Chapter One

The Essentials: Introduction to Laser

Things you need to know!!

Before studying about lasers, you must be familiar with basic terms used to describe electromagnetic waves: Wavelength (λ) Frequency (f) Period (T) Velocity of light (c) Index of refraction (n)

We will briefly review these terms, but it is much better if you are familiar with: Some terms from geometric optics such as: refraction, reflection, thin lenses etc. Some terms from "Modern Physics" such as photons, Models of atoms, etc.

1.1 Electromagnetic Radiation

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:

$$c = 300,000 \text{ [km/sec]} = 3*10^8 \text{ [m/sec]}$$

One of the most important parameters of a wave is its wavelength.

Wavelength

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

Frequency

In a parallel way it is possible to define a wave by its frequency. Frequency is defined by the number of **times** that the wave **oscillates per second**.

Between these two parameters the relation is:

$$c = \lambda * f$$

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

<u>As an example</u>: the speed of light is the same for visible light, radio waves, or x-rays. Light, radio waves, x-rays, γ-rays are all E.M radiation, the only difference between them is their frequency.

1.2 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

Displacement as a function of space, when time is "frozen" (held constant). 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

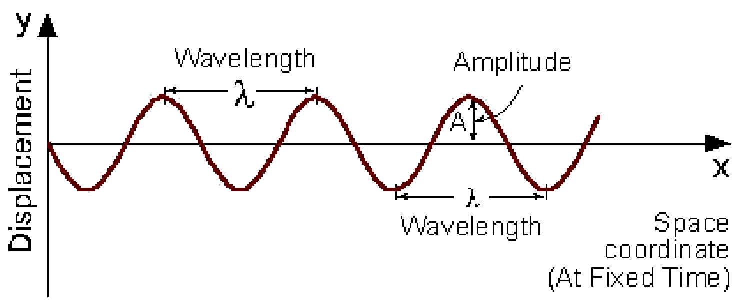


Fig 1.1: Displacement as a function of space coordinates (at fixed time)

A = Amplitude = Maximum displacement from equilibrium.

2. Displacement as a function of time

Displacement as a function of time, in a specific place in space, as described in figure. 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

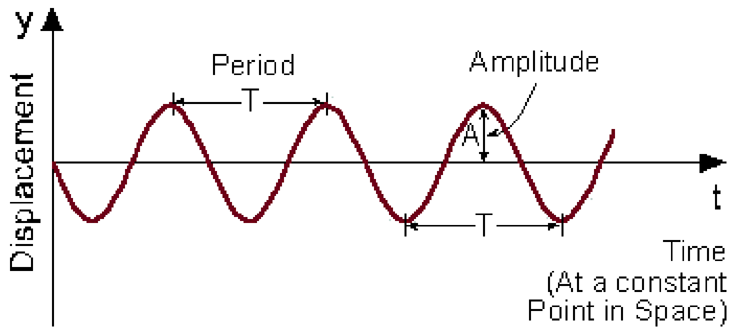


Figure 1.2: Displacement as a function of time (at a fixed point in space)

1.3 Wavelengths Comparison

The Figure 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.

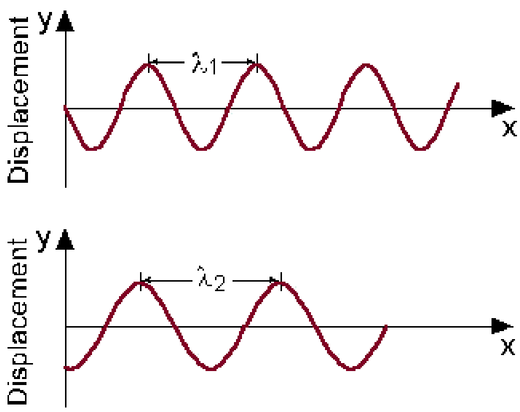


Figure 1.3: Short wavelength (λ_1) compared to longer wavelength (λ_2)

1.4 The electromagnetic spectrum

The energy of a quantum of light depends on its frequency.

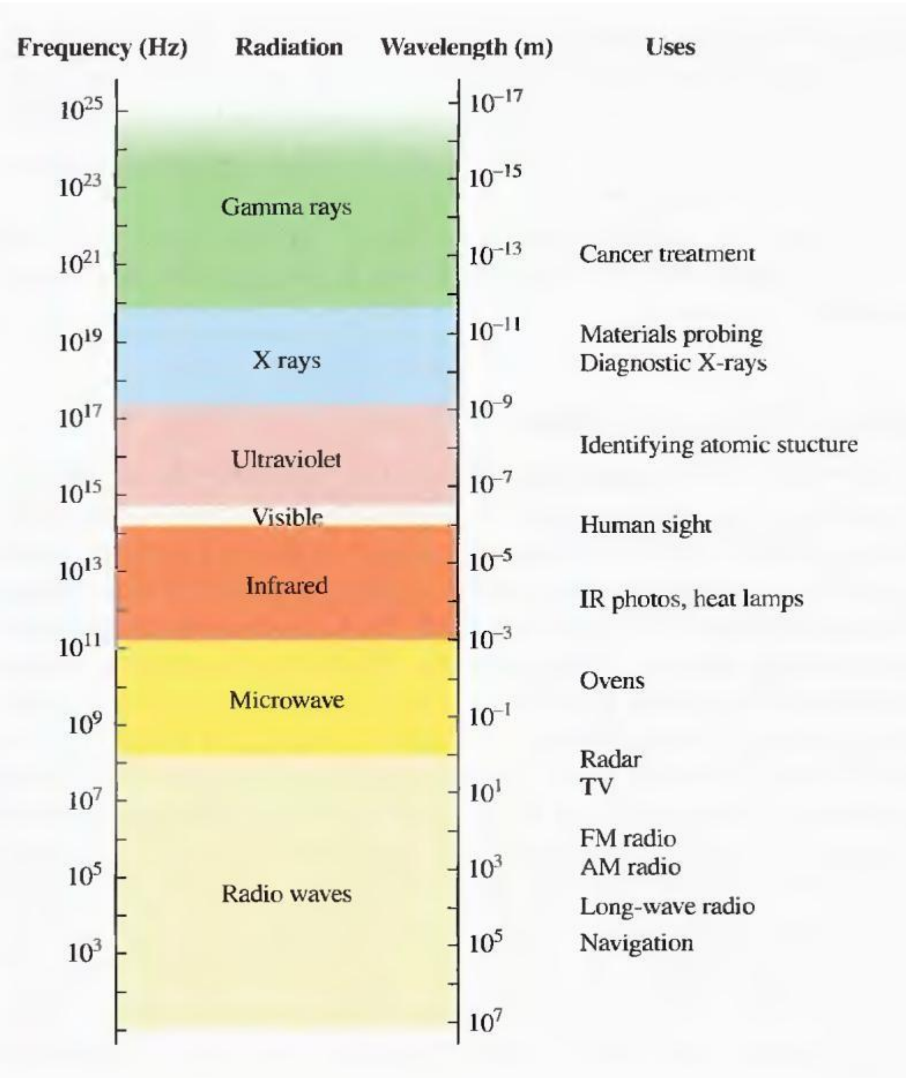
$$\mathbf{E = h*\mathit{f} = h * \upsilon}$$

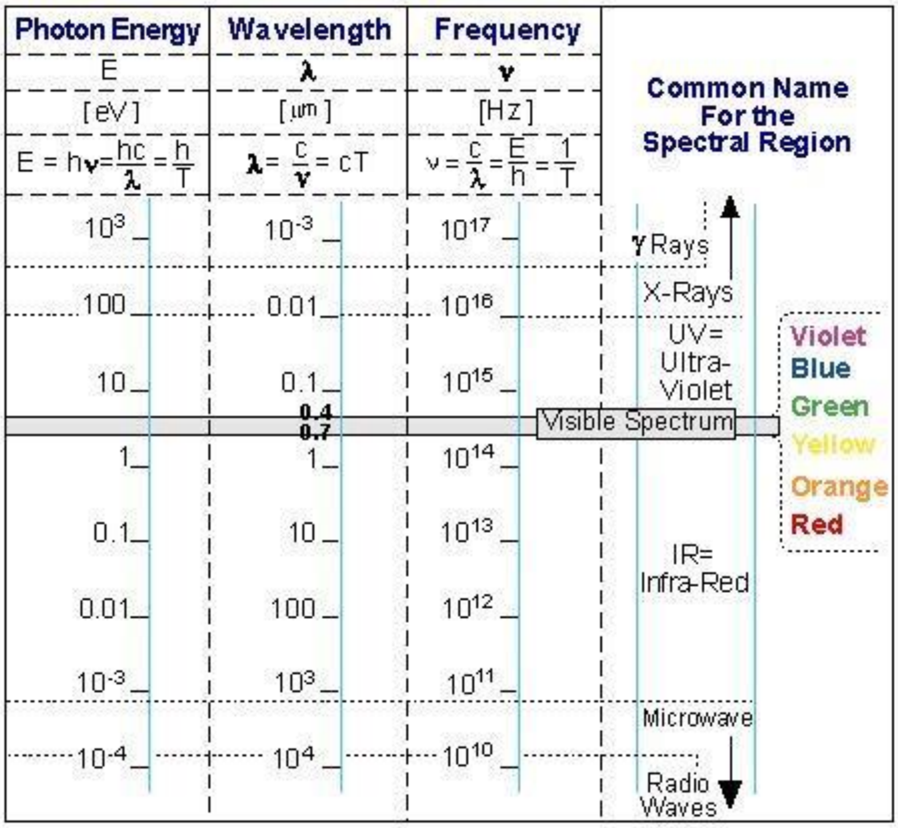
Where:
h= planck's constant = $6.63*10^{-34}$ J.s
f = frequency cycles per sec (cps) or Hz
E in joules & f in Hz = s^{-1}
E (joule) = hc/ λ = $(6.63*10^{-34} *3*10^{8})$ / λ (joules) But: **1 ev = $1.6*10^{-19}$ J**

So:
E in (ev) = $(6.63*10^{-34} * 3*10^{8}) / (\lambda * 1.6 *10^{-19})$ ev $=(1.243*10^{-6})/ \lambda$ ev

Units

Multiplication factor	name	symbol
10^{12}	Tera	T
10^{9}	Giga	G
10^{6}	Mega	M
10^{3}	Kilo	K
10^{-2}	Centi	c
10^{-3}	Milli	m
10^{-6}	Micro	µ
10^{-9}	Nano	n
10^{-12}	Pico	p
10^{-15}	Femto	f
10^{-18}	atto	a





The most important ideas summarized in figure 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:

- Radio-waves which have wavelength of the order of meters, so they need big antennas.
- Microwaves which have wavelength of the order of centimeters. As an example: in a microwave oven, these wavelengths cannot 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.

- x-Rays which are used in medicine for taking pictures of the bone structure inside the body.
- Gamma Rays which are so energetic, that they cause ionization, and are classified as ionizing radiation.

1.5 Electromagnetic Radiation in Matter

1.5.1 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 = (speed of light in vacuum)/(speed of light in matter)

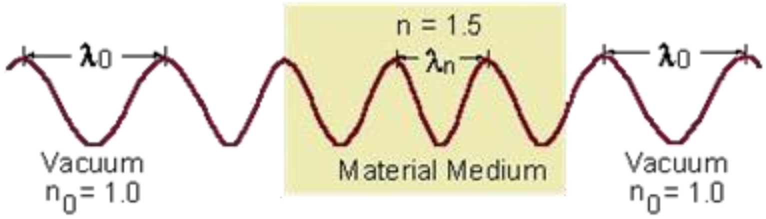
$$n = c/v$$

Gases, including air, are usually considered as having index of refraction equal to vacuum $n_0=1$.

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 2.0 - 4.0.

1.5.2 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



1.5.3 Refraction of Light: 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***

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Ref. index of air is ~ 1.0028 for visible light, the effect on λ due to air may be ignored except for high accuracy work.

Example:

The velocity of Red light (λ_0= 0.6 μm) in a certain medium is $1.5*10^8$ m/s. What is the wavelength of this light in this material?

Solution:

First find the index of refraction:

Using n, calculate the wavelength in the material:

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

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

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

1.6 The Essentials: Atoms

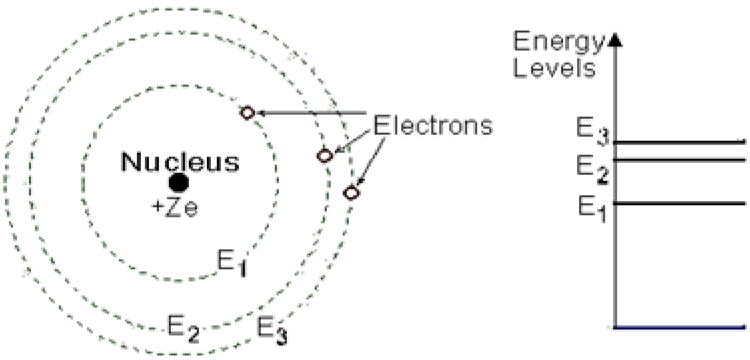
1.6.1 Bohr model of the atom

Lasing action is a process that occurs in **matter**. Since matter is composed of atoms, we need to understand 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: e = $1.6*10^{-19}$ [Coulomb]

The figure 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. **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: E1, E2, E3, etc.

1.6.2 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**, which is the naturally preferred energy 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. 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 cannot 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).

1.6.3 Energy transfer to and from the atom

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

<u>Collisions with other atoms</u>, and the transfer of kinetic energy as a result of the collision. This kinetic energy is transferred into internal energy of the atom.

<u>Absorption and emission of electromagnetic radiation</u>.

Since we are now interested in the lasing process, we shall concentrate on the second mechanism of energy transfer to and from the atom.

1.6.4 Photons and the energy diagrams

Electromagnetic radiation has, in addition to its wave nature, 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):

$$\mathbf{E = h\nu}$$

The proportionality constant in this formula is Planck's constant (**h**):

$$\mathbf{h = 6.626*10^{-34}\ [Joule\text{-}sec]}$$

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

$$\mathbf{E = h\ \nu}$$

This formula can be expressed in different form, by using the relation between the frequency (ν) and the wavelength: $\mathbf{c = \lambda*\nu}$ to get:

$$\mathbf{E = h * c/ \lambda}$$

This formula shows that the energy of each photon is inversely proportional to its wavelength. This means that each photon of shorter wavelength (such as violet light) carries more energy than a photon of longer wavelength (such as red light).

Since ***h*** and ***c*** are universal constants, so either wavelength or frequency is enough to fully describe the photon.

Example: 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:

The frequency of **violet light**:

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

The frequency of **red light**:

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

The difference in frequencies: The energy of a **violet photon**:

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

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

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

The energy of a **red photon**:

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

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

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

$2.15*10^{-19}$ J.

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

H.W 1:

Is it allowed to calculate first the wavelength difference (λ_2-λ_1), and then use the relation between frequency and wavelength (ν_2-ν_1) = c / (λ_2- λ_1)?

H.W 2:

Calculate in units of Nanometer, the wavelength of light emitted by the transition from energy level E_3 to energy level E_2 in a **3** level system in which:

E_1 = 0 eV **E_2 = 1.1 eV** **E_3 = 3.5 eV**