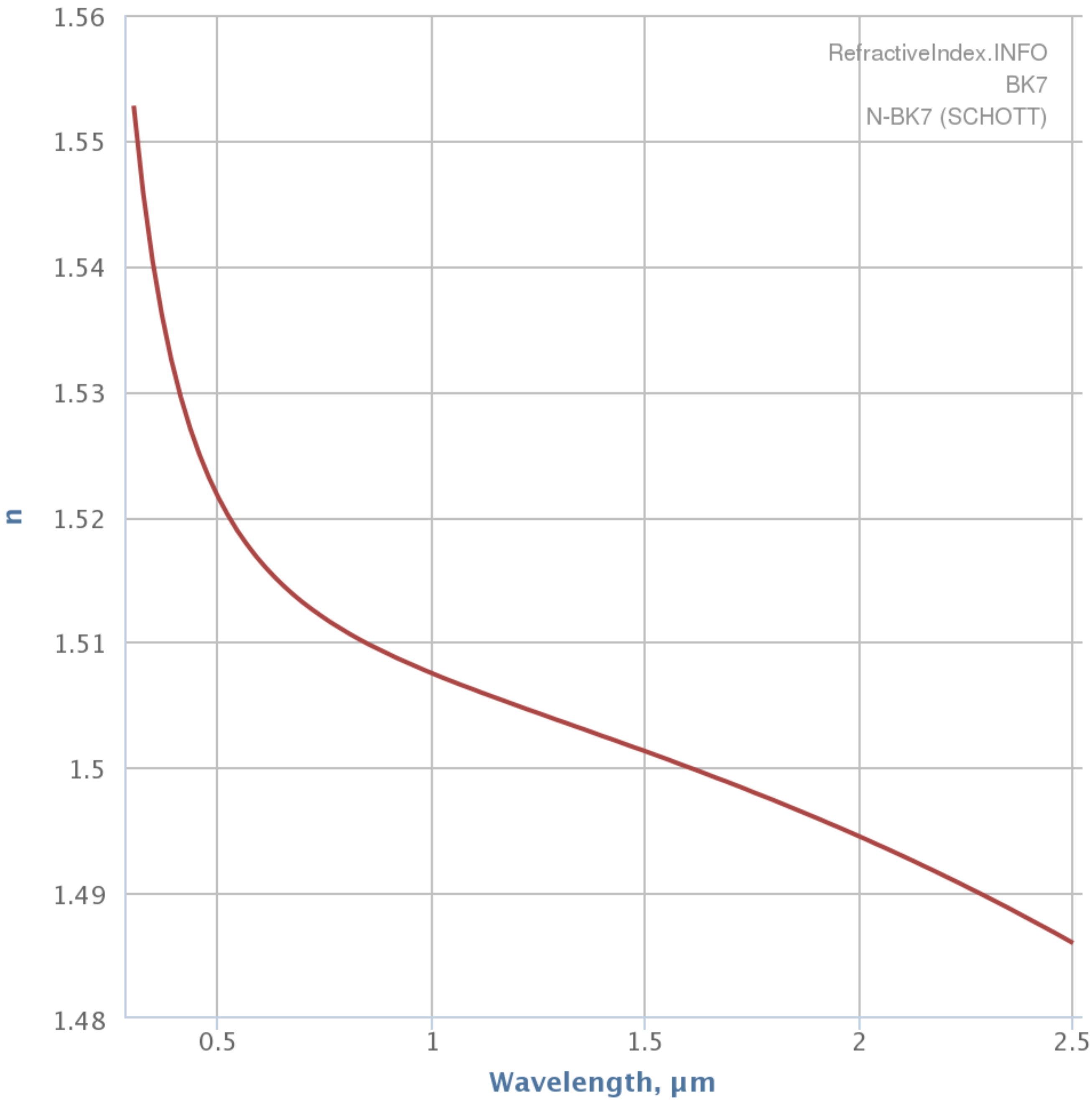

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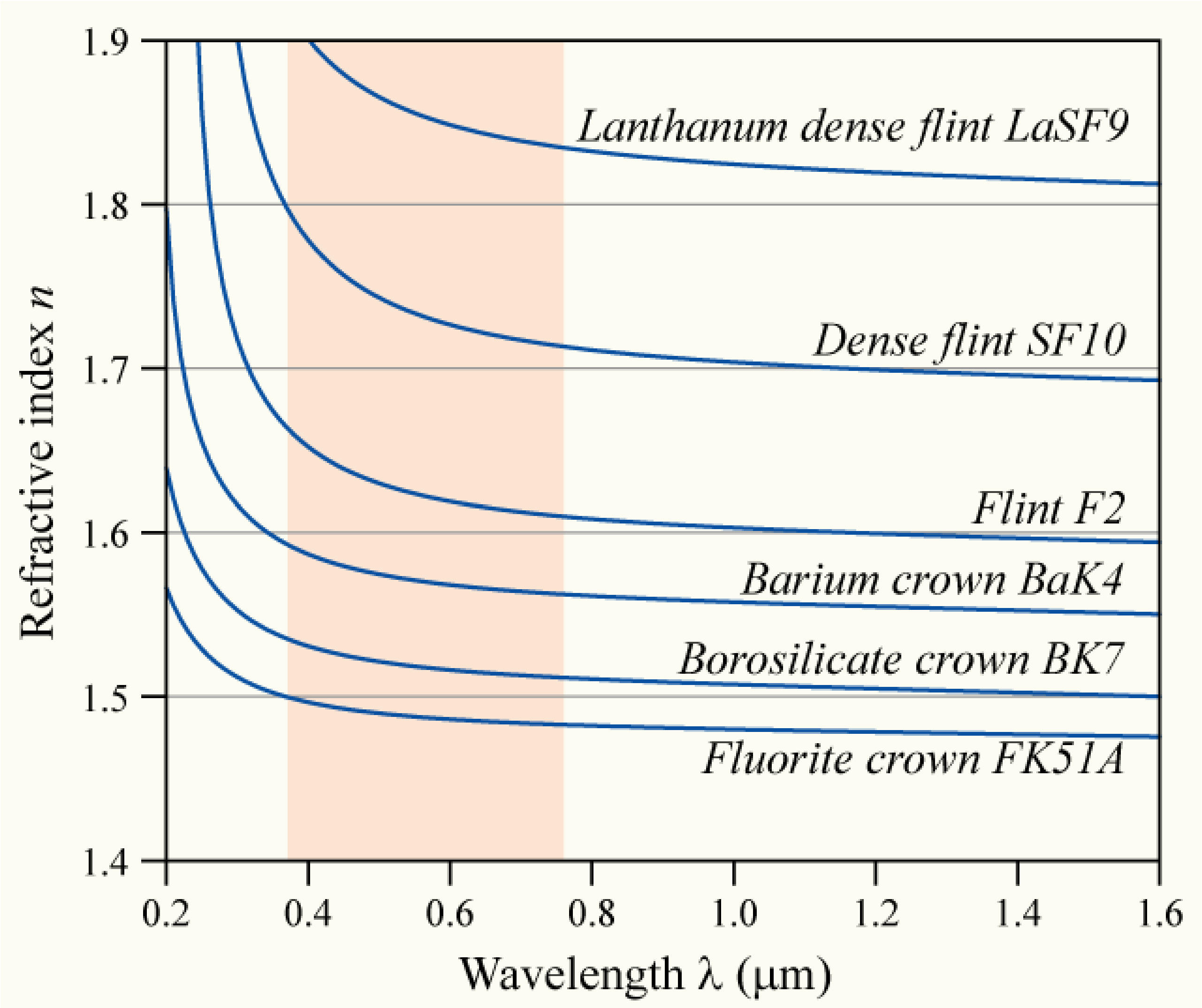
n depends on wavelength.

n = f(λ)



Abbe Number

One way of characterizing dispersion is the Abbe number (V):

$$V = \frac{n_D - 1}{n_F - n_C}$$

where

n_F = refractive index at 486.1 nm (blue)
n_D = refractive index at 589.3 nm (green)
n_C = refractive index at 656.3 nm (red)

Typical values range from about 20 to 70.
Larger V indicates a smaller change in index.

PART III

RAY and WAVE APPROXIMATIONS of LIGHT

Ray Approximation

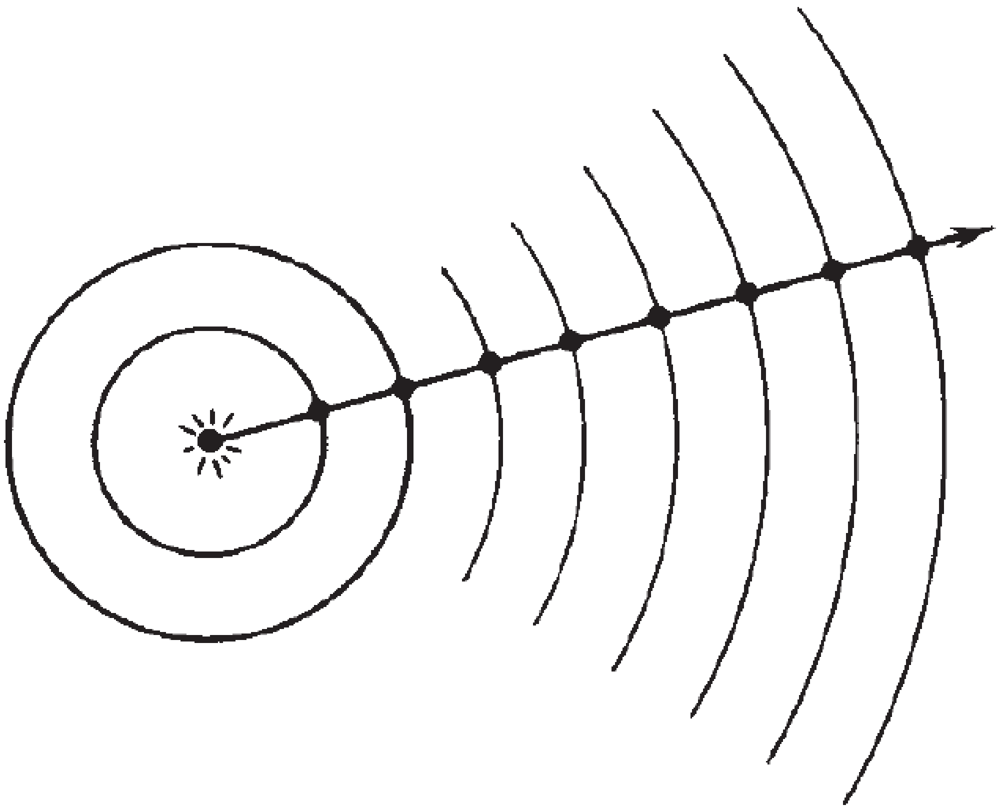
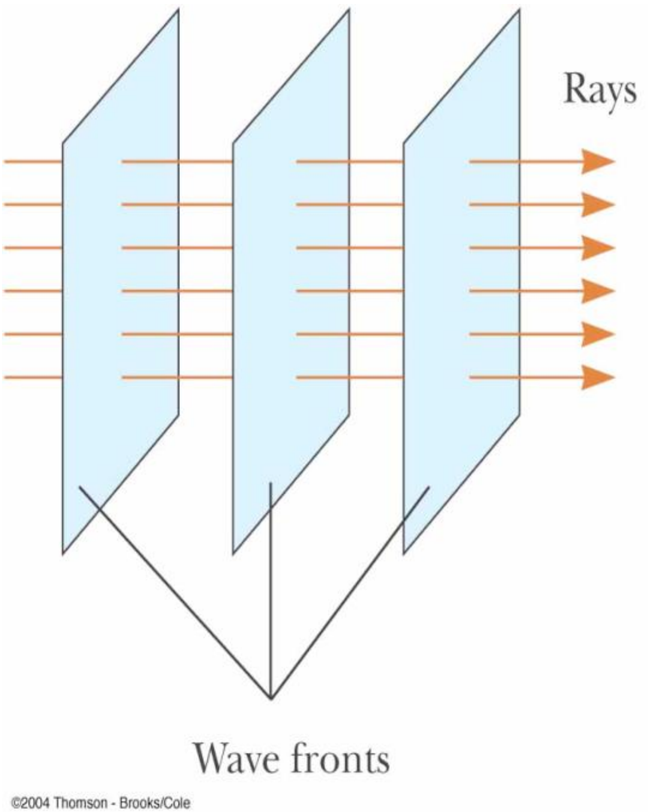
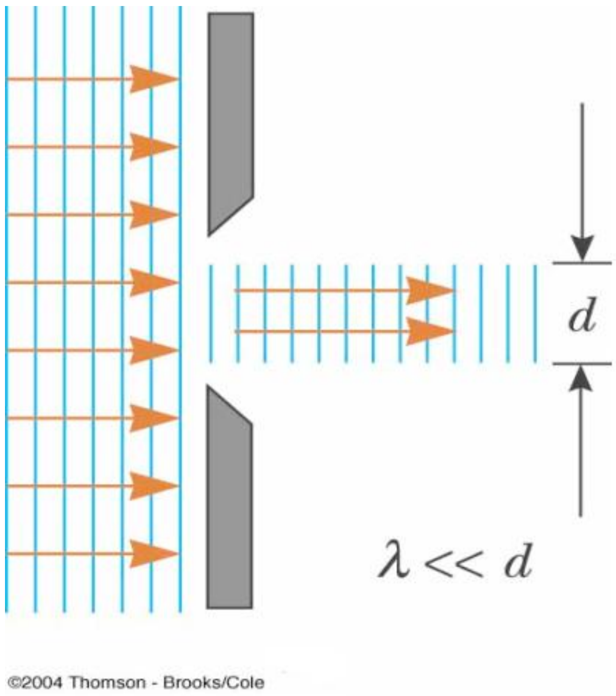


Figure 1.3 Light waves radiating from a point source in an isotropic medium take a spherical form; the radius of curvature of the wave front is equal to the distance from the point source. The path of a point on the wave front is called a light ray, and in an isotropic medium is a straight line. Note also that the ray is normal to the wave front.

Ray Approximation



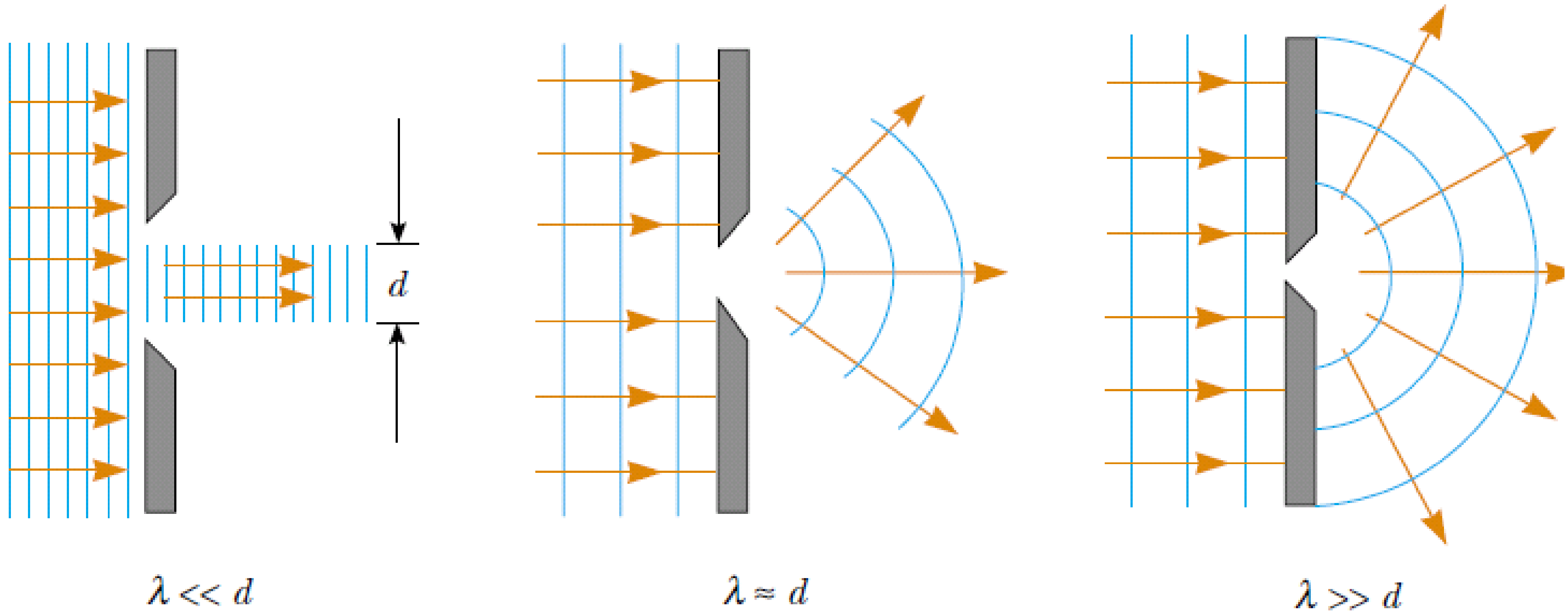


The rays are straight lines perpendicular to the wave fronts

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.

Wave Approximation



if $\lambda \sim d$ or $\lambda >> d$ then we cannot use the ray approximation since the light can make interference or diffraction.

http://phet.colorado.edu/en/simulation/quantum-wave-interference

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 of water (200 ml) if its initial temperature is 20 oC? (*You may answer this question at the end of semester!*)
4. Explain why the 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 light-bulb is radiated as photons. Calculate 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.
7. What is the Abbe number of the water?
8. What is the Abbe number of the air?
9. Calculate the index of refraction of the air at 30 oC for λ = 500 nm.
10. Calculate the index of refraction of the air at 30 oC for λ = 500 nm.

11. 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

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

13. 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

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

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

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

17. 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

References

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