Ministry of Higher Education and Scientific Research

College of health and medical techniques kufa

Dept.Asthetic and laser technique

Learning package in field of

Laser physics

Presented to the 1st class students

Designed by

Dr-Thulfiqar Nadhim

2024-2025

1.1 Electromagnetic Radiation

The electromagnetic radiation out of the laser can be in any part of the spectrum, including the visible spectrum, the Ultra-Violet (UV) spectrum, the Infra-Red (IR) spectrum, and beyond In the following pages the properties of Electromagnetic radiation is briefly described:

1.1.1 Electromagnetic Radiation in vacuum.

1.1.2 Electromagnetic Radiation in Matter.

1.1.1 Electromagnetic Radiation in vacuum

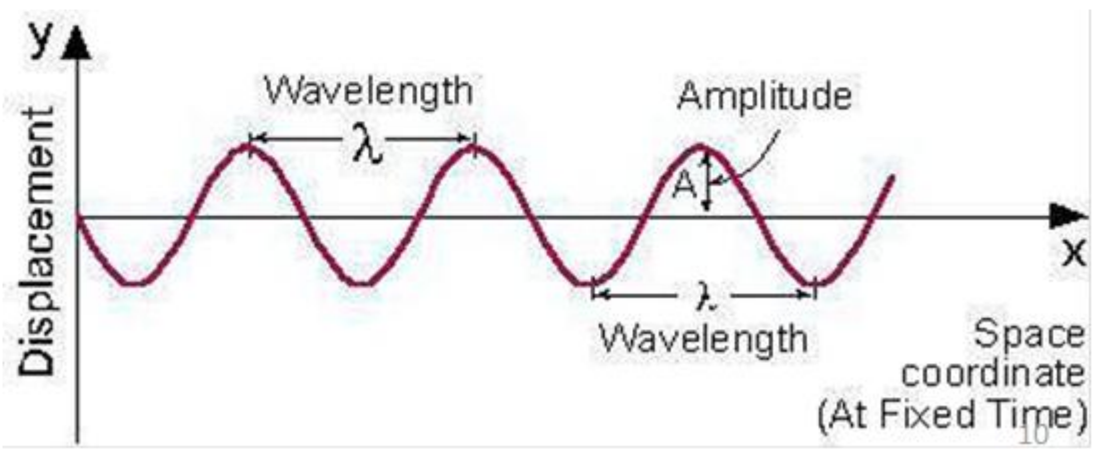
- Electromagnetic Radiation is a transverse wave, advancing in vacuum at a constant speed which is called: velocity of light.

All electromagnetic waves have the same velocity in vacuum, and its value is approximately:

- C = 3*108 [m/sec]

One of the most important parameters of a wave is its

wavelength.



- Wavelength (λ) is the distance between two adjacent points on the wave, which have the same phase. As an example (see figure 1.1) the distance between two adjacent peaks of the wave.

- In a parallel way it is possible to define a wave by its frequency.

- Frequency (v) is defined by the number of times that the wave oscillates per second (The number of periods of oscillations per second).

- Between these two parameters the relation is:

$C = \lambda * v$

From the physics point of view, all electromagnetic waves are equal (have the same properties) except for their wavelength (or frequency).

As an example: the speed of light is the same for visible

light, radio waves, or x-rays.

Wave Description

A wave can be described in two standard forms:

1.Displacement as a function of space when time is held constant.

2.Displacement as a function of time at a specific place in space.

1- **Displacement as a function of space,** when time is "frozen" (held constant), as described in figure 1.1. In this description, the minimum distance between two adjacent points with the same phase is wavelength (λ). Note that the horizontal (x) axis is space coordinate

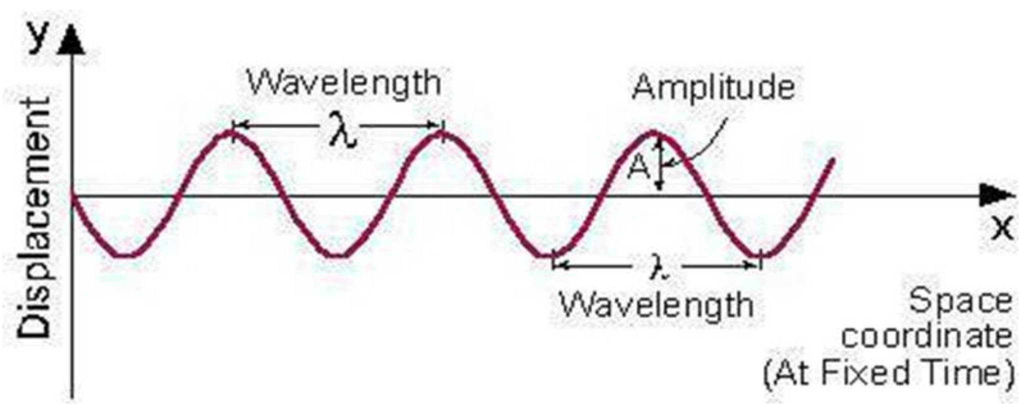


Fig 1.1: Displacement as a function of space coordinate (at fixed time)

A = **Amplitude** = Maximum displacement from equilibrium.

2-Displacement as a function of time

in a specific place in space, as described in figure

1.2. In this description, **the minimum distance between two adjacent points with the same phase is period (T). Note that the horizontal (x) axis is time coordinate !**

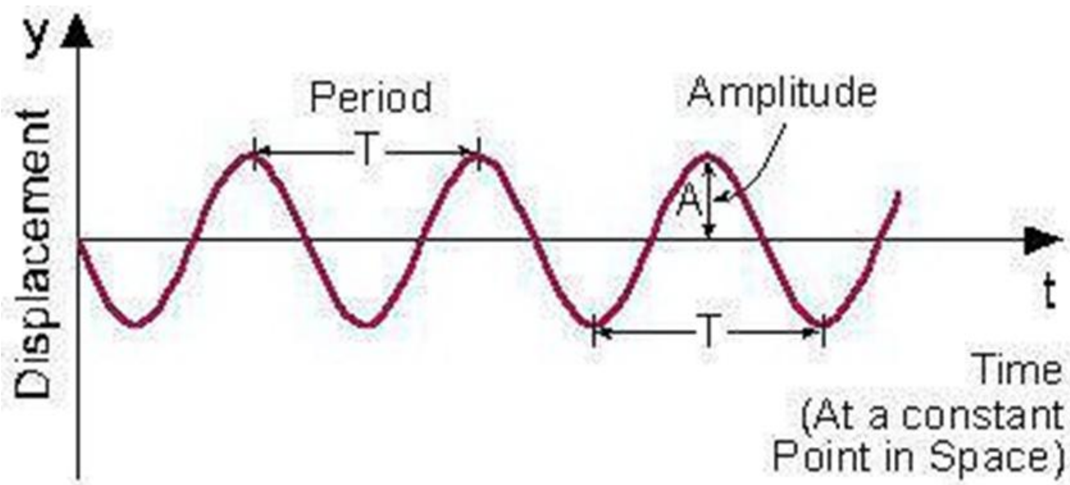


Figure 1.2: Displacement as a function of time (at a fixed point in space)

Wavelengths Comparison:

Figure 1.3 describes how two different waves (with different wavelengths) look at a specific moment in time. Each of these waves can be uniquely described by its wavelength.

For electromagnetic waves, this wavelength is related to the type of radiation of the wave.

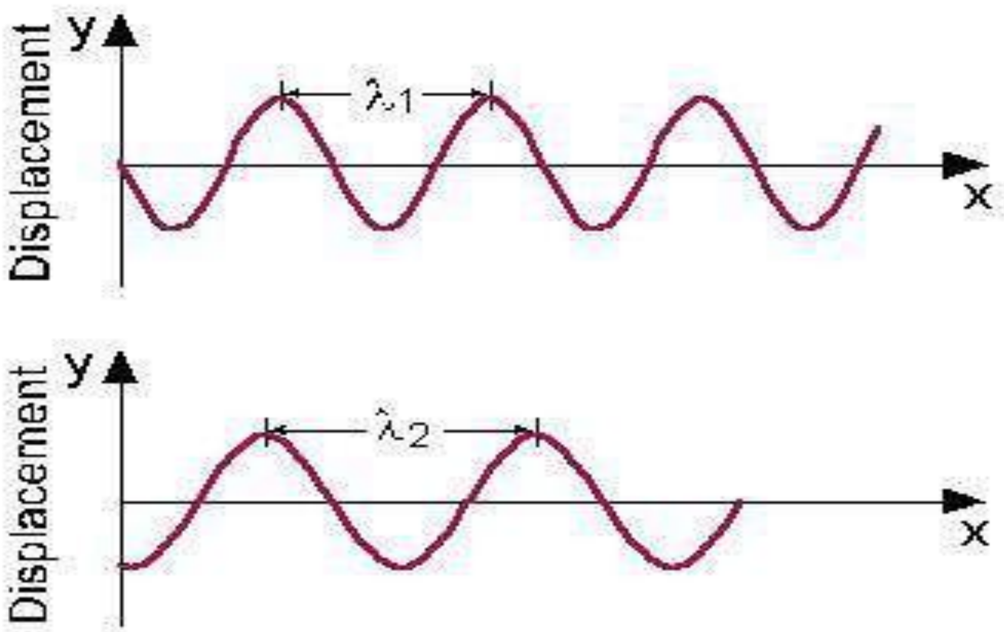
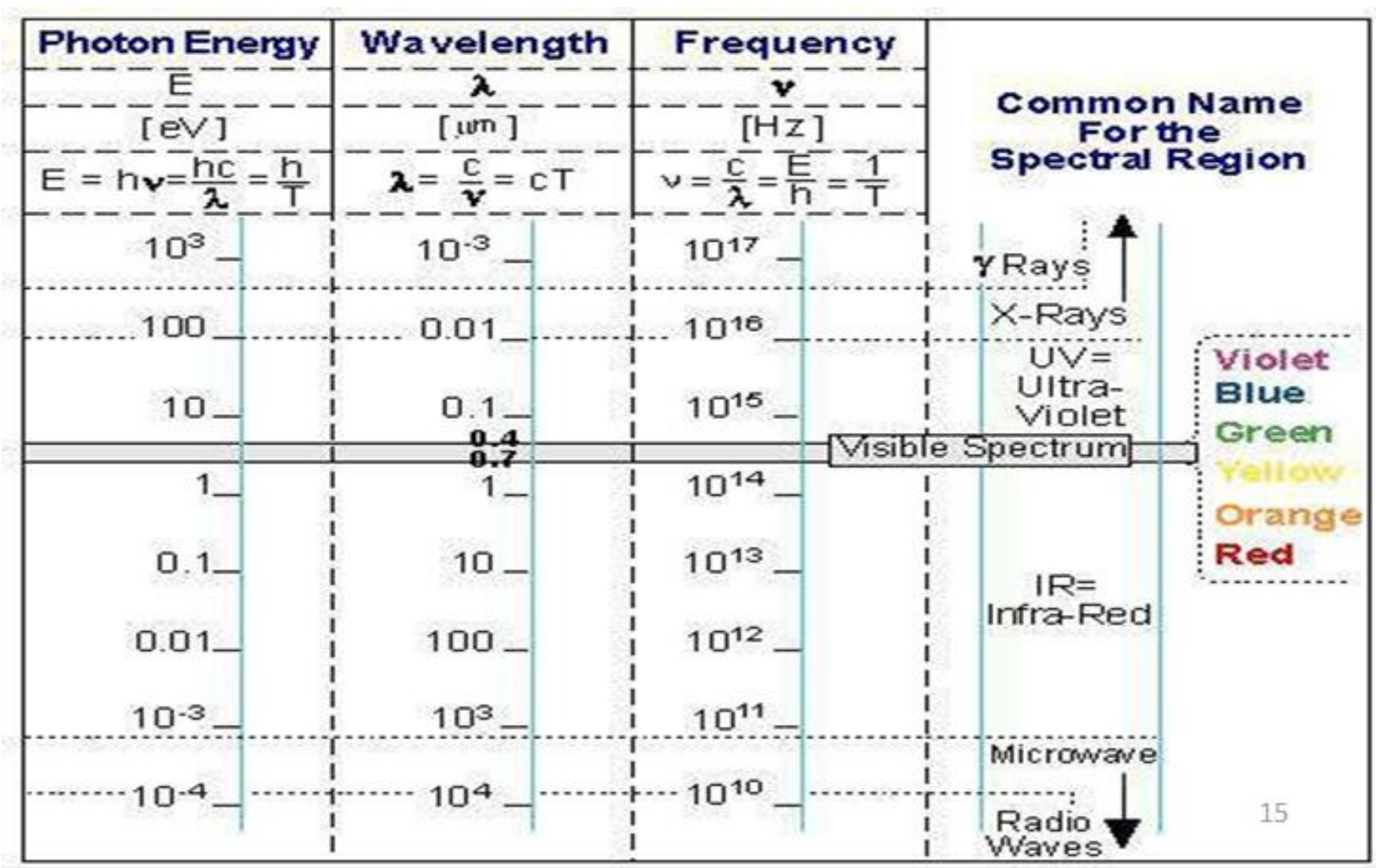


Figure 1.3: Short wavelength (λ_1) compared to longer wavelength (λ_2)

The electromagnetic spectrum

Figure 1.4 describes the **electromagnetic spectrum**

Each part of the spectrum has a **common name**, and its range of wavelengths, frequencies and energies. The borders between the ranges are not sharp and clear, but are defined according to the applications of radiation in that portion of the spectrum.



The most important ideas summarized in figure 1.4 are:

1. Electromagnetic waves span over many orders of magnitude in wavelength (or frequency).
2. **The frequency of the electromagnetic radiation is inversely proportional to the wavelength**.
3. The visible spectrum is a very small part of the electromagnetic spectrum.
4. **Photon energy** increases as the wavelength decreases. The shorter the wavelength, the more energetic are its photons.

Examples for electromagnetic waves are:

1. Radio-waves which have wavelength of the order of meters, so they need big antennas (The dimensions of an antenna are of the same order of magnitude as the wave).
2. Microwaves which have wavelength of the order of centimetres. As an example: in a microwave oven, these wavelengths can not be transmitted through the protecting metal grid in the door, while the visible spectrum which have much shorter wavelength allow us to

see what is cooking inside the microwave oven through the protecting grid.

3. x-Rays which are used in medicine for taking pictures of the bone structure inside the body.

4. Gamma Rays which are so energetic, that they cause ionization, and

are classified as ionizing radiation.

The discrete aspects of electromagnetic radiation is the result of Einstein's work at the beginning of the 20th century.

1.1.2 Electromagnetic Radiation in Matter:

- (We shall use the words "electromagnetic radiation" and "light" as synonyms)
- **Light Velocity in Matter**

When electromagnetic radiation passes through matter with index of refraction n, its velocity (v) is less than the velocity of light in vacuum (c), and given by the equation:

$v = c / n$

This equation is used as a definition of the index of refraction (n):

- n = (speed of light in vacuum)/(speed of light in matter)

= c/v

Gases, including air, are usually considered as having index of refraction equal to vacuum n0=1.

The values of the index of refraction of most materials transparent in the visible spectrum is between 1.4-1.8, while those of materials transparent in the Infra-Red (IR) spectrum are higher, and are 2- 4 .

Wavelength in Matter:

We saw that the velocity of light in matter is slower than in vacuum. This slower velocity is associated with reduced wavelength: $\lambda = \lambda_0/n$, while the **frequency remains the same** (see figure 1.5).

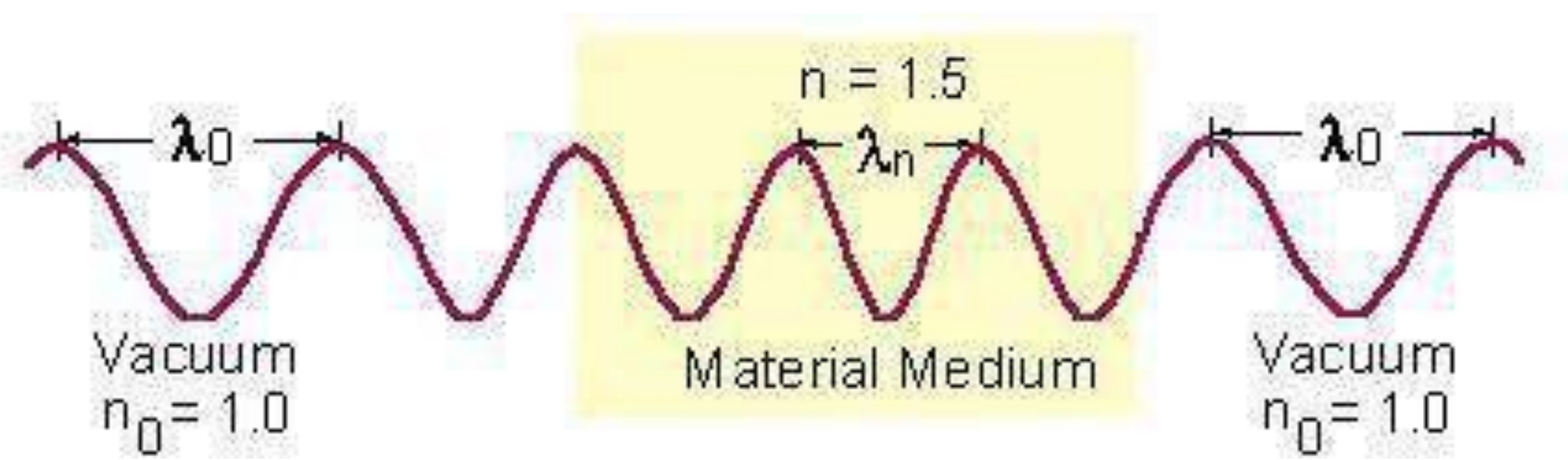


Figure 1.5: Change of wavelength in matter

Refraction of Light Beam - Snell Law:

- Reducing the velocity of light in matter, and reducing its wavelength, causes refraction of the beam of light.

While crossing the border between two different materials, the light changes its direction of propagation according to the Snell Equation:

$$n_1 \cdot \sin(\Theta_1) = n_2 \cdot \sin(\Theta_2)$$

- **Example 1.1:The velocity of Red light (λ_0= 0.6mm) in a certain medium is $1.5*10^8$ [m/s].**

What is the wavelength of this light in this material?

Solution to example 1.1:

First find the index of refraction:

$$n = \frac{c}{v} = \frac{3 \cdot 10^{8} \cdot \frac{m}{s}}{1.5 \cdot 10^{8} \cdot \frac{m}{s}} = 2.0$$

Using n, calculate the wavelength in the material:

$$\lambda_n = \frac{\lambda_0}{n} = \frac{0.6 \cdot \mu m}{2.0} = 0.3 \cdot \mu m$$

Conclusion: The wavelength of Red light in a material with an index of refraction of 2.0, is 0.3 [mm]

1.2 Properties of Laser Radiation:

- "Ordinary light" (from the sun or lamps) is composed of many different wavelengths, radiating in all directions, and there is no phase relation between the different waves out of the source.

- Laser radiation is characterized by certain properties which are not present in other electromagnetic radiation**:**

1.2.1 Monochromaticity.

1.2.2 Directionality.

1.2.3 Coherence.

1.2.1 Monochromaticity

- **Monochromaticity means "One colour".**

To understand this term, examine "**white light**" which is the colour interpreted in the mind when we see all colours together.

When "white light" is transmitted through a prism, it is divided into the different colours which are in it, as seen in figure 1.6.

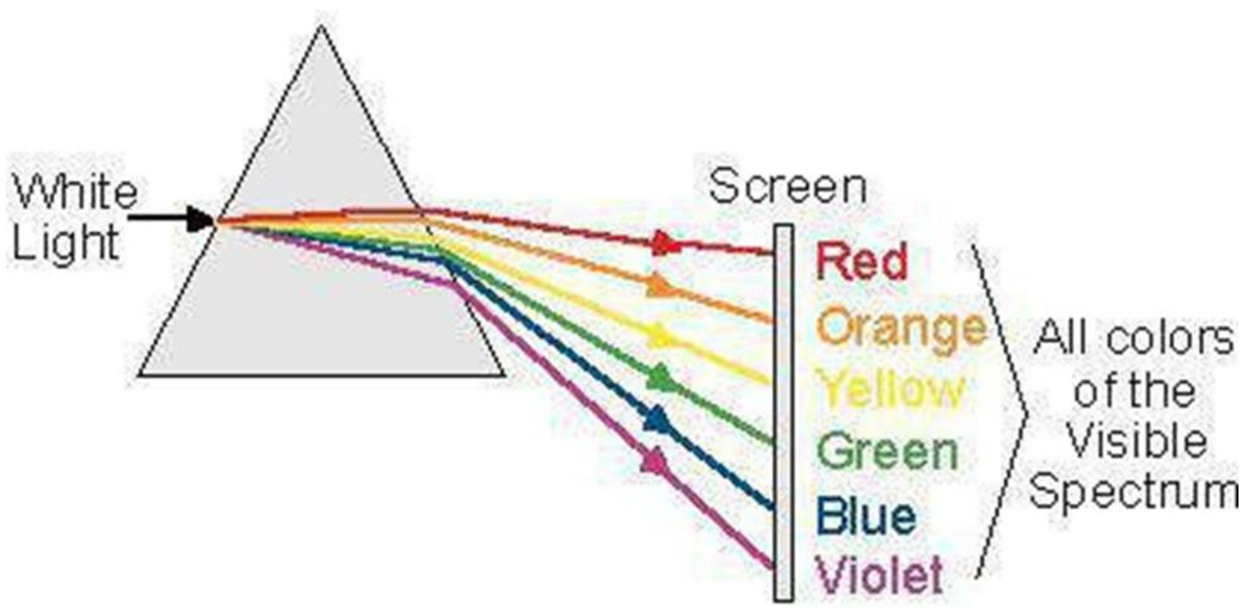


Figure 1.6: White light passing through a prism

–The Meaning of "One Colour"

In the theoretical sense "**One Colour**", which is called "**spectral line**", means **one wavelength** (λ_0).

A graph of light intensity versus wavelength for ideal "one colour" is shown on the right side of figure 1.7. The right side o figure 1.7shows an artistic description of realistic "one colour". It has a peak of its value of "the colour“,but include a spread around the central peak. In reality, every spectral line has a **finite spectral width ($\Delta\lambda$)** around its **central wavelength (λ_0)**, a can be seen in the left side of figure 1.7.

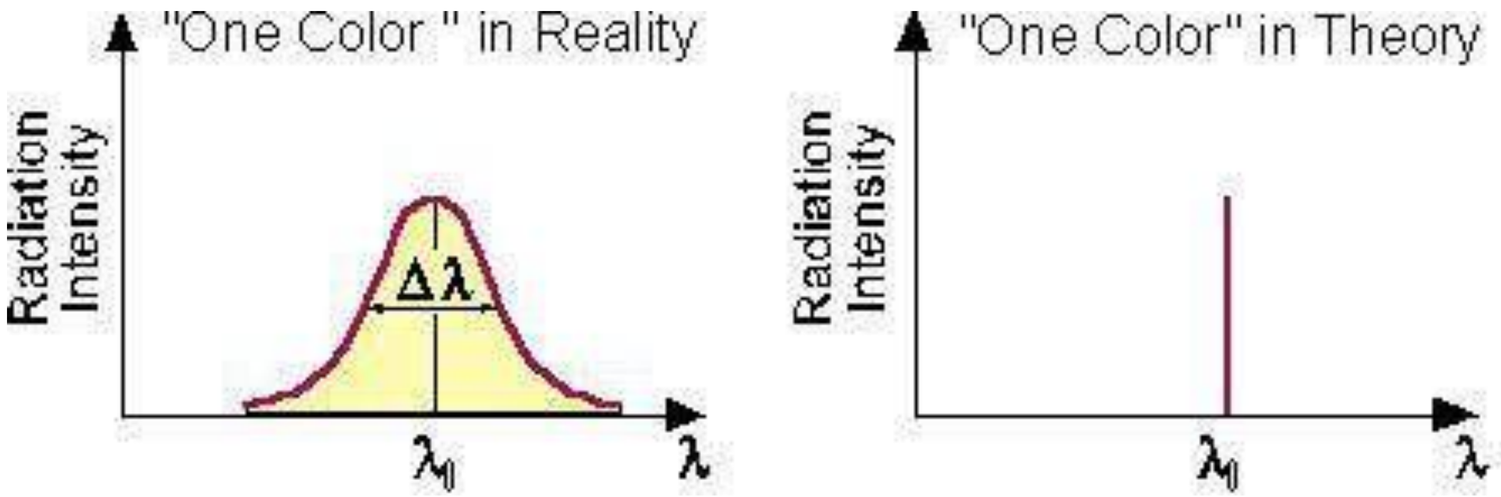


Figure 1.7: Bandwidth of laser radiation in Theory and in Reality

1.2.2. Directionality:

- Radiation comes out of the laser in a certain direction, and spreads at a defined **divergence angle (θ)** (see fig. 1.8, and example 1.2). **This angular spreading of a laser beam is very small compared to other sources of electromagnetic radiation**, and described by a **small divergence angle** (of the order of **milli-radians**).
- In **chapter 7**, laser radiation characteristics are discussed in more detail, and different methods for measuring beam divergence are described.

In figure 1.8, a **comparison** is made between the radiation out of a laser, and the radiation out of a standard lamp.

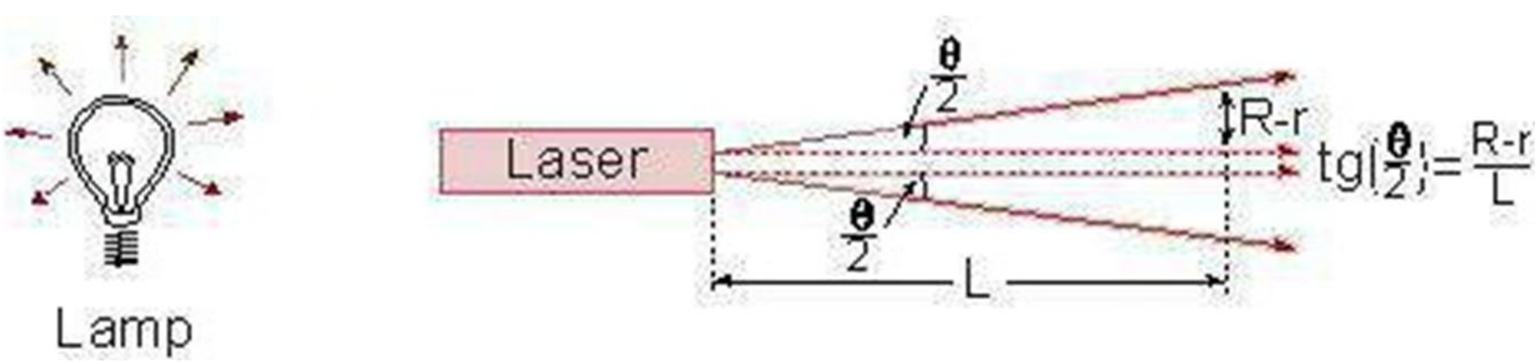


Fig.1.8: comparison between the light out of a laser, and the light out of an incandescent lamp

Divergence Angle:

- **Divergence Angle** is the **full angle** of opening of the beam. (Some books use half of this angle as divergence angle). The relation between radians and degrees is given by:

360^0 = 2π Radians 1 Radian = 57.3^0

1 milli-Radian = 1 m.rad = 0.057^0

Using the relation between minutes and degrees: 1^0=60’, we get:

- **1 m.rad = 0.057*60’= 3.5’** Sec.
- Since laser radiation divergence is of the order of **m.radians**, **the beam is almost parallel, and laser radiation can be send over long distances**.

We shall see in **<u>chapter 8</u>**, how a laser beam was sent to the moon, and returned to Earth to measure the distance between Earth and the moon with accuracy of tens of centimetres.

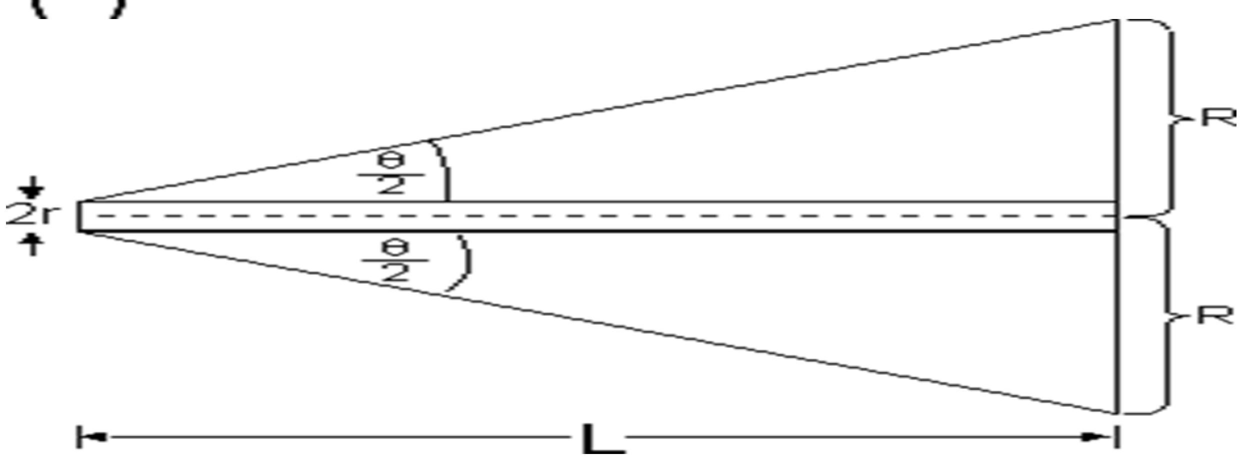
Spot Size Measurement:

R = Radius of the illuminated spot at a distance L from the laser (see

figure below).

If the spot size measurement is done near the laser (where the spot is small), then the size of the beam at the output of the laser needs to be taken into account:

$$\tan\left(\frac{\Theta}{2}\right) = \frac{R-r}{L} \approx \frac{\Theta}{2}$$



Because the laser radiation has a very small divergence, the small angle approximation can be used. Thus, we have set the tangent of the angle equal to the angle.

- Example: A laser with beam divergence of

1 m. radian creates a spot of about 10 [mm] at a distance of 10 [m].

The laser power measured over a defined unit surface area is called Power Density.

Looking at figure 1.8, it is clear that from a laser it is possible to achieve higher power density than from conventional sources (see example 1.2).

- This is the reason why a 5 [m.W] laser radiation is considered dangerous, and the light out of a 100 W incandescent lamp is not !!!

- **Example 1.2: Numerical Calculation of Power Density**
  Calculate the **power density** of radiation per unit area at a distance of 2 meters, from an incandescent lamp rated 100 [W], compared to a Helium- Neon laser of 1 [mW]. The laser beam diameter at the laser output is 2 [mm], and its divergence is 1 [m.rad].

- **Solution:**

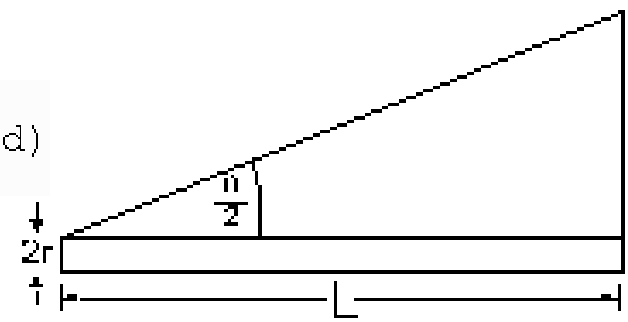
Light from incandescent lamp is radiated to all directions, so it is distributed on a surface of a sphere with a radius of 2 [m]. The surface area is: ⍰ R^2, so the power density at a distance of 2 m is:

$$\frac{100 \cdot W}{pi \cdot 200^2 \cdot cm^2} = 0.2 \cdot \frac{mW}{cm^2}$$

Compared to the incandescent lamp, the laser beam diameter at a distance of 2 [m] increased to 4 [mm] (see drawing below):

$$\tan\left(\frac{\Theta}{2}\right) = \frac{R - r}{L} = \frac{\Theta}{2} \quad \text{(in radians)}$$

$$R = r + L \cdot \tan\left(\frac{\Theta}{2}\right) = 1 \cdot mm + 2000 \cdot tg(0.5 \cdot mrad)$$



R = 2.1 [mm] = 0.2 [cm]

The power density of the laser radiation is:

$$\frac{1 \cdot mW}{pi \cdot 0.2^2 \cdot cm^2} = 8 \cdot \frac{mW}{cm^2}$$

!!! When calculating radiation power in the visible spectrum (used for illumination), the low efficiency of the incandescent lamp must be considered (A 100 [W] lamp emits only 1-3 [W] of visible radiation, and all the rest is in the infrared spectrum).

At a distance of 2 [m] from the radiation source, the power density of the laser radiation is 40 times higher than from the lamp, although the power from the lamp is many times greater than original power of the laser.

1.2.3 Coherence:

- Since **electromagnetic radiation** is a wave phenomena, every electromagnetic wave can be described as a sum (**superposition**) of sine waves as a function of time. From **wave theory** we know that every wave is described by a **wave function**:

$y = A\cos(\omega t+\phi)$

A = **Amplitude**.

$\omega = 2\pi\nu$ = **Angular Frequency**.

ϕ = **Initial Phase** of the wave (Describe the starting

point in time of the oscillation).

$(\omega t+\phi)$ = **Phase** of the wave.

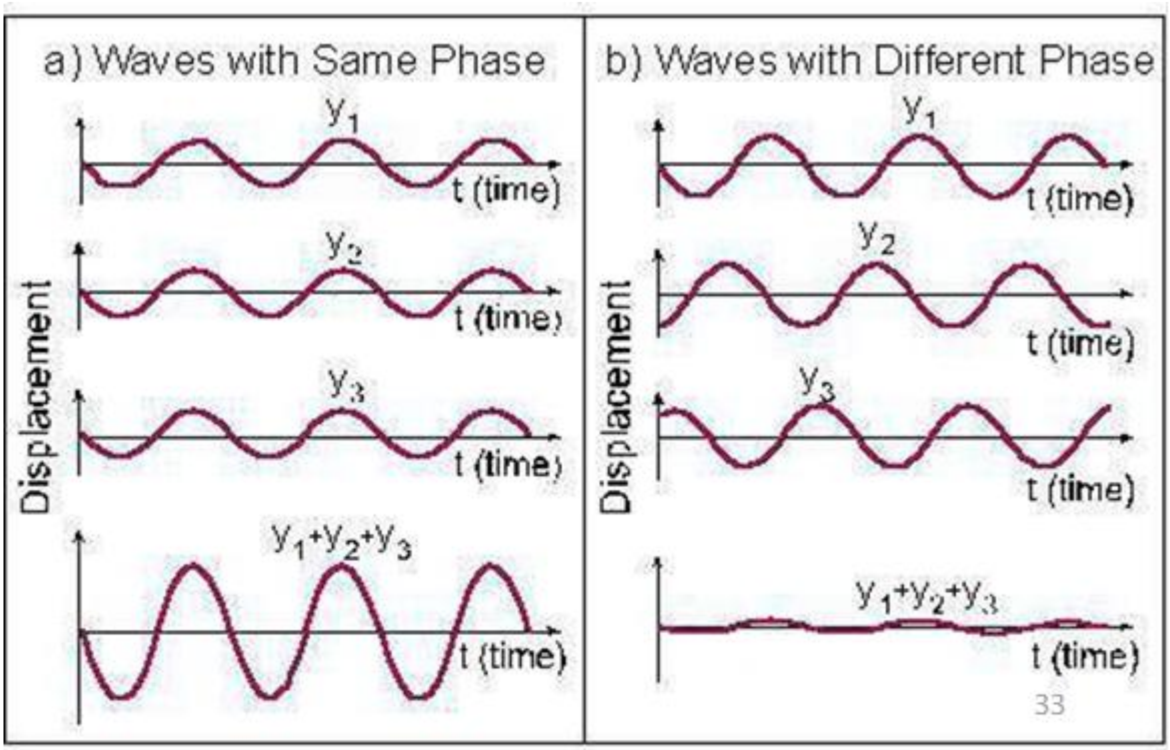
Superposition of Waves:

- Coherent waves are waves that maintain the relative phase between them.

Figure 1.9 describes, using the same time base, 3 waves marked y1, y2, y3, and their superposition. In figure 1.9a, the waves are coherent, like the waves out of a laser. In figure 1.9b, the waves have the same wavelength, but are not coherent with each other.

Light from an incandescent lamp is composed of waves at many wavelengths, and each wave appears randomly with no systematic relation between its phase and that of the other wave.

Laser radiation is composed of waves at the same wavelength, which start at the same time and keep their relative phase as they advance. By adding (superposition) the wave amplitudes of the different waves, higher peaks are measured for laser radiation.



- Example 1.3: Can waves with different wavelength be coherent?
- Solution to example 1.3:

Waves with different wavelengths can have the same phase in one point in space (or even in some points), but they can not keep this phase difference as can be seen in figure 1.10.

As can be seen from this example, **coherence depends on monochromaticity**.

Coherence is important for applications like **interference** and **diffraction**, and the entire process of **holography**.

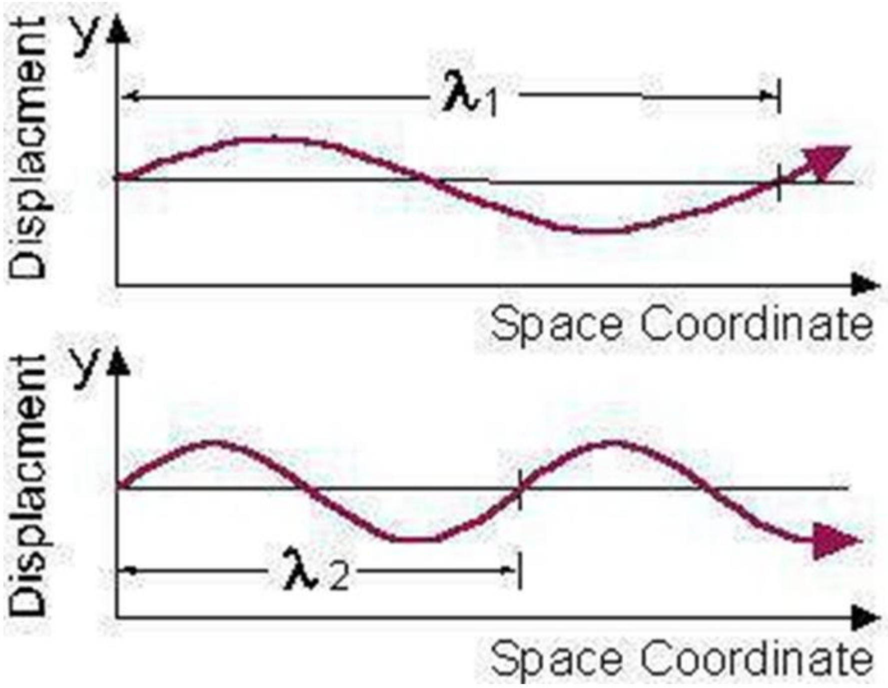


Figure 1-10: Waves with different wavelengths

Bohr model of the atom:

Lasing action is a process that occurs in matter. Since matter is composed of atoms, we need to understand (a little) about the structure of the atom, and its energy states. We shall start with the **semi-classical model**, as suggested in 1913 by **Niels Bohr**, and called: **The Bohr model of the atom**.

According to this model, every atom is composed of a very **massive nucleus** with a **positive**

electric charge (Ze),

around it electrons are moving in specific paths.

Z = Number of protons in the nucleus,

e = Elementary charge of the electrons:

Figure 2.1 illustrates a simple, but adequate,

picture of the atom, the Bohr model:

Every "**allowed orbit**" of the electron around the nucleus, is connected to a specific energy level.

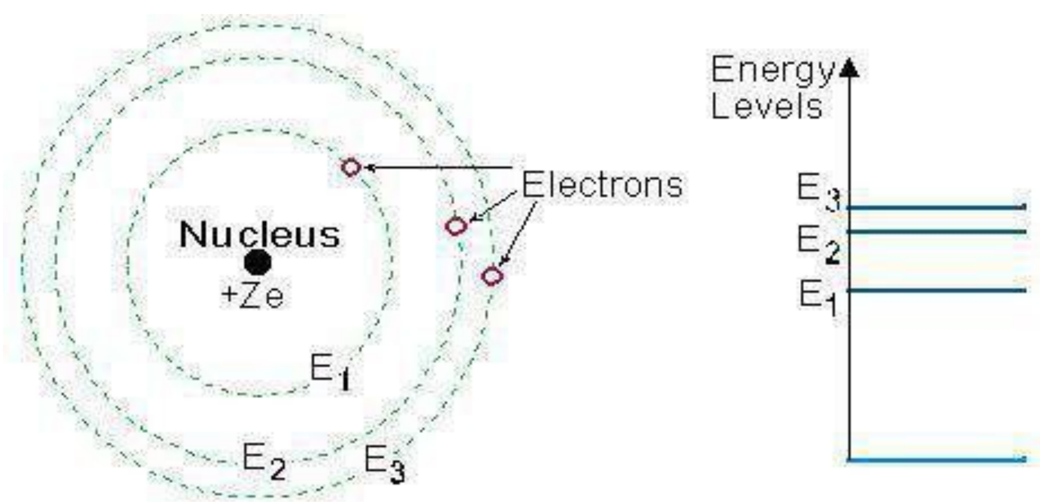


Fig 2-1:Bohr picture of the Atom

The energy level is higher as the distance of the "orbit" from the nucleus increases.

Since for each atom there are only certain "allowed orbits",

only certain discrete energy levels exist, and are named: **E_1, E_2, E_3**, etc..

Energy States (Levels):

Every atom or molecule in nature has a specific structure for its energy levels.

The lowest energy level is called the **ground state**.

As long as no energy is added to the atom, the electron will remain in the ground state

When the atom receives energy (electrical energy, optical energy, or any form of energy), this energy is transferred to the electron, and raises it to a higher energy level (in our model further away from the nucleus). The atom is then considered to be in an **excited state**. The electron can stay only at the specific energy states (levels) which are unique for each specific atom.

The **electron can not be in between these "allowed energy states"**, but it can "jump" from one energy level to another, while receiving or emitting specific amounts of energy.

These specific amounts of energy are equal to the **difference between energy levels within the atom.**

Each amount of energy is called a "**Quantum**" of energy

(The name "**Quantum Theory**" comes from these discrete amounts of energy).

Energy transfer to and from the atom:

Energy transfer to and from the atom can be performed in two different ways:

1. **Collisions with other atoms**, and the transfer of kinetic energy as a result of the collision. This kinetic energy is transferred into internal energy of the atom.

2. **Absorption and emission of electromagnetic radiation**. Since we are now interested in the **lasing process** we shall concentrate on the second mechanism of energy transfer to and from the atom

(The first excitation mechanism is used in certain lasers

, like Helium-Neon, as a way to put energy into the laser,

and will be discussed in chapter 6 about the different kinds of lasers).

2.1 Photons and the energy diagrams:

Electromagnetic radiation has, in addition to its wave nature (described in **Chapter 1.1**),

some aspects of "**particle like behavior**". In certain cases, the electromagnetic radiation behaves as an ensemble of discrete units of energy that have momentum. These discrete units (quanta) of electromagnetic radiation are called "**Photons**". The relation between the **amount of energy (E)** carried by the photon, and its **frequency (ν)**, is determined by the formula (first given by Einstein):

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

This formula shows that **the frequency of the radiation (ν), uniquely determines the energy of each photon in this radiation.**

Or with wavelength: $E = h * c/\lambda$

This formula shows that **the energy of each photon is inversely proportional to its wavelength**.

Summary

- The interactions between electromagnetic radiation and matter cause changes in the energy states of the electrons in matter.
- Electrons can be transferred from one energy level to another, while absorbing or emitting a certain amount of energy. This amount of energy is equal to the : energy difference between

these two energy levels (E_2-E_1).

We shall see later in this chapter that:

- When this energy is absorbed or emitted in a form of electromagnetic radiation, the energy difference between these two energy levels (E_2-E_1) determines uniquely the frequency (ν) of the electromagnetic radiation:

$$\Delta E = E_2 - E_1 = h\nu = \hbar\omega$$

Example 2.1: Visible Spectrum

The visible spectrum wavelength range is:

0.4 - 0.7 [μm] (400-700 [nm]).

The **wavelength of the violet light is the shortest**, and **the wavelength of the red light is the longest**. Calculate:

a) What is the **frequency range of the visible spectrum**.

b) What is the amount of the photon's energy associated with the violet light, compared to the photon energy of the red light.

Solution to example 2.1:

The frequency of violet light:

$$\nu_1 = \frac{c}{\lambda_1} = \frac{3 \cdot 10^{8} \cdot \dfrac{m}{sec}}{0.4 \cdot 10^{-6} \cdot m} = 7.5 \cdot 10^{14} \cdot \frac{1}{sec}$$

$$\nu_2 = \frac{c}{\lambda_2} = \frac{3 \cdot 10^{8} \cdot \dfrac{m}{sec}}{0.7 \cdot 10^{-6} \cdot m} = 4.3 \cdot 10^{14} \cdot \frac{1}{sec}$$

The frequency of red light:

The difference in frequencies:

$$\Delta\nu = \nu_1 - \nu_2 = 7.5 \cdot 10^{14} - 4.3 \cdot 10^{14} = 3.2 \cdot 10^{14} \cdot \frac{1}{sec}$$

The energy of a violet photon:

$$E_1 = h \cdot \nu_1 = (6.626 \cdot 10^{-34} \cdot J \cdot sec) \cdot \left(7.5 \cdot 10^{14} \cdot \frac{1}{sec}\right)$$

$$E_1 = 5 \cdot 10^{-19} \cdot Joule$$

The energy of a red photon:

$$E_2 = h \cdot \nu_2 = (6.626 \cdot 10^{-34} \cdot J \cdot sec) \cdot \left(4.3 \cdot 10^{14} \cdot \frac{1}{sec}\right)$$

$$E_2 = 2.85 \cdot 10^{-19} \cdot Joule$$

The difference in energies between the violet photon and the red photon is :

[19-10*2.15 J

This example shows how much more energy the violet photon have compared to the red photon

2.3 Absorption of electromagnetic Radiation:

We saw that the process of **photon absorption** by the atom is a process of raising the atom (electron) from a lower energy level into a higher energy level (excited state), by an amount of energy which is equivalent to the energy of the absorbed photon.

Our discussion involved a **microscopic system** in which one photon interacts with one atom. In a **macrosc- opic system**, when electromagnetic radiation passes through matter, part of it is transmitted, and part is absorbed by the atoms.

The **intensity (I)** of the transmitted radiation through a thickness (x) of homogeneous material, is described by the experimental equation of exponential absorption (**Lambert Law**):

$$I=I_0\exp(-\alpha x)$$

I_0 = Intensity of incoming radiation.

α = Absorption coefficient of the material.

The thicker the material (bigger x), the lower the transmitted beam.

The **transmission (T)** of this material is described by the relation between the transmitted intensity (I) to the incident intensity (I_0):

$$T=I/I_0$$

From the last two equations we get the Transmission:

$$T = \exp(-\alpha x)$$

the units of the absorption coefficient (α) are: [cm^{-1}]

Every material is transparent differently to different wavelengths, so **the absorption coefficient (α) is a**

function of the wavelength: $\alpha (\lambda)$.

This fact is very important (as we shall see) to understand the interaction of electromagnetic radiation with matter, in the variety of applications of the laser

Example 2.2: Absorption Coefficient (α)

Calculate the absorption coefficient (α) of materials which transmit 50% of the intensity of the incident radiation on a 10

[mm] width, to the other side.

Solution to example 2.2:

Using the exponential absorption law:

α **= 1/x * ln(1/T)** = 1/1 * ln(1/0.5) = 0.69 [cm^{-1}]

Results from the exponential absorption law:

- For every material, **absorption depends on the width of the material**. The thicker the material, less radiation will be transmitted through.
- For a certain width (x) of the material, absorption depends only on the **absorption coefficient (α), which is characteristic of each material**.

2.1 Spontaneous emission of electromagnetic Radiation:

One of the basic physical principles (which is the basis of a subject in physics called Thermodynamics) is that:

Every system in nature "prefers" to be in the lowest energy state. This state is called the **Ground state**. As an example, we mentioned this principle in the **Bohr model of the atom**.

When energy is applied to a system, The atoms in the material are **excited**, and **raised to a higher energy level**.

(The terms "excited atoms", "excited states", and "excited electrons" are used here with no distinction)

These electrons will remain in the excited state for a certain period of time, and then will return to lower energy states while emitting energy in the exact amount of the difference between the energy levels (ΔE).

If this package of energy is transmitted as electromagnetic energy, it is called **photon**. The emission of the individual photon is random, being done individually by each excited atom, with no relation to photons emitted by other atoms.

When photons are randomly emitted from different atoms at different times, the process is called **Spontaneous Emission**. Since this emission is independent of external influence, there is **no preferred direction for different photons, and there is no phase relation between photons emitted by different atoms.**

1. **What is the range of the index of refraction for most materials transparent in the visible spectrum?**
2. **Electromagnetic Wave Function?**
3. **What is the relationship between the speed of light in a medium (v) and the speed of light in a vacuum (c)?**
4. **If the absorption coefficient (α) of a material is 0.69 cm−1cm−1, what percentage of radiation is absorbed when passing through a thickness of 1 cm?**
5. **According to the Bohr model, what happens when an electron jumps from a higher energy level to a lower one?**
6. **What property distinguishes laser radiation from ordinary light?**

Reference

1- Textbook of Physics Laser