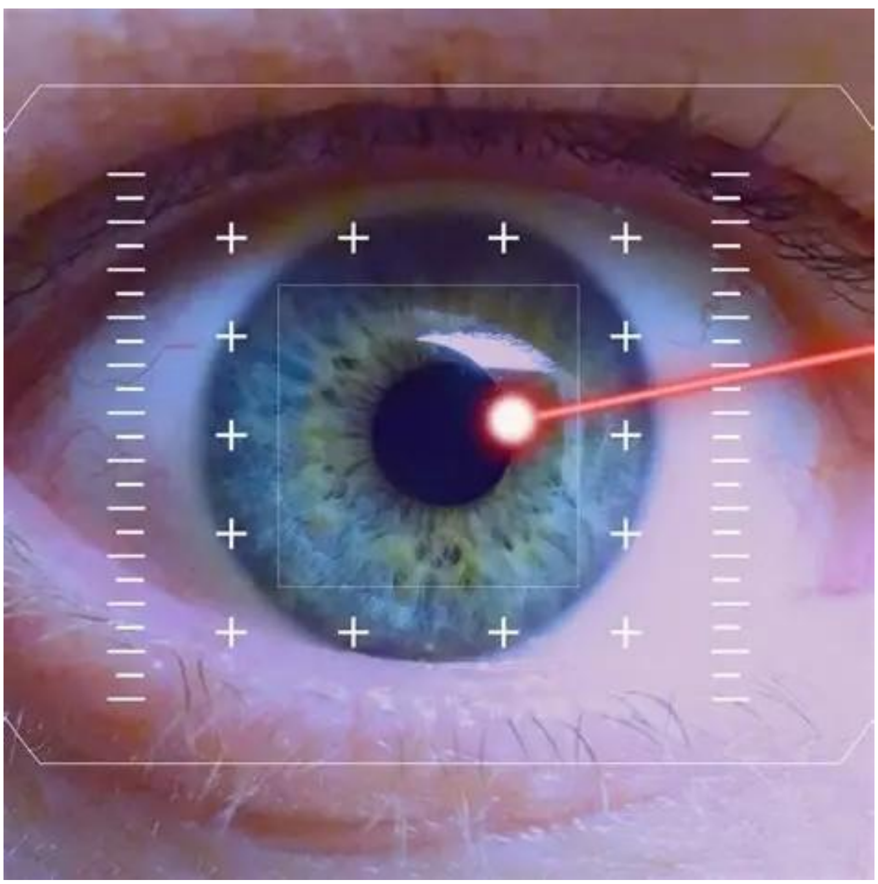
Laser Physics and Medical Applications

Dr: Thulfikar Nadhim



Introduction to Laser Physics – History, definitions, light properties

Lecture 1

DR: THULFIKAR NADHIM

1. Introduction

The most outstanding invention of the 20^{th} century is the laser. The word LASER is an acronym for "Light Amplification by Stimulated Emission of Radiation". A laser is a device that uses energy to transmit light at a specified wavelength and amplifies that light by producing a very narrow beam of radiation. Laser is very much different from the traditional light sources and it is not used for illumination. The difference between ordinary light and laser light is like the difference between ripples in your bathtub and huge waves on the sea. It comes in sizes ranging from approximately one-tenth the diameter of a human hair to the size of a very large building, in powers ranging from 10^{-9} to 10^{20} W, and in wavelengths ranging from the microwave to soft X-ray spectral regions with corresponding frequencies from 10^{11} to 10^{17} Hz [1, 2]. In addition, lasers have very high pulse energies i.e. up to 10^{4} J with very short pulse durations i.e. 10^{-16} s. The laser produces a very narrow beam of radiation. The emission generally covers an extremely limited range of visible, infrared and ultraviolet wavelengths.

In 1917, Albert Einstein laid the foundation for laser technology, when he predicted the phenomenon of "stimulated emission", which is fundamental to

the operation of all lasers . In 1939, Valentin Fabricant theorized the use of stimulated emission to amplify radiation. Then Charles Townes, Nikolay Basov, and Alexander Prokhorov developed the quantum theory of stimulated emission and demonstrated stimulated emission of microwaves in 1950. They later received the Nobel Prize in Physics for this ground-breaking work. In 1959, Gordon Gould proposed that stimulated emission can be used to amplify light. He described an optical resonator that could produce a narrow beam of coherent light. He called it a LASER. Theodore Maiman built the first working prototype of a laser in 1960 [5]. He used a synthetic ruby as the active medium in this laser which emits a deep red beam of light with a wavelength of 694.3 nm. Thereafter a variety of lasers with highly varied characteristics have been developed which are being used in many applications.

Lasers are remarkable devices. When the principle of laser technology became known, everything suddenly proceeded rapidly in terms of development. Particularly in the field of medicine, it became the "beam that heals" and has been utilized in nearly every discipline of medicine, in diagnosis, therapy, surgery and medical instrumentation. The purpose of this article is to give the general principle of laser along with their properties and components and medical applications of lasers.

2. Basic principles of lasers

The principle of a laser [6-8] is based on three separate features: (a) stimulated emission within an amplifying medium, (b) population inversion and (c) an optical resonator.

To explain the process of light amplification in a laser, an understanding of the energy transition phenomena in the atoms of its active medium is required. There are three major aspects of a laser:

1. **Stimulated absorption:** Electrons can be excited from one energy state to another by transferring energy from an external source. So, if a photon (light) comes across an electron in a lower energy state, it can push the electron to a higher energy state. The energy of the photon is now a part of the excited electron. As the electron is stimulated, it absorbs the photons energy. This process is called Stimulated absorption - the absorption of a photon by an electron.
2. **Spontaneous emission:** After stimulated absorption, we have an excited electron. But the electron will not stay in its excited (upper) state for long, and will "quickly" fall from its excited state to its original state. When we say quickly, we mean roughly 10^{-8} s (in some cases, although the time varies for different materials). When it falls to its original state, it will release a photon with energy equal to the difference in the energy states.

   E_{Photon} ($\hbar\nu$) = $E_2 - E_1$, where ħ is the reduced plank constant.

The higher the fall, the higher the energy of the emitted photon. If the energy of the photon is in the visible range of wavelength, then we would see it as colour. This process is called Spontaneous emission - the emission of excited energy, i. e. a photon from an electron.

These common processes of absorption and spontaneous emission cannot lead to the amplification of light. The best that can be achieved is that for every photon absorbed, another is emitted.

3. **Stimulated emission:** The last process is when a photon interacts with an electron that is already excited. This new photon can force the excited electron to fall back to a lower energy state and emits another photon. We then have two photons: the incoming (stimulated) photon and the emitted photon from the electron. What's important about this process is that the emitted photon will be identical to the stimulated photon, because the incoming photon has to be of the energy difference between the two states, $E_2 - E_1$, and the new emitted photon is by definition the released energy of the electron going from state 2 to state 1, again, $E_2 - E_1$. Therefore, the two photons will be identical, and have the same energy, frequency, phase and polarization - they will be coherent with each other.

These processes are shown in Figure 1.

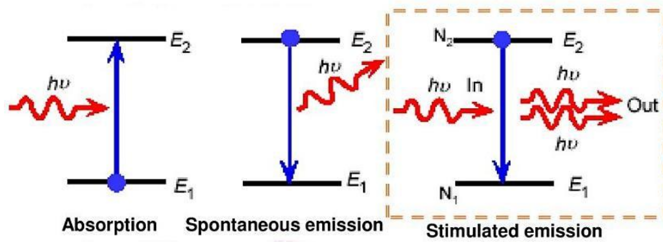


Fig 1: Illustrations for Absorption, Spontaneous and Stimulated Emissions.

All the three processes occur simultaneously within a medium. However, in thermal equilibrium, stimulated emission does not account to a significant extent. The reason is there are far more electrons in the ground state than in the excited states. And the rates of absorption and emission is proportional the number of electrons in ground state and excited states, respectively. So, absorption process dominates.

To obtain a continuous laser beam, metastable state and population inversion are essential.

(a) Metastable state

Metastable state is an excited state of an atom or other system with a longer lifetime than the other excited states. However, it has a shorter lifetime than the stable ground state. Atoms in the metastable state remain excited for a considerable time in the order of 10^{-6} to 10^{-3}. During metastable state, all the parameters associated with state hold stationary values. A large number of excited atoms are accumulated in the metastable state.

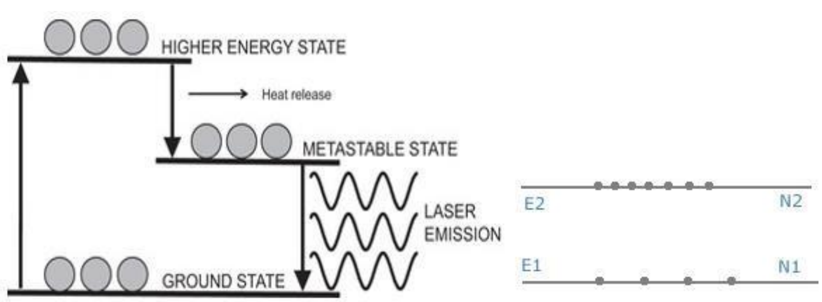


Fig 2: Population inversion in laser

(b) Population inverse

To achieve population inversion, we must have metastable states. Population inversion is the state in which the number of atoms in higher energy state (N_2) is more than those in lower energy state N_1 i. e. $N_2>N_1$. It is required in laser so that stimulated emission is more probable than induced absorption. Light is amplified when the population inversion is positive.

Population inversion is easily achieved when the system of molecules or atoms have the energy levels with favourable properties. For example, the upper energy level has a long lifetime and the lower energy level has a short lifetime. In order to achieve population inversion, we need to supply energy to the laser medium. The process of supplying energy to the laser medium is called pumping. The source that supplies energy to the laser medium is called pump source. The type of pump source used is depends on the laser medium. Pumping may be electrical, optical or chemical.

(c) Optical resonator

An optical resonator (or resonant optical cavity) is an arrangement of optical components which allows a beam of light to circulate in a closed path. Such resonators can be made in very different forms [1, 9]. A laser consists of a

gain medium inside a highly reflective optical cavity. The gain medium is a material with properties that allow it to amplify light by stimulated emission. A cavity consists of two mirrors arranged such that light bounces back and forth, each time passing through the gain medium. Typically, one of the two mirrors, the output coupler, is partially transparent. The light that bounces up and down between the resonator mirrors is amplified many times and therefore reaches a high intensity. The output laser beam is emitted through this mirror as shown in Figure 3.

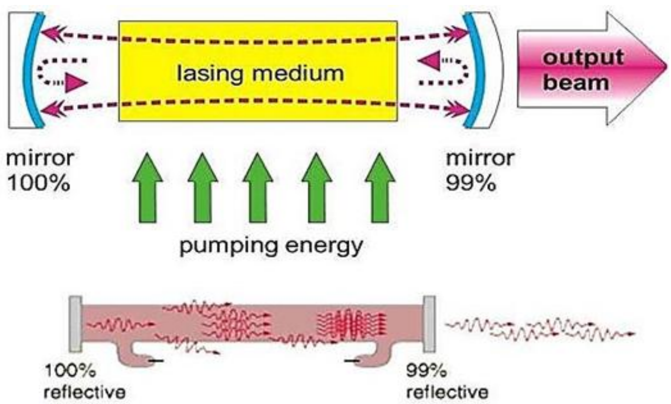


Fig 3: Scheme showing the basic components of a laser system

Light Properties

- Wavelength (λ): The distance between successive peaks of the wave.

- Frequency (ν): The number of wave cycles passing a point per second.

- Energy ($E = h\nu$): Each photon carries energy proportional to its frequency.

- Phase: The relative position of the wave oscillations at a given time.

- Polarization: The orientation of the electric field vector of the wave.

- Intensity: The power transmitted per unit area.

Comparison between Ordinary Light and Laser Light

Ordinary Light	Laser Light
Emits in many wavelengths (incoherent, broad spectrum)	Single wavelength (monochromatic)

Light waves have random phases (incoherent)	Waves are in phase (coherent)
Divergent beam (spreads quickly)	Very narrow beam (low divergence)
Low intensity	High intensity, highly focused
Not polarized (generally)	Can be polarized

Applications of Lasers

- Communications: Optical fiber data transmission.
- Industry: Cutting, welding, and precision measurement.
- Medicine: Surgery, diagnostics, cosmetic treatments.
- Science: Spectroscopy, atomic and molecular studies.
- Daily life: Barcode scanners, CD/DVD players, laser printers.

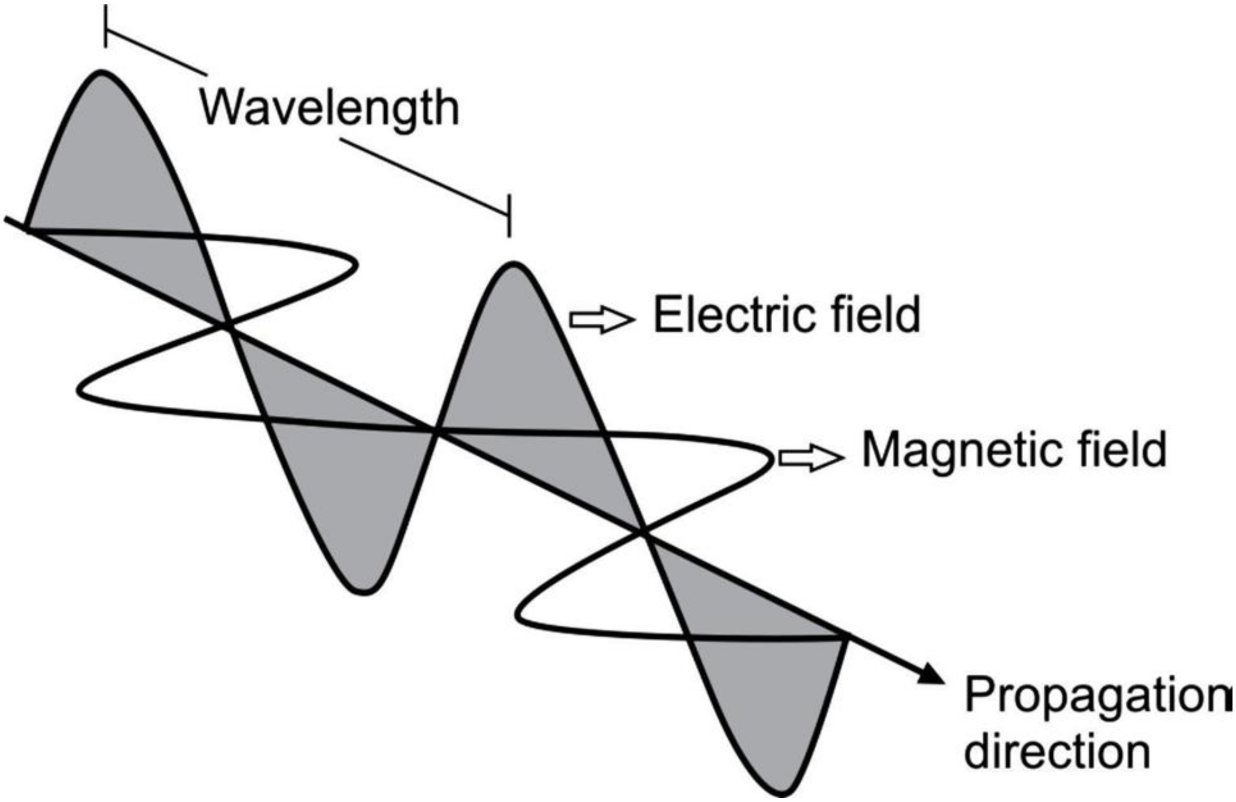
Lecture 2

Nature and propagation of light

Dr. Thulfiqar Nadhim

1. Introduction

Electromagnetic (EM) radiation is a form of energy that travels through space as oscillating electric and magnetic fields and is characterized by its wavelength, frequency, and amplitude. It is produced by accelerating charged particles, moves at the speed of light in a vacuum, and can be described as both waves and packets of energy called photons. The EM spectrum encompasses a wide range of radiation types, from long-wavelength radio waves to short-wavelength gamma rays, with categories including visible light, infrared, ultraviolet, X-rays, and microwaves.



- An electric charge is surrounded by an electric field and if the charge moves, a magnetic field is produced.
- When the charge undergoes an acceleration or deceleration, the magnetic and the electric fields of the charge will vary.
- The combined variation of the electric and magnetic fields results in loss of energy.
- The charge radiates this energy in a for^{2}m known as electromagnetic radiation.

- The electromagnetic radiation moves in the form of sinusoidal waves.
- The nature of the electromagnetic radiation (X-rays, ultraviolet, etc.) depends on the way in which the electric charges are disturbed.
- Electromagnetic radiations are transverse waves that transfer energy away from the electric charge.
- Electromagnetic radiations may be absorbed or scattered in a medium, resulting in loss of energy

- **Optics**, the study of light, is conveniently divided into three fields are geometrical optics, physical optics and quantum optics.
- **Geometrical optics,** which includes the study of light propagation in straight lines, speed of light, properties of light, reflection, refraction, desperation, lenses and mirrors.
- **Physical optics,** which is concerned with the nature of light and involves primarily the theory of waves. This includes interference and diffraction.
- **Quantum optics,** which deals with the interaction of light with the atomic entities of matter and which for an exact treatment requires the methods of quantum mechanics.

1. Light and vision

- **Light or visible light** is electromagnetic radiation that is visible to the human eye, and is responsible for the sense of vision. It has a wavelength in a range from (400 - 700 nm).
- Light travels in straight lines and has the primary properties such as intensity, propagation direction, frequency or wavelength and polarization.
- Light is a form of energy, which is emitted and absorbed in tiny "packets" called photons, the smallest unit of light. Photons are emitted when electrons in an atom jump from one orbit to another, exhibits properties of both waves and particles. This property is referred to as the wave–particle duality.
- For a given frequency f of the radiation, each photon has a fixed amount of energy E which is

$$\boldsymbol{E} = \boldsymbol{hf} \text{.............. (1)}$$

Where h is **Planck's constant**, equal to (**6.63×10^{-34} joul.sec**)

- The wavelength (λ) is the distance between 2 peaks of the wave.
- Frequency (f) is the number of wave/second.
- The relationship between wavelength and frequency is given by:

Speed of light = wavelength × frequency

$$\mathbf{c} = \boldsymbol{\lambda} \times \boldsymbol{f} \text{............ (2)}$$ where **c** = **3×10^{8} m.s^{-1}**

- Light is faster than sound and can travel through a vacuum.

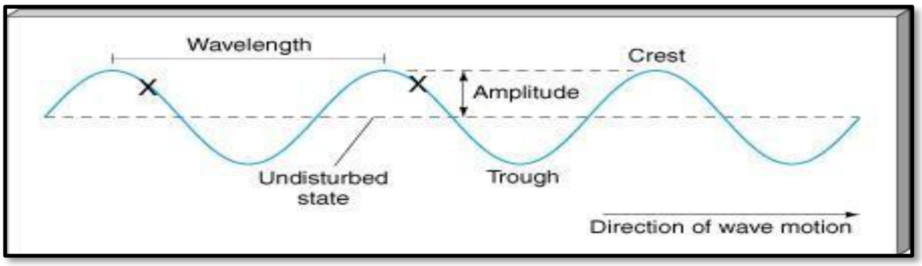


Figure 1: Motion of the light wave

2. Electromagnetic spectrum

- Electromagnetic (EM) radiation is classified by wavelength into radio, microwave, infrared, the visible region we perceive as light, ultraviolet, X-ray and gamma (γ) ray.
- The behavior of EM radiation depends on its wavelength. Higher frequencies have shorter wavelengths, and lower frequencies have longer wavelengths as shown in Fig 1.
- Light is a form of electromagnetic waves- travels through space, each colour is associated with a different wavelength as shown in Table 1.
- White light is a mixture of the colors of the rainbow; a prism splits white light into the various colors.

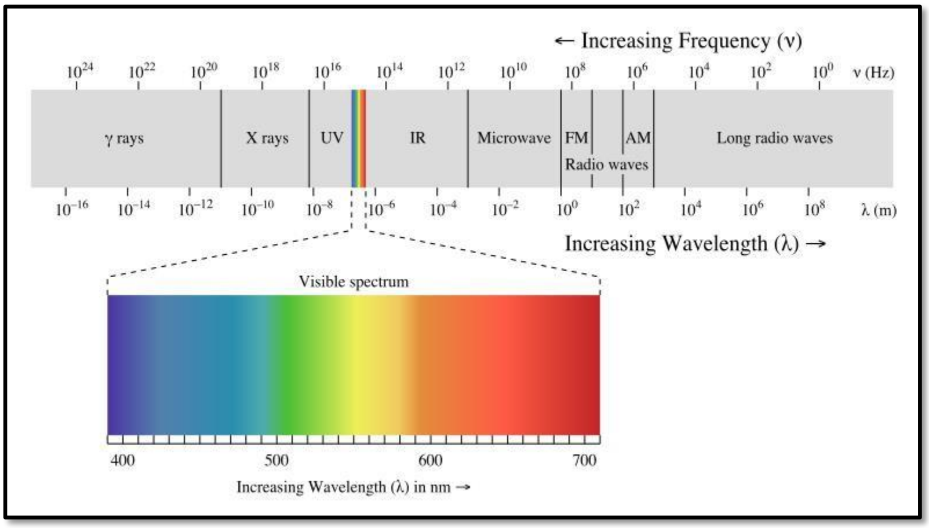


Figure 2: Electromagnetic spectrum

Table 1: The range of the wavelength for colors of visible light

Color	**Range of wavelength (λ) nm**
Violet	400 – 450
Blue	450 – 520
Green	520 – 560
Yellow	560 – 600
Orange	600 – 625
Red	625 – 700

3. Light rays and beams

- A ray of light is the direction along which the light energy travels, while the beam of light is a collection of rays.
- Substances like wood which do not allow light to pass through them are called opaque.
- Transparent substance, like glass, which allows some of light energy incident on it to pass through, the remainder of the energy being absorbed or reflected.

4. Index of refraction (refractive index)

- Definition- is defined as a ratio of the speed of light in vacuum or air relative to the speed of light in a considered medium. This can be written as:

$$\boldsymbol{n}=\frac{velocity\ of\ light\ in\ vacum}{velocity\ of\ light\ in\ medium}=\frac{c}{v} \quad \text{..............} (3)$$

- Refractive index describes how light or other radiation propagates through that medium and it has no units.
- Refractive index of air and water is 1 and 1.33 respectively, meaning that light travels 1.33 times as fast in vacuum as it does in water.
- When light travels from one medium to another, its **wavelength (λ) changes** but its **frequency (*f*) remains constant**.

Example 1: The wavelength of green light is *522 nm*, what is the frequency of this radiation?

Solution:

$\lambda = 522\ nm = 522 \times 10^{-9}\ m,$ c = $3\times10^{8}\ m.s^{-1}$

$c = \lambda \times f \quad f = c / \lambda$

$f = 3\times10^{8}\ m.s^{-1} / 522 \times 10^{-9}\ m = 5.47 \times 10^{14}\ Hz.$

Example 2: A light beam travels at $1.94 \times 10^{8}\ m.s^{-1}$in quartz. Find the index of refraction of quartz at this wavelength?

Solution:

$v = 1.94 \times 10^{8}\ m.s^{-1},$ $c = 3\times10^{8}\ m.s^{-1}$

$n = c / v$

$n = 3\times10^{8}\ m.s^{-1} / 1.94 \times 10^{8}\ m.s^{-1}$ = 1.55.

Example 3: The wavelength of green light is *522 nm*, what is the Energy of this radiation?

Solution:

$\lambda = 522\ nm = 522 \times 10^{-9}\ m,$ c = $3\times10^{8}\ m.s^{-1}$

$c = \lambda \times f \quad f = c / \lambda$

$f = 3\times10^{8}\ m.s^{-1} / 522 \times 10^{-9}\ m = 5.47 \times 10^{14}\ sec^{-1}$

$E = hf$

$E = 6.6 \times 10^{-34}\ joul.sec \times 5.47 \times 10^{14}\ sec^{-1} = 36.1 \times 10^{-24}\ joul$

➢ ***<u>Home works about lecture 1</u>***

Q1: Find the speed of light in the glass if the refractive index of the glass is 1.45?
(A) 4×10^{8} m.s^{-1} (B) 3×10^{8} m.s^{-1} (C) 2×10^{8} m.s^{-1} (D) 1×10^{8} m.s^{-1}

Q2: The range of visible light in the electromagnetic filed is:
(A) 100 – 300 nm (B) 400 – 700 nm (C) (800 – 1100 nm) (D) (1200 – 1500 nm)

Q3: The range of weave length of violet colour is:
(A) (560 – 600 nm) (B) (520 – 560 nm) (C) (450 – 520 nm) (D) (400 – 450 nm)

Q4: Defined as a ratio of the speed of light in air relative to the speed of light in a considered medium?
(A) Refractive index (B) frequency (C) wave length (D) ray

Q5: The formula of frequency (f) expressed as:
(A) $f = \lambda / c$ (B) $f = c / \lambda$ (C) $f = c \times \lambda$ (D) $f = \lambda \times c$

Lecture 3

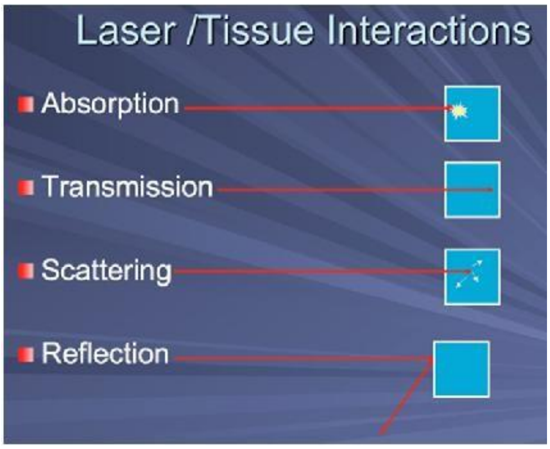
Optical and Thermal Response of Tissue to Laser Radiation

Dr. Thulfiqar Nadhim

As the Laser reaches the skin, it may interact by one of the following:

Absorption

A chromophore is the part of a molecule responsible for its color. The color arises when a molecule absorbs certain wavelengths. Absorbed light energy is then converted into other forms of energy like heat.



Transmission

The laser energy can pass through tissues to interact with deeper areas. Retinal surgery is an example; the laser passes through the lens to treat the retina.

Scattering

Once the laser enters the target tissue it will scatter in various directions

Reflection

Laser beam reflect with no penetration or interaction. Reflection is usually an undesired effect, but is useful for calculating the amount of energy absorbed

Fluorescence

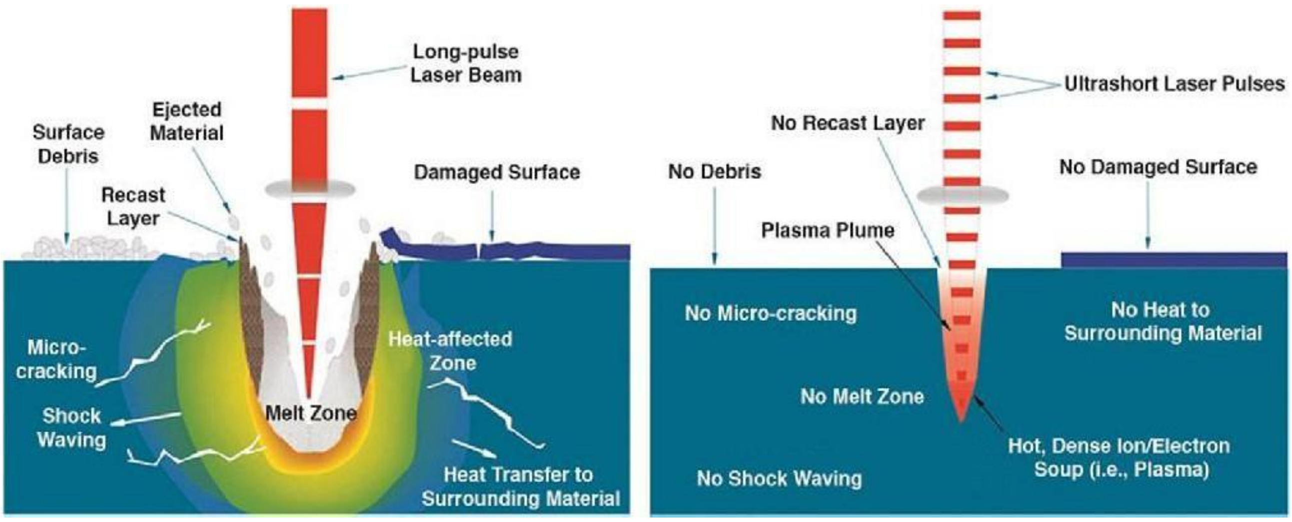
which is the emission of light by a substance that has absorbed light or other electromagnetic radiation

Biological effects of Laser on the live tissue

- **Photo disruptive effects (Photo ablation) التفتيت الضوئي**

Laser can cause electrons to oscillate if they absorb energy, and elaborate electrons from their nuclei, producing an entirely different physical state of matter called plasma. Thermal damage is very unlikely as almost no residual heat is created.

The photo disruption procedure involves the delivery of large amounts of energy into very small focal spots in very brief durations (nanoseconds to picoseconds). The result is an instantaneous, highly localized temperature increase (15,000° C). However, heating is so quick that the heat dissipates outwardly and the procedure is considered non-thermal. Molecules and atoms are stripped of their electrons and ionization occurs. The light energy causes tissue to be reduced to a form of matter called plasma. Photo disruption also produces acoustic pulses (sound waves)--forces that propagate outward in all directions



- **Photochemical reactions**

A chemical reaction initiated by the absorption of light to create states whose chemical and physical properties differ greatly from the original molecules. These new chemical species can fall apart, change to new structures, combine with each other or other molecules, or transfer electrons

- **Photocoagulation or Photo thermal effects**

This laser-tissue interaction is accomplished with the argon and krypton lasers. This process is pigment-dependent and will not occur without melanin in treated tissues. During photocoagulation, the doctor focuses laser light on the pigmented tissue, which absorbs the light and converts it into heat. When tissue is warmed 10-20° C, photocoagulation occurs. This is considered a thermal event, so these lasers are referred to as thermal or "hot" lasers.

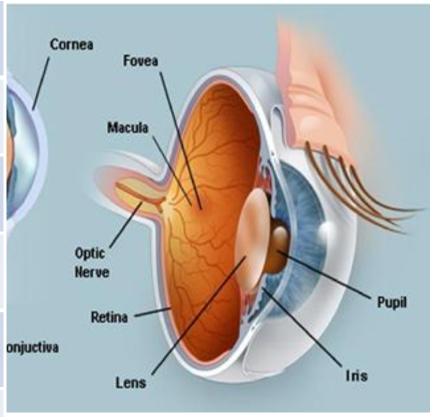
The effects may take hours to appreciate. Photocoagulation involves the denaturing of proteins. It coagulates blood and produces irritation. adhesions, sealing leakages in retinal vascular disease.

- **Photobiomodulation or Bio stimulation**

refers to lasers ability to biological effects like:
speed healing, increase blood circulation, minimize pain, increased collagen synthesis. The exact mechanism of these photobiomodulation effects is still not fully clear

Eye Injuries

Vitreous body	الجسم الزجاجى
Fovea	النقرة
Iris	قزحية
Pupil	بؤبؤ العين
Cornea	القرنية
Retina	الشبكية



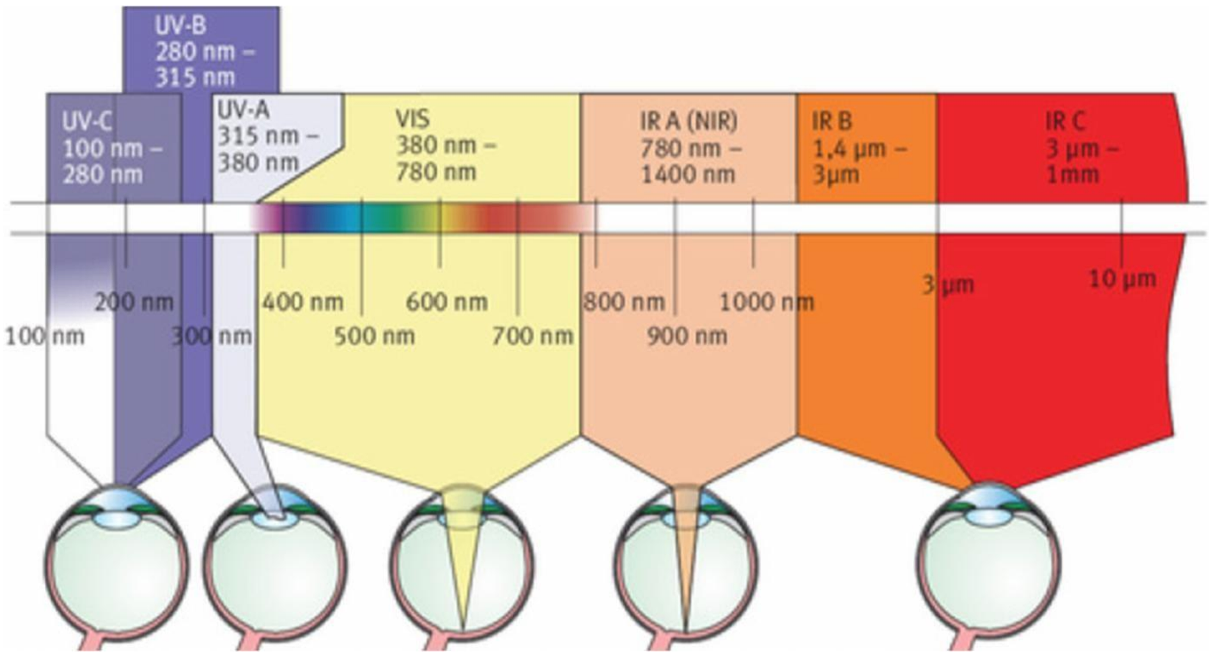
Important components of the eye, such as the cornea, lens, and retina are susceptible to damage by laser light. Light enters through the transparent layers of the **cornea** and then is focused by the **lens** onto the retina. The eye in essence intensifies light energy, particularly the visible and the near-infrared wavelengths, in some cases as much as 100,000 times. For example, if there is a $1 mW/cm^2$ irradiance of light entered the eye, it can be intensified on the retina to an irradiance of $100\ W/cm^2$.

- The **fovea** on the retina is a small area (~ 4%) that is responsible for acute and color vision, so that damage to this portion of the eye can result in a serious loss of sight.
- **cornea** is a transparent tissue in the front part of the eye. It is a curved spherical structure that is responsible for focusing the light onto the inside of the eye. Contact lenses sit on top of the cornea to change it's curvature and eliminate the need for glasses.

- The **iris** is the colored part of the eye. It opens up in dark rooms and at night to let more light into the eye. Conversely, in bright lights the iris constricts to decrease the amount of light that enters the back of the eye.
- The **pupil** is the black spot in the Centre of the through which light passes.
- The lens is responsible for helping to fine adjust the focus of the eye. The lens changes shape to allow clear vision both in the distance and for reading.
- The **vitreous** is a clear jelly-like material which fills the inside of the eyeball. Light passes through the vitreous on its way to being focused onto the retina.
- The **retina** is a thin film of tissue (like film in a camera) where images are brought into focus. The retina lines the inside surface of the eyeball and is connected to the brain where the visual signals are processed.

Spectral Absorption of Eye Parts

Some areas of the eye absorb more light in one spectral region than



in other regions. Absorption of laser radiation above a certain level leads to tissue injury. Laser protective eyewear is specific to the types of laser radiation that absorb emitted Laser at that band.

Lecture 4

Skin Injuries

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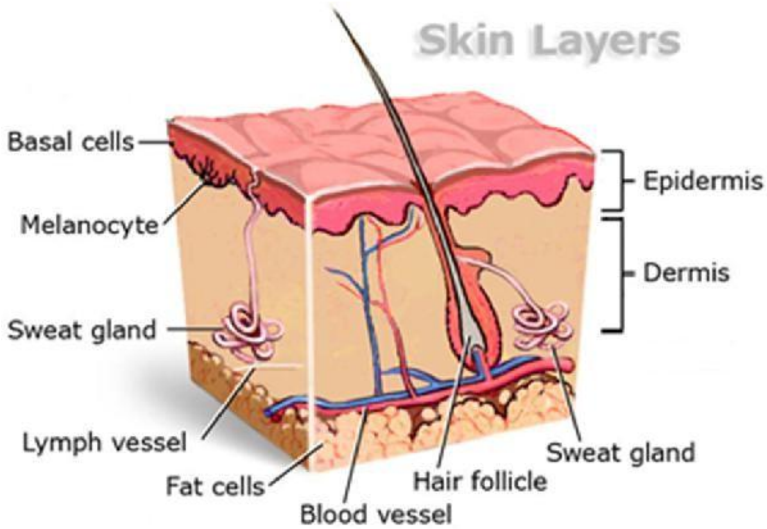
Risks to the skin are considered secondary to risks to the eyes, because skin injuries affect only the external dead layer of the skin cells; and even more penetrating damage usually will heal eventually. Laser radiation can affect the skin thermally or photo chemically. Skin consists of two main layers:
the **epidermis** (surface layer) and the **dermis** (the underlying layer). The outermost layer of the epidermis consists mainly of dead cells.

This gives protection against water loss, scratch, dust, air, and sun energy. This layer of dead cells is about 8 μm to 20 μm thick.

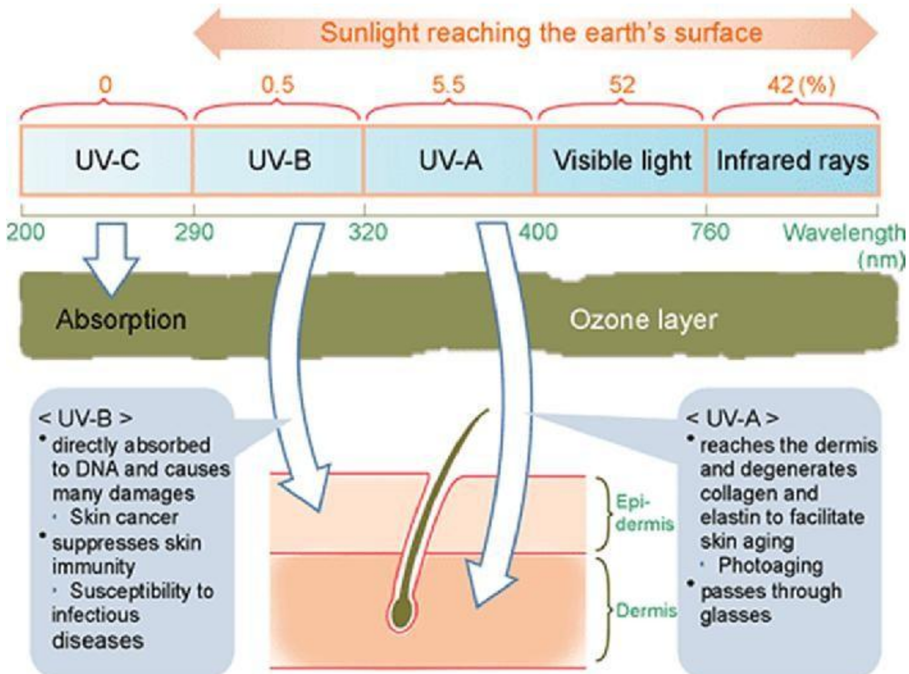
In the next layer of the epidermis just below the dead cells, there are specialized cells that produce melanin that help to protect the dermis against harmful ultraviolet radiation. As they absorb radiation, they darken. So they're responsible for the skin's color. The entire epidermis averages about 0.1 mm in thickness.



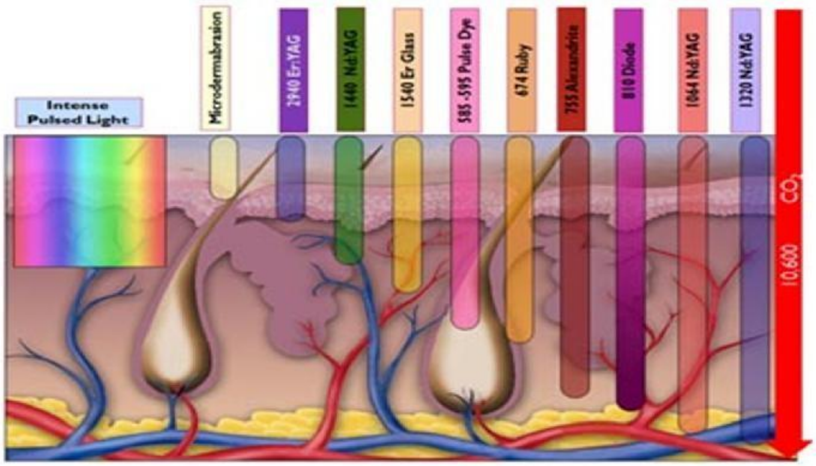
The **dermis** has numerous **<u>blood vessels</u>**, **<u>nerve cells</u>**. It also contains **<u>connective tissue</u>** (that gives elasticity and support to the skin), **<u>sweat glands</u>** (to regulate body temperature and allows for evaporative cooling of the body), and **<u>hair follicles</u>**.

Nerve cells include heat sensors, cold sensors, pain sensors, and touch sensors. Blood vessels allow for the maintenance of healthy tissue and play an important role in heat regulation.

The skin reflects most visible and IR-A (near-infrared) radiation. The epidermis is highly absorbing at UV-B and UV-C wavelengths and at IR-B and IR-C wavelengths. The melanin in the epidermis absorb much of the ultraviolet radiation incident upon the skin and protect the dermis from harmful UV.



However, with enough power and duration, the incident radiation of any wavelength in the optical spectrum can penetrate the protective filter of the epidermis and cause deep internal injury.



Ultraviolet radiation in the UV-B and UV-C regions causes reddening (sunburn) and eventual erythema. Erythema is a photochemical occurrence. Chronic exposures to UV are known to accelerate aging of the skin. They increase the risk of skin cancer.

Types of Laser-Induced Skin Effects

Effect Type	Typical Wavelength	Nature of Damage	Application Example
Thermal	10.6 µm (CO_2)	Vaporization, coagulation	Mole removal, cutting
Photochemical	UV-B, UV-C	DNA damage, free radicals	Sunburn, skin aging
Photoacoustic	532–1064 nm	Shock waves in tissue	Tattoo, pigment removal

Some definitions used in Laser Surgery

Thermal relaxation time: It is the time taken for the target to dissipate about 63% of the incident thermal energy. It is related to size of target chromophore, e.g., few nanoseconds (tattoo particles) to hundred milliseconds (leg venules الساقين دوالي)

Thermo modulation: The ability of low-energy light to upregulate (modulate) certain cellular biologic activities without producing an injury

Extinction length: The thickness of material necessary to absorb 98% of incident energy

Power density (irradiance): The amount of incident laser power on a unit surface area, expressed as $watts/cm^2$

Energy fluency: The energy contained within light is expressed in joules (J). The *energy fluency* determines the amount of laser energy delivered in a single pulse and is expressed in $joules/cm^2$

Q-Switch: An optical device (Pockels cell) that controls the storage or release of laser energy from a laser optical cavity. Q-switching is a means of creating very short pulses (5-100 ns) with extremely high peak powers. Q stands for quality

Photoacoustic effect: The ability of Q-switched laser light to generate a rapidly moving wave within living tissue that destroys melanin pigment الجلد في ازالة الوشم من على

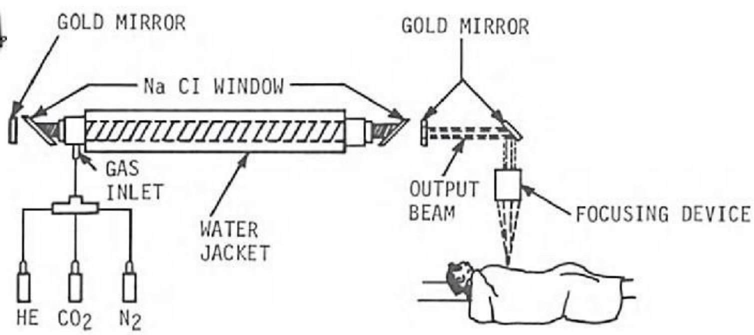
Selective photo thermolysis: is a precise microsurgery technique used to target tissue in a specific area. It matches the specific wavelength of light and heats the tissue and destroys it with a laser without affecting or damaging surrounding tissue. The targeted cells are destroyed by the absorption of light and transfer of energy

Protection and Safety Measures

- Always wear wavelength-specific protective eyewear.
- Avoid direct exposure of unprotected skin.
- Use transparent shields during procedures.
- Adjust power, duration, and focus precisely for tissue type.

C02 lasers in Surgery

In 1966, the first 20-watt CO_2 laser started operating. This was a typical physics laboratory laser. The problem was to make a small permanent hole in a dog's skin. After successful experiments, the device is used in humans.



Because of its specific properties, it has an advantage in the following conditions:

1. In all operations where the anticipated blood loss would be significant.
2. In surgery performed on highly vascular areas of the body.
3. In extirpation of vascular tumors and malignant disease
4. In surgery performed on patients with bleeding tendencies.
5. In operations performed through highly infected tissue.
6. In operations performed on organs where simultaneous monitoring is necessary.
7. In cavitation surgery with suitable endoscopic or microscopic attachments.

Lecture 4

Laser Parameters

DR: Thulfiqar Nadhim

There is a vast range of common laser systems from applications as diverse as materials processing, laser surgery, and remote sensing, but many laser systems share common key parameters. Establishing common terminology for these parameters prevents miscommunication, and understanding them allows for properly specifying laser systems and components to meet your application needs.

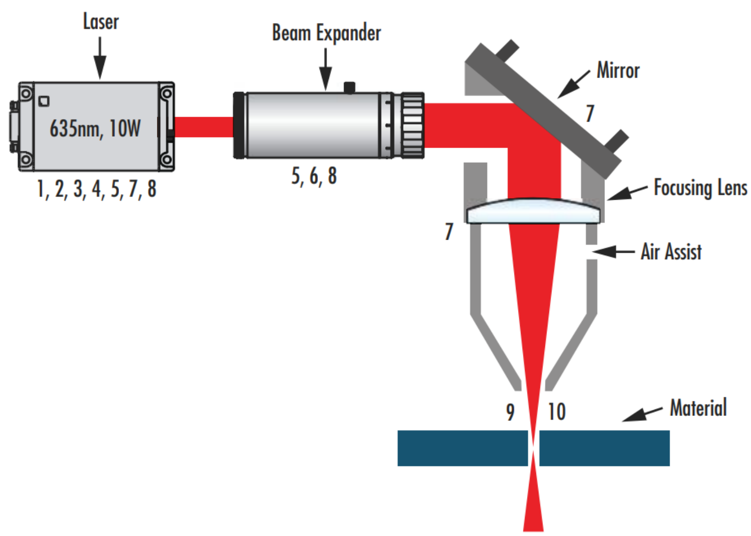


Figure 1: Schematic of a common laser materials processing system in which each of the 10 key parameters of a laser system are indicated by their corresponding numbers

Fundamental Parameters

The following fundamental parameters are the most basic concepts of laser systems and are critical for understanding more advanced topics.

1: Wavelength (Typical Units: nm to µm)

A laser's wavelength describes the spatial frequency of the emitted light wave. The optimal wavelength for a given use case is highly application-dependent. Different materials will have unique wavelength-dependent absorption properties in materials processing, leading to different interactions with the material. Similarly, atmospheric absorption and interference will affect certain wavelengths differently in remote sensing, and various complexions will absorb certain wavelengths differently in medical laser applications. Shorter wavelength lasers and laser optics are advantageous for creating small and precise features with minimal peripheral heating because of a smaller focused spot. However, they typically are more expensive and prone to damage than lasers at longer wavelengths.

2: Power and Energy (Typical Units: W or J)

The power of a laser is measured in watts (W) and is used to describe either the optical power output of a continuous wave (CW) laser or the average power of a pulsed laser. Pulsed lasers are also characterized by their pulse energy, which is directly proportional to average power and inversely proportional to the laser's repetition rate (*Figure 2*). Energy is measured in joules (J).

Pulse Energy=Average Power Repetition Rate

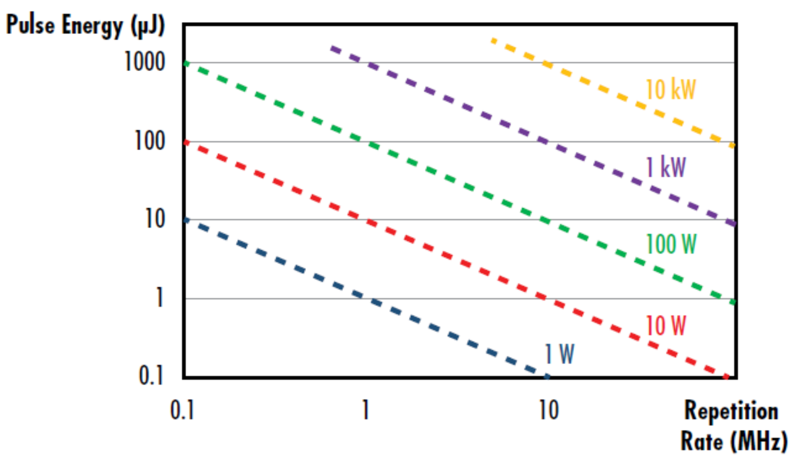


Figure 2: Visual representation of the relationship between pulse energy, repetition rate, and average power for pulsed lasers

Higher power and energy lasers are typically more expensive, and they generate more waste heat. As powers and energy increase, it also becomes increasingly more difficult to maintain high beam quality. More information on pulsed and CW lasers can be found in our Understanding and Specifying LIDT of Laser Components application note.

3: Pulse Duration (Typical Units: fs to ms)

The laser pulse duration, or pulse width, is commonly defined as the full width at half-maximum (FWHM) of the laser's optical power vs. time (*Figure 3*). Ultrafast lasers, which have numerous benefits for a range of applications including precise materials processing and medical lasers, are characterized by short pulse durations on the order of picoseconds (10^{-12} s) to attoseconds (10^{-18} s). More information can be found in our Ultrafast Dispersion and Highly-Dispersive Mirrors application notes.

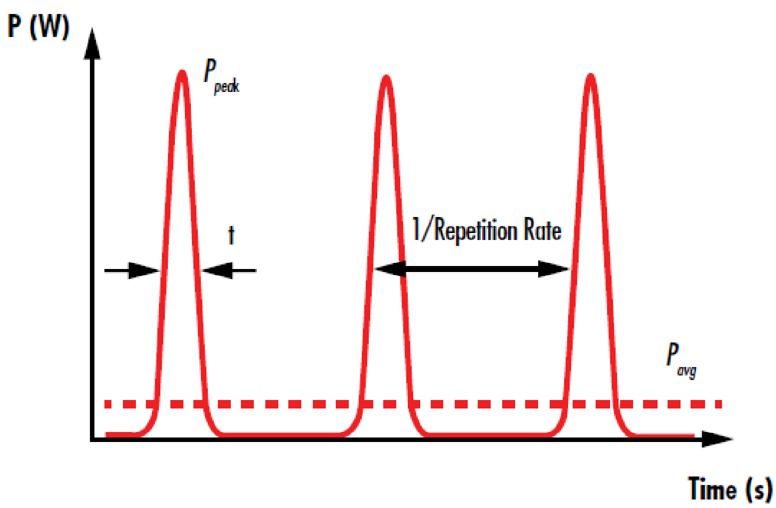


Figure 3: The pulses of a pulsed laser are temporally separated by the inverse of the repetition rate

4: Repetition Rate (Typical Units: Hz to MHz)

A pulsed laser's repetition rate, or pulse repetition frequency, describes the number of pulses emitted every second, or the inverse temporal pulse spacing (*Figure 3*). As mentioned earlier, repetition rate is inversely proportional to pulse energy and directly proportional to average power. While repetition rate is often dependent on the laser gain medium, in many cases it can be varied. Higher repetition rates result in less thermal relaxation time at the surfaces of the laser optics and at the final focused spot, which leads to more rapid material heating.

5: Coherence Length (Typical units: mm to m)

Laser light is coherent, meaning that there is a fixed relationship between the electric field phase values at different times or locations. This occurs because laser light is produced by stimulated emission, unlike most other types of light sources. Coherence degrades throughout propagation and the coherence length of a laser defines a distance over which its temporal coherence is maintained to a certain quality.

7: Beam Diameter (Typical Units: mm to cm)

A laser's beam diameter characterizes the transverse extension of the beam, or its physical size perpendicular to the direction of propagation. It is often defined at the $1/e^2$ width, which is bounded by the points where the beam's intensity reaches $1/e^2$ (≈ 13.5%) of its maximum value. At the $1/e^2$ point, the electric field strength drops to 1/e (≈ 37%) of the maximum value. The larger the beam diameter, the larger the optics and the overall system need to be to avoid clipping the beam, which adds cost. However, decreasing beam diameter increases the power/energy density, which can also be detrimental (see next parameter).

8: Power or Energy Density (Typical Units: W/cm^2 to MW/cm^2 or $\mu J/cm^2$ to J/cm^2)

Beam diameter is related to the power/energy density, or the optical power/energy per unit area, of a laser beam. The larger the beam diameter, the smaller the power/energy density of a beam of constant power or energy. High power/energy densities are often ideal at the final output of a system (such as in laser cutting or welding), but low power/energy densities are often beneficial inside a system to prevent laser-induced damage. This also prevents high power/energy density regions of the beam from ionizing the air. For these reasons, among others, laser beam expanders are often used to increase the diameter, and thereby decrease the power/energy density inside of a laser system, as described in our Laser Beam Expanders application note. However, care must be taken to not expand a beam so much that it experiences clipping from apertures in the system, leading to wasted energy and potential damage.

9: Beam Profile

A laser's beam profile describes the distribution intensity at a cross-section of the beam. Common beam profiles include Gaussian and flat top beams, whose beam profiles follow Gaussian and flat top functions, respectively (*Figure 4*). However, no laser can produce a perfectly Gaussian or perfectly flat top beam whose beam profile matches its characteristic function perfectly, as there is always some amount of hotspots or fluctuations inside a laser. The difference between a laser's actual beam profile and that of an ideal beam is often described through metrics including a laser's M^2 factor. More information about beam profiles and characterizing beam quality can be found in our Gaussian Beam Propagation and Beam Shape, Beam Quality, and Strehl Ratio application notes.

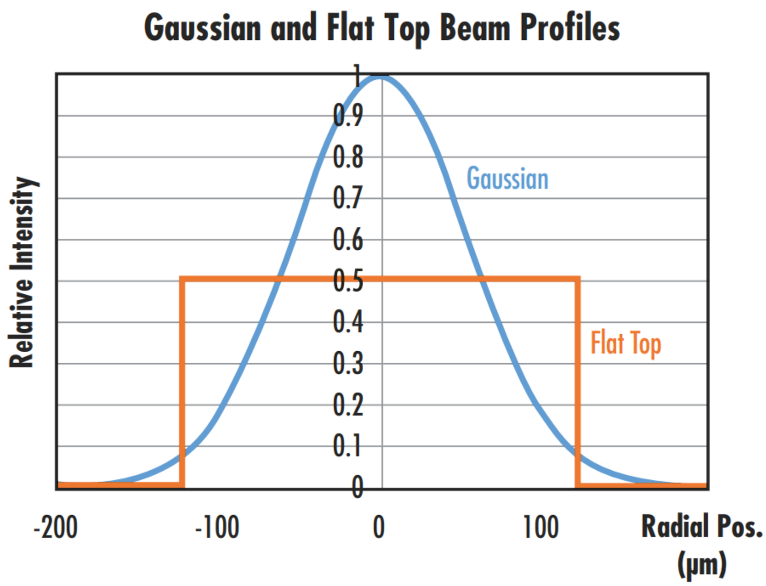


Figure 4: A comparison of the beam profiles of Gaussian and flat top beams with the same average power or intensity shows that the Gaussian beam will have a peak intensity 2X that of the flat top beam

10: Divergence (Typical Units: mrad)

While laser beams are often assumed to be collimated, they always contain some amount of divergence, which describes how much the beam spreads out over increasing distance from the laser's beam waist, because of diffraction. Divergence becomes an especially significant issues in applications with a long working distance, such as LIDAR systems where an object may be hundreds of meters away from the laser system. Beam divergence is typically defined by the laser's half angle, and the divergence (θ) of a Gaussian beam is defined as:

$$\theta=\lambda\pi w0$$

λ is the laser's wavelength and w_0 is the laser's beam waist. More information about divergence can be found in our Gaussian Beam Propagation application note. Divergence can be decreased by increasing the beam diameter, as described in our Laser Beam Expanders application note.

11: Spot Size (Typical Units: µm)

The spot size of a focused laser beam describes the beam diameter at the focal point of a focusing lens system. In many applications, such as materials processing and medical surgery, the goal is to minimize spot size. This maximizes power density and allows for the creation of especially fine features (*Figure 5*). Aspheric lenses are often used instead of conventional spherical lenses to reduce spherical aberrations and produce smaller focal spot sizes. Some types of laser systems do not end in focusing the laser down to a spot, in which case this parameter is not applicable.

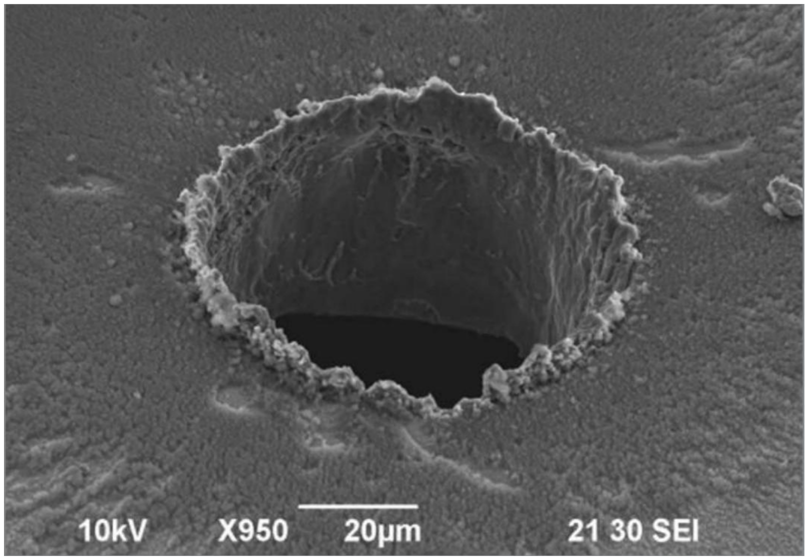


Figure 5: Laser micro-machining experiments at the Italian Institute of Technology showed a ten-fold increase in the ablation efficiency of a nanosecond laser drilling system when decreasing the spot size from 220μm to 9μm at constant fluence[1]

12: Working Distance (Typical Units: μm to m)

The working distance of a laser system is commonly defined as the physical distance from the final optical element (typically a focusing lens) to the object or surface the laser is focusing onto. Certain applications, such as medical lasers, often seek to minimize working distance, while other applications, such as remote sensing, often aim to maximize their working distance range.

Lecture 6

Properties of laser light

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Classification of lasers

Medical applications require different types of lasers. Based on their gain medium, lasers are classified into five main types: **Solid-state laser:** A solid-state laser is a laser that uses solid as a laser medium. In these lasers, glass or crystalline materials are used. In these lasers, *r*are earth elements such as neodymium, chromium, erbium, thulium, or ytterbium are commonly used as dopants. The most commonly known solid-state lasers are the Ruby and Nd:YAG lasers.

- **Gas lasers:** A gas laser is a laser in which an electric current is sent through a gas to generate light through a process known as population inversion. Examples of gas lasers include carbon dioxide (CO_2) lasers, helium-neon lasers, argon lasers, krypton lasers, and excimer lasers.

- **Semiconductor lasers (Laser diodes):** Laser diodes, also called diode lasers and semiconductor lasers, are similar to regular diodes in that they have a positively-negatively (PN) charged junction. In semiconductor lasers, a p-n junction of a semiconductor diode forms the active medium or laser medium. The optical gain is produced within the semiconductor material. The difference is that laser diodes have an intrinsic layer at the PN junction made of materials that create spontaneous emission. The intrinsic layer is polished so that the generated photons are amplified, ultimately converting the electric current into laser light.

- **Liquid lasers (Dye lasers):** Liquid lasers use an organic dye in liquid form as their gain medium. They are also known as dye lasers and are used in laser medicine. One of the advantages of dye lasers is that they can generate a

- much wider range of wavelengths, making them good candidates to be tunable lasers, meaning that the wavelength can be controlled while in operation.

- **Fiber lasers:** A fiber laser is a special type of solid-state laser that is a category of its own. In fiber lasers, the gain medium is an optical fiber (silica glass) mixed with a rare-earth element. The light guiding properties of the optical fiber are what makes this type of laser so different: the laser beam is straighter and smaller than with other types of lasers, making it more precise. Fiber lasers are also renowned for their small footprint, good electrical efficiency, low maintenance and low operating costs. Examples of fiber lasers used for these applications include ytterbium and erbium-doped fiber lasers.

Medical applications of lasers

The special properties of lasers make them much suitable for targeting medical applications. Lasers are widely used for medical applications including dermatology, plastic surgery, wound healings, nerve stimulation, dentistry, ophthalmology and many other therapeutic and surgical procedures. Each laser operates within a very narrow wavelength range and the light emitted is coherent. They can also be very powerful. The beams can be focused to a very small point, giving them a high-power density. These properties have led to lasers being used in many areas of medical diagnosis and treatment.

When laser radiation falls on human tissues, different phenomenon may take place like reflection, transmission, scattering, re-emission and absorption [13]. It is the absorption phenomenon, which is most important. The main laser absorbing components in tissues are:

- Oxyhemoglobin (In blood): The blood's oxygen carrying protein, absorption of UV and blue and green light. Lasers for selective absorption include excimer, argon, KTP, Dye and Ruby.
- Melanin: A pigment in skin, hair, moles, etc.: absorption in visible and near IR light (400nm-1000nm). Lasers for selective absorption in melanin include Diode and Nd: YAG.

- Water (In tissues): transparent to visible light but strong absorption of UV light below 300nm and IR over 1300nm. Lasers for selective absorption in water molecules in tissues include Ho: YAG, Er: YAG and CO_2.

Some typical applications of medical lasers are:

1-Lasers in ophthalmology

Ophthalmology is the branch of medicine and surgery dealing with the diagnosis and treatment of problems of the eye. Laser has become a common tool now in photocoagulation such as the one used to reattach a detached retina. For example, the green beam of argon ion laser is focused on a certain point of the retina. The beam penetrates through the lens of the eye and the vitreous chamber without being absorbed. But the beam gets strongly absorbed by the red blood cells of the retina and the resultant thermal effect leads to reattachment of retina. In the past, high-powered xenon lamps were also often used to concentrate enough heat in the area of the unattached retina. The problem here was that the optical power could not be rapidly focused.

Photocoagulation

The laser produces a pulse of light energy as directed by the surgeon, which is passed to the eye under treatment. The pulse of light is focused by the lens of the patients' eye to produce a minute lesion or coagulation of the tissue of the retina and the choroids (the vascular membrane of the eyeball between the sclera and retina). The retina is so welded to the choroids by a series of these lesions through several repeated pulses from the laser. The amount of energy required for coagulation is different for different patients. The two lasers are commonly used in ophthalmology, are the ruby laser of 0.69 μ m and argon ion laser of 488 to 514 nm.

a- Treatment of corneal ulcers

The other application of lasers in the treatment of eye disease is in corneal ulcers. Here, an argon-ion laser is used in combination with a fluorescein dye. The infected site is dyed with the fluorescein dye by using antibodies, specific for the infecting organism, labelled with the dye.

Fluorescein absorbs argon laser strongly and raises the temperature of the organism, thereby destroying it, without damaging the surrounding tissues.

b- Laser in the treatment of glaucoma

Glaucoma is caused by an increase in pressure inside the eye, which destroys nerve cells and causes vision loss. Conventional surgery to treat this condition is to cut a channel in the eye to drain out the excess fluid. However, this procedure is biset with a 5% risk of blindness. There are several drugs that could be administered to reduce the pressure. But they also cause serious side effects such as increase in blood pressure and bronchospasms. Laser surgery seems to give no side effect.

2- Gynecology

Gynecologists were among the specialists who first truly appreciated the potential of the laser. One of the first lasers they used was the CO2 laser, which they found tremendously effective in treating patients with erosion of the cervix. New gynecological applications were introduced and with instrumentation refinements, the laser advanced laparoscopic surgery to a fine art. The laser was then found useful for cutting, coagulating and vaporizing during intraabdominal procedures. Also, the laser was coupled with the hysteroscopy to perform surgery within the uterus. Other clinical applications continue to be developed by innovative gynecologists who strive to provide

less invasive less complicated procedures to benefit their patients. Many different wavelengths are being used effectively for a variety of gynecological applications, including lower tract, laparoscopic, hysteroscopy, and intraabdominal procedures.

3- Urology

Lasers were first experimentally used in urology within gas-filled bladders. The laser was inserted through conventional rigid cystoscopes with special deflecting prisms or shutoff windows to conduct the laser energy. Advances have led to the development of cystoscope accessories and quartz fibers to conduct the beam through a fluid-filled bladder. In the 1970s, Dr. A. Hof Stetter successfully performed Nd: YAG laser cystoscopy to irradiate bladder tumors. This accomplishment led to tremendous advances in treating recurrent bladder tumors and initiated the development of other urological laser applications. A variety of laser wavelengths are used today to successfully treat many urological conditions. The CO2, Nd: YAG, frequency doubled YAG and argon lasers are commonly used for different procedures.

4- Dermatology

Laser is already being successfully used for cauterization and local treatment of skin growths and skin deformities.

Laser treatment provides two major advantages over conventional treatment in case of burn injuries and skin grafting. They are:

a) The area, which has been treated remains sterile and hence provides an ideal bed for immediate skin grafting.

b) The blood loss is minimal.

Laser finds wide application in dermatology especially in the following areas:

a) Homeostasis, which means stopping of bleeding.

b) Removal of hair, tattoos, warty keratosis, cell carcinomas, freckles, acne and various growths, both benign and malignant.

CO2 lasers have been used for treating skin tumors. Another application of laser more specifically photo medicine, is in the surgical treatment of port wine stains (PWS). A port wine stain is a defect in the skin, which is manifested by discolored or blotchy and darkened patches in the skin. The most commonly used laser in the treatment of PWS is the pulsed argon laser.

5- Cardiology

Another important area of medical application of lasers is the laser assisted balloon angioplasty, which has become very common in clearing blocked arteries.

In balloon angioplasty, a tiny deflated balloon, housed in a thin catheter, is threaded through the artery in the blocked region. When it reaches the right spot, the balloon is inflated to open up the vessel by compressing the obstructing plaque against the walls of the artery. This method is less expensive and less prone to complications, as compared to conventional bypass surgery.

The disadvantage with balloon angioplasty is that the vessel can close again because there is no permanent removal of the clot. About an estimated 30% case need repetition of the process. This technique is of no use in case of totally blocked arteries.

Lasers have helped in overcoming this problem. Lasers can pave the way for the balloon or clear the arteries on their own. In laser-assisted angioplasty, an Ar+ laser delivers the energy through the catheter and disposable balloon. The balloon helps in inflating the site for blood flow cessation and centering the optical fibre, which transmitting the laser and the opening the vessel. Taking turns, the balloon and the laser, clear the path for each other, through the block.

6- Gastroenterology

Gastrointestinal diseases primarily include ulcers and tumors of the esophagus, Stomach liver, gallbladder and intestine. The intestine further consists of the jejunum, ileum, colon, and rectum. According to the position of these organs, the gastrointestinal tract is subdivided into an upper and a lower tract. Most intestinal tumors are reported to occur inside the colon or the rectum. In general, any kind of ulcer or tumor can be treated with lasers if it is accessible with endoscopic surgery. Gastroenterology is one of the major domains of the CW Nd: Y AG laser only in photodynamic therapy are dye lasers applied. There exist mainly two indications for laser therapy: gastrointestinal hemorrhages and benign, malignant Since CW Nd: YAG laser is acting thermally; it can stop bleeding by means of coagulation. The CO2 laser is not suitable for clinical gastroenterology, since it is not transmitted through optical fibers which belong to the mandatory equipment of successful endoscopic surgery.

7- Surgery

Laser surgery was confirmed as an effective and safe procedure in 1981 due to the following reasons:

- The development of new laser technology and technique.
- Finding of new and cheaper fiber optics which is used in endoscopy.
- Understanding the concept of laser tissue interaction.
- Availability of new high-power surgical applications technique including laser interstitial thermal therapy (LITT).

Lecture 7

Lasers in Ophthalmology

DR: Thulfiqar Nadhim

Since the introduction of the ruby laser more than three decades ago, ophthalmic laser applications have experienced rapid growth with use of the argon, krypton, argon pumped dye, Nd:YAG, and, most recently, diode lasers. This part will review the current status of clinical and experimental applications of laser technology in ophthalmology

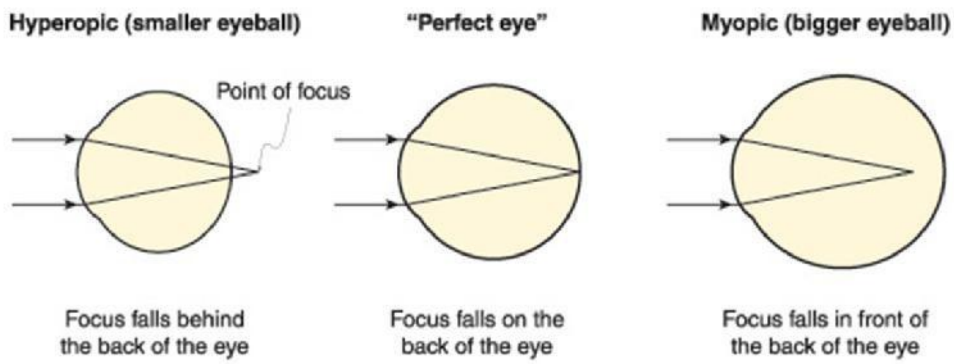
The eye has a focal length of about 16.7 mm in air. Ophthalmologists prefer to use optical units of diopters (l diopter=l/F meters) when measuring the refractive error of the eye or the power of the eye's optical elements.

The lens can change shape and increase its focusing power for near vision (accommodation) until about the fifth decade of life, when, for most people, reading glasses become a necessity for clear viewing of close objects. Because the cornea is the predominant optical element of the eye, a small change in its curvature causes a large effect on the total optical power of the eye, a principle utilized by corneal refractive surgeons. An **emmetropic eye**

العين السليمة, or one without refractive error, focuses a distant point source of light on the

fovea, the region of the retina with the highest density of cones (1 µm diameter with 1.3 µm spacing), the photoreceptors that provide the highest resolution (15–30 min. of arc).

Nearsighted or myopic eyes have too much optical power for their length, resulting in displacement of the focal point anterior to the retina. **Farsighted or hyperopic eyes** have insufficient power for their length, with a focal plane that is located "behind" the retina.



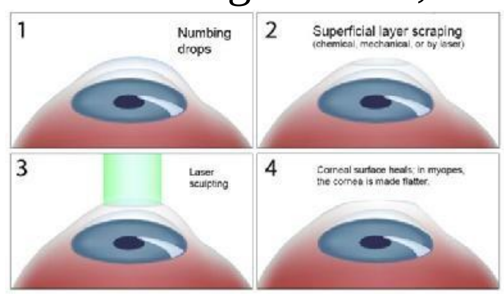
Laser Treating of myopia (قصر النظر) and Hyperopia (طول النظر)

Refractive surgery corrects vision by changing shape of the cornea that covers the outer surface of the eye. One laser pulse removes 1/4000 millimeter of tissue, an amount so small it would take 200 pulses of the laser to etch through a human hair.

Photorefractive keratectomy (اقتطاع في القرنية بالليزر) (PRK)

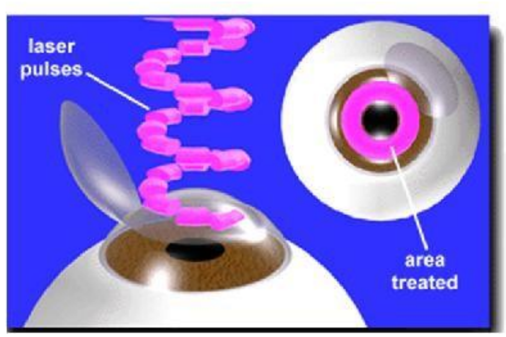
uses an excimer laser to

remove thin layer of the cornea to correct nearsightedness, farsightedness, and astigmatism.



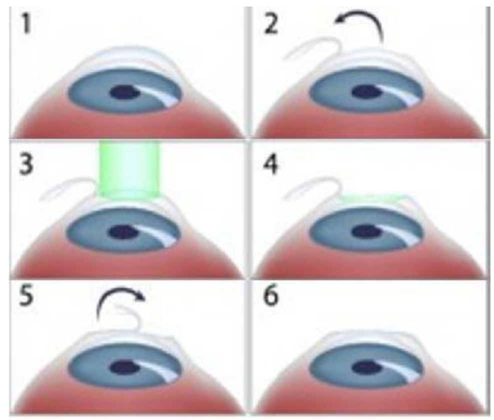
For nearsighted, more corneal tissue is removed from the center than from the sides to flattens the cornea and correct vision

For someone who is farsighted, more corneal tissue is removed from the sides than from the center. This makes the cornea steeper, and thus correcting the farsightedness.



Laser in Situ Keratomileusis (LASIK) القرنية بالليزر تصحيح تحدب

A surgical instrument is used to cut a flap in the surface of the cornea, which is then folded back rather than removed. An Excimer laser is used to change the shape of the cornea, after which the flap is folded back down to its original position and held in place by natural suction.

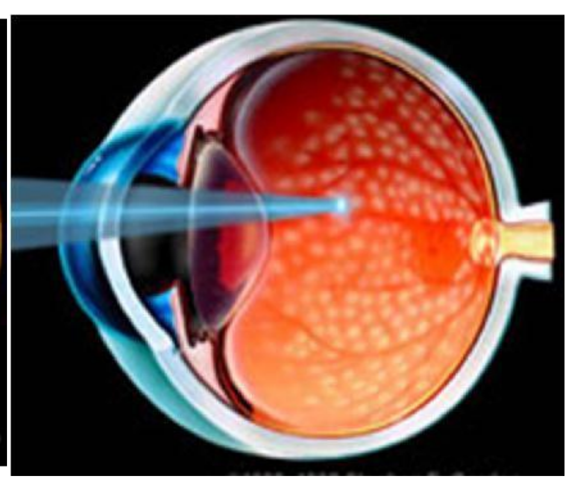


Photocoagulation therapies for Retinal diseases

The use of lasers as a heat source to coagulate retinal tissue is one of the most important and widely adopted ophthalmic laser applications. The argon laser was introduced at both 488 and 514.5 nm and offered improved beam stability. The irradiance of the Ar^+ laser treatment is approximately 100 W/cm^2 with an application time of 0.1–1 second. Photocoagulation has proven most useful in the treatment of diabetic retinopathy الشبكية السكري
اعتلال

In some people with diabetic retinopathy, blood vessels may swell and leak fluid. In other people, abnormal new blood vessels grow on the surface of the retina. Blood vessels damaged from diabetic retinopathy can cause blurring vision or vision loss.

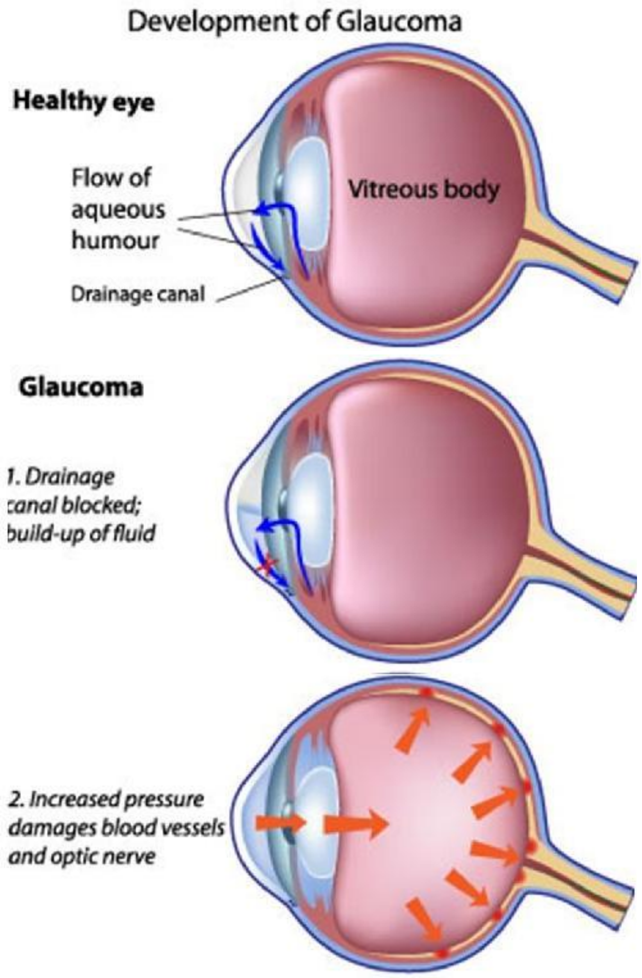
Laser photocoagulation is a surgical procedure which utilizes a powerful, very precisely focused beam of light (laser) to create microscopic thermal burns and treat abnormalities of the fovea and/or retina. Treatment is to seal specific leaking blood vessels in a small area of the retina It usually consists of

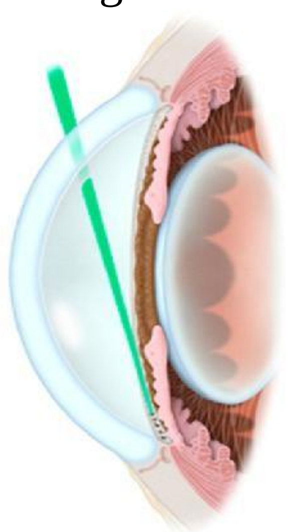


Glaucoma treatment -Selective Laser Trabeculoplasty (SLT)

Glaucoma is a group of eye diseases causing optic nerve damage. Optic nerve carries images from the retina to the brain so we can see.

In glaucoma, eye pressure plays a role in damaging the nerve fibers of the optic nerve. When a significant number of nerve fibers are damaged, blind spots develop in the field of vision. Once nerve damage and visual loss occur, it is permanent. Most people don't notice these blind areas until much of the optic nerve damage has already occurred. If the entire nerve is destroyed, blindness results. Continuous argon, krypton, or dye lasers are used to burn a small hole through the iris



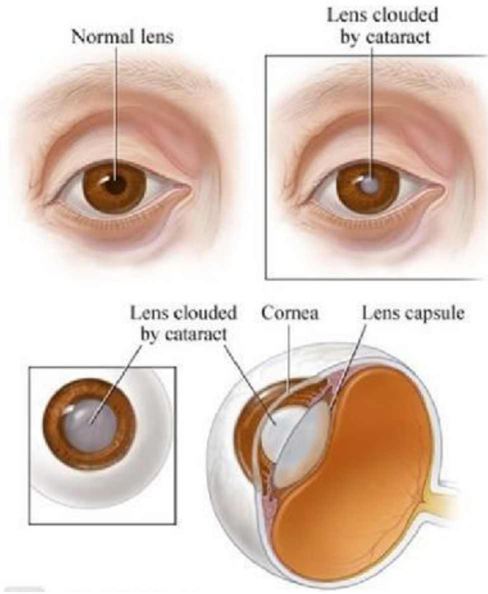


g in the peripheral iris allows an alternate eous humor when its normal pathway is blocked.

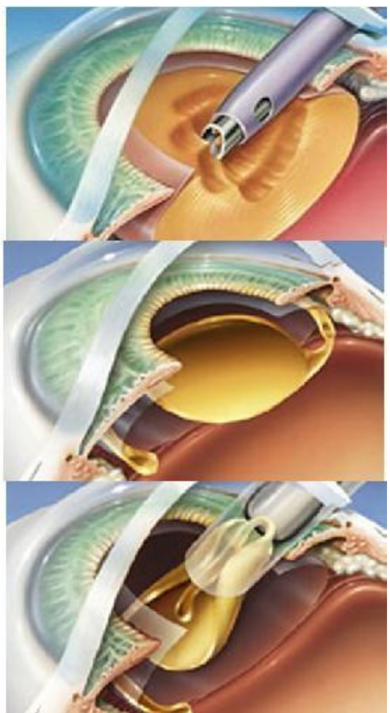
Cataract treatment

Cataract is a clouding of the lens inside the eye which leads to a
decrease in vision that most commonly due to aging

Cataract surgery is the removal of the natural lens of the eye and an artificial lens is implanted. A thin probe is inserted through a small hole 2.85 millimeters wide on the side of the cornea. Then a small phaco tip (a medical machine helps in removal of eye lens) is placed in the eye which vibrates at a high of speed by ultrasonic..



Ultrasonic vibration breaks the cataract into pieces, and are suctioned out of the eye through the phaco tip. After all the cataract material is removed, the lens capsule is left intact and the artificial lens is carefully placed inside. Once injected into the eye, the artificial lens unfold within the capsular bag and begin focusing light on the retina.



By directing YAG laser into optical fiber, cataract removal could be performed endoscopic ally. The optical penetration depth can be less than 1 μm by choosing IR wavelength corresponds to the absorption peak of lens tissue (2.9–3.0 μm). The laser energy is then confined to a very small volume, preventing photons from reaching other intraocular structures such as the retina or the cornea. The short penetration depth of mid-IR laser radiation also minimizes thermal damage to adjacent tissue, providing the pulse duration is shorter than the thermal relaxation time of the lens tissue.