# Laser Safety Training Manual

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# 1 INTRODUCTION

This training manual is intended for the users of open beam class 3B and class 4 lasers. It is mainly written for academic research laboratory environments i.e. university laboratories users but can be successfully used for the laser safety training of users in industry or medical applications. The content covers the requirements of the American Standard for the Safe Use of Lasers (ANSI Z-136.1) for the training of the personnel routinely working with or potentially exposed to Class 3B or Class 4 laser radiation.

The training manual is based on laser safety training lectures presented for more than 15 years to students, staff, and faculty at the University of Toronto.

The manual covers basic notions regarding light and optics at the level considered necessary to understand the principles of laser operation and the safety aspects of working with open beam high-class lasers. The fundamentals of laser operations – physical principles, construction, types of lasers, modes, pulse shapes, etc.– are treated in greater detail. Starting from the general principles of health and safety, the principles of laser safety are discussed in section 4.5 with the laser classification. In laser safety literature, hazards to eyes and skin directly connected to a laser beam are called beam hazards. These are explained together with fundamental notions about the anatomy of an eye and the skin and their function. All other hazards encountered in a laser workplace are covered in the chapter on non-beam hazards.

In the vision of the authors, the user's first defence against hazards is his or her knowledge of lasers. Based on this, training on laser safety is essential for controlling hazards and reducing the risks of working with open beam high-class lasers. Engineering, administrative, and procedural controls as well as personal protective equipment are covered in the chapter dedicated to laser hazards control. Principles of beam alignment and beam measurements are explained in chapter 8.

A solid laser safety program is the best method to prevent injuries to ensure compliance with regulations. The main components of the program are: responsibilities, inventory, training, inspections, audits, commissioning and decommissioning lasers and laser rooms, and the duties and responsibilities of the Laser Safety Officer.

Principles of laser accident investigations learned lessons, improvements of the program as a result of incidents and accidents, are presented in the last chapter.

DISCLAIMER

This training manual uses materials (tables, pictures, diagrams, etc.) available on the world wide web. All materials used are taken from pages anyone can access free, without a password.

# 2 LIGHT

*Figure 1-1: Optics is Light Work.*

This picture was taken from a door of one of the laser labs in a department at the University of Toronto. If the word “OPTICS” is replaced by “LASER”, it is easy to understand why there is a need to have basic notions of the nature of light, light emission, absorption, reflection, refraction to learn about laser safety.

## 2.1 Nature of light

For many centuries, the nature of light was a mystery, rising many controversies. During the XVII$^{th}$ century, two main theories were developed. In the first one, the light was considered as being formed of particles of matter and in the second one, the light was considered a wave. Both theories were successful in explaining some properties of light.

A **wave** is a disturbance that transfers energy through matter or space. Waves consist of oscillations or vibrations of a physical medium or a field, around relatively fixed locations. There are two main types of waves: mechanical and electromagnetic. Mechanical waves propagate through a physical medium, whose matter is being deformed. Restoring force of the physical medium then reverses the deformation and transmit the deformation further into the medium.

Sound waves propagate via air molecules colliding with their neighbours. When molecules collide, they also bounce away from each other. This keeps molecules from continuing to travel in the direction of the wave. Sound waves are mechanical longitudinal waves.

The source of the wave is the point in the physical medium that moves first. If the movement of the source is periodic (repeats after a certain time) the points of the

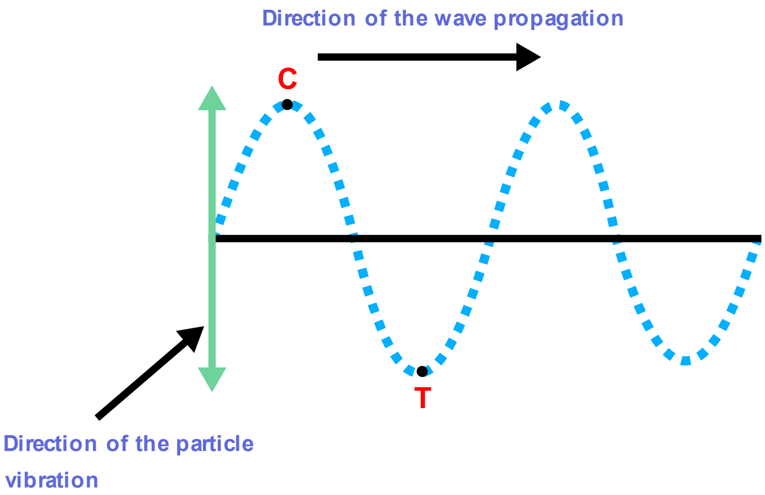


*Figure 2-2: Typical shape of a longitudinal wave. C showing the crest and T showing the trough.*

physical medium will repeat the movement of the source with a certain delay. This delay depends on the speed of propagation of the wave in the physical medium.

Transverse waves are waves that propagate in a direction perpendicular to the direction of oscillations/vibrations.

Waves propagate in a string when the perturbation happens in a direction perpendicular to the string. This is an example of a mechanical transverse wave.

Longitudinal waves propagate in the same direction as the oscillations/vibrations.

The period of the oscillation is the time after which the motion repeats and is noted with "T". The frequency of the oscillation is noted with *"f"*, which is equal to 1/T, and measures the number of oscillations in a unit of time. In the International System of Units, the period

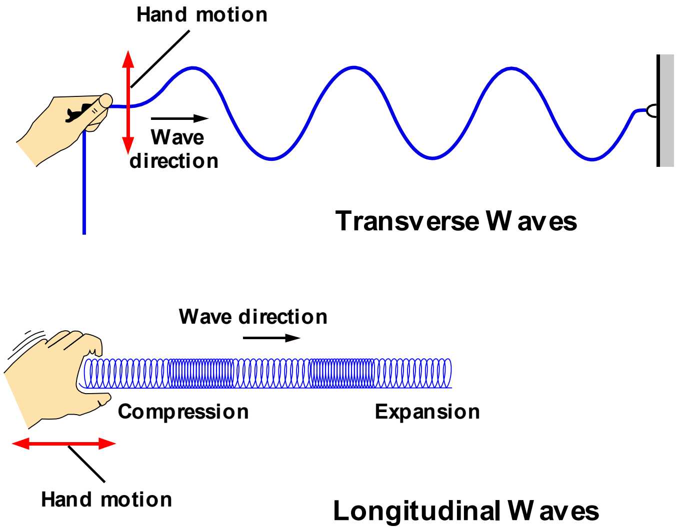


*Figure 2-3: Transverse (top) and longitudinal (bottom) waves.*

is measured in seconds (s) and the frequency in $s^{-1}$. The unit for frequency is also called hertz (Hz).
In one period T, the oscillation propagates in the medium a distance called the wavelength. The wavelength is noted with “$\lambda$” and is measured in meters (m). With the speed of propagation of the wave in the medium “$v$”, we have the following equation:

$$\lambda = vT = \frac{v}{f}\ ; v = \frac{\lambda}{T} = \lambda f$$

The set of points in the medium that starts oscillating at a given time is called the wavefront. If the oscillation is sinusoidal, these points on the wavefront oscillate in the same phase. The wavefront can be a point (if the wave is transmitted in a linear medium like the ones in a string), a circle if the waves are transmitted in a 2-dimension medium, or a sphere when waves are transmitted in a 3-dimensional medium.

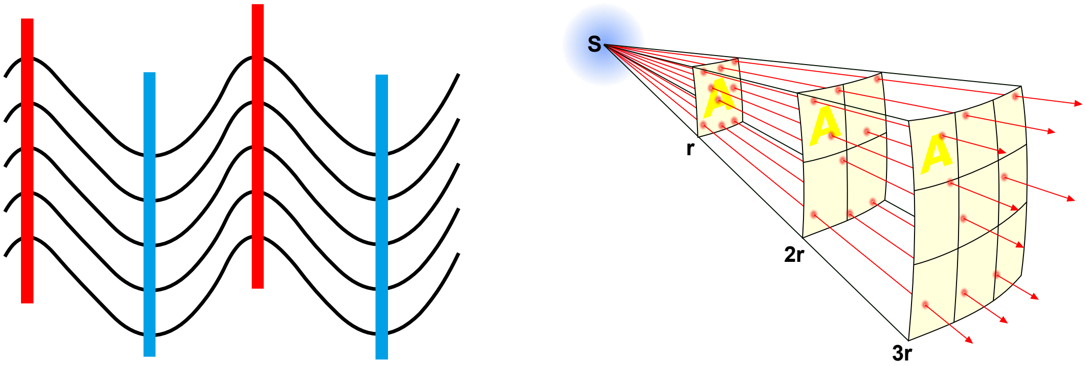


*Figure 2-4: Wavefront in a 2-dimensional medium (left) and 3 dimensional medium (right).*

In the XIXth century, electromagnetic waves were discovered. These waves are generated by moving electrical charges.

An electric charge generates an electric field in the surrounding space. If the electric charge moves (say it vibrates back and forth), then the motion will be transferred to the electric field lines, which will become wavy. Ørsted discovered that a moving electric charge generates a magnetic field. The magnetic field lines also become wavy when the electric charge moves back and forth. The combined electric and magnetic fields waves reinforce one another. This perturbation can be transmitted at distance from the original moving electric charges, as electromagnetic waves. Electromagnetic waves can travel through a physical medium, but also through a vacuum.

The electric and the magnetic fields created by the moving of charged particles oscillate perpendicular to each other.

Classical physics proved that light is an electromagnetic wave. The electromagnetic wave, and therefore light, is transmitted in a direction perpendicular to the oscillation of electric field (**E**) and magnetic field (**M**). This direction is called a light ray. The speed of light in a vacuum is noted as “$c$” ($c \approx 3*10^8$ m/s). The wavelength, the frequency and the speed of light relate to the formula $\lambda = c*f$. The speed of light in a physical medium “$v$” is

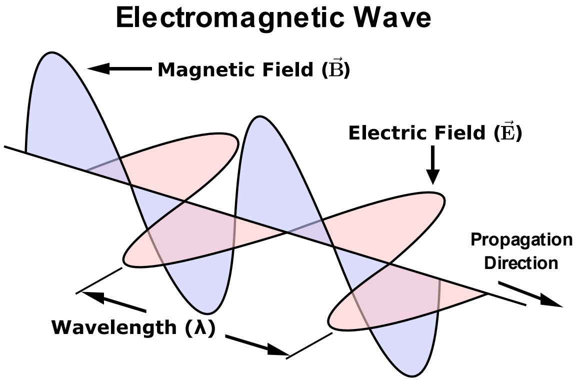


*Figure 2-5: Electromagnetic wave.*

lower than the speed of light in the vacuum. The ratio between the two speeds is called the index of refraction of the physical medium and is noted with “$n$” ($n$ is a dimensionless number greater than 1).

$$n = \frac{c}{v}$$

By the end of the XIX$^{th}$ century even though the electromagnetic wave theory of light was widely accepted, it could not explain the energy emission of a black body and the newly discovered photoelectric effect (emission of electrons when some metals were illuminated).

The emission of the black body was explained by Max Planck in 1900. At the core of his explanation stays the idea that the emission of electromagnetic radiation is possible only in multiples of a fundamental unit he called quanta of energy.

In 1905 Albert Einstein proposed that not only emission of electromagnetic radiation is quantized, but also absorption and transmission.

The quanta of electromagnetic energy were later called photons. The energy of a photon relates to the frequency of the electromagnetic field with the formula:

$$E = hf$$

where “$h$” is the Plank’s constant (a quantum of action equal to 6.626 * $10^{-34}$ J*s), and “$f$” is the frequency of the electromagnetic radiation measured in Hz.

These new ideas led to the creation of quantum physics. Quantum physics revolutionized the understanding of the atomic and sub-atomic processes and generated applications that affect every aspect of civilization.

Atomic and sub-atomic particles behave in many ways similar to macroscopic bodies. For example, these have a certain energy, mass, speed, or momentum. However, these particles behave differently than macroscopic bodies in many aspects. As such, sub-atomic particles have a specific quantum property called spin. The spin has no similar classical physics property. It is measured by a number that can be positive or negative;

and can have values either an integer (like 0, 1, -1, 2, -2, etc.) or multiples of ½ (1/2, -1/2, 3/2. -3/2, etc.).

The atomic and sub-atomic particles with integer spin behave differently from the ones with half spins. To explain this difference, Paul Dirac used an idea that came from Satyendra Nath Bose. Bose explained that throwing two coins that are both nickels gives a different result than the one obtained by throwing a nickel and a dime. Even though the outcome events are similar (tail-tail, tail-head, head-tail, or head-head), and the probability of each event is the same, the two situations are different.

Dirac called particles with integer spin bosons and the particles with half spin fermions. Bosons obey a statistical law called Bose-Einstein, and fermions a statistical law called Fermi-Dirac.

In 1940 Wolfgang Pauli formulated the exclusion principle that in a quantum system no two fermions can occupy the same quantum state. The exclusion principle explains how electrons, which are fermions, are arranged inside an atom.

All fermions obey the exclusion principle, but bosons do not. Experiments show that photons are bosons. Since photons do not obey the Pauli exclusion principle, it is possible to create a system in which all photons occupy the same quantum state. Due to the process of stimulated emission (see chapter 3), all photons in laser pulse are in the same quantum state. They have the same direction, the same energy (frequency and wavelength), the same phase and polarization.

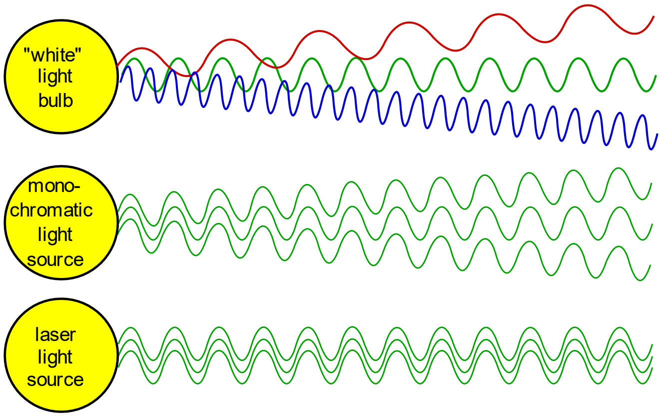


*Figure 2-6: Coherent and non-coherent light sources.*

The fundamental difference between laser light and light from a regular bulb is that laser light is one wave (many photons in the same quantum state), while regular light is a quantum system with many states mixed. This fact makes laser light much more dangerous than non-coherent light.

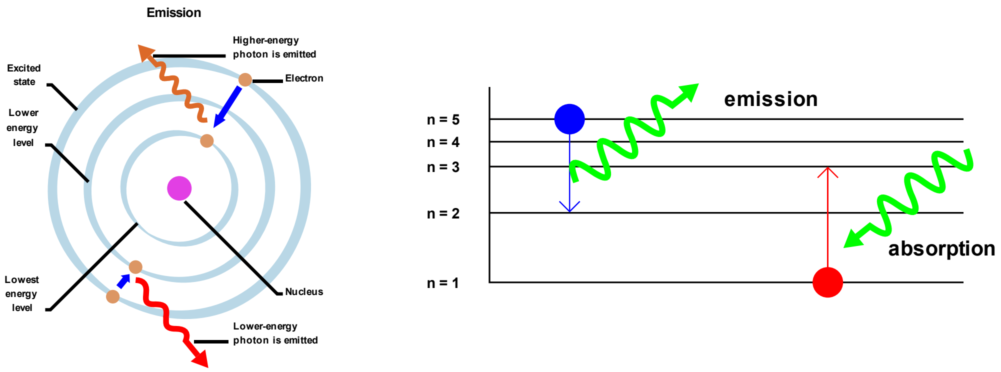


*Figure 2-7: Absorption and emission of photons by electrons changing energy levels.*

## 2.2 Emission and absorption of light

The acronym LASER stands for Light Amplification by Stimulated Emission of Radiation. In 1905 Albert Einstein answered the old question "How light is produced?" by explaining the photoelectric effect.

Excitation of atoms can be caused, for example, by an increase in temperature.

Depending on the temperature, many atoms in a light source (like an incandescent bulb) will be in the fundamental state, and others will be in excited states. Atoms in the excited state i.e. with electrons in a higher energy state, the de-excitation occurs at a random moment, and radiation (light) is emitted. This process is known as the spontaneous emission of radiation. Since emission happens randomly, from different atoms, the radiation is emitted in all directions with various energies and at different moments. The emitted radiation is non-coherent; it cannot produce interference (see section 2.3.5). The light emitted in this way has different frequencies (wavelengths), different phases, different polarizations, different directions.

In 1917 Einstein publishes the article "The Quantum Theory of Radiation" in which he explains the stimulated emission of radiation.

When a photon passes nearby an atom excited in the same energy level as the energy of the photon, de-excitation of the atom occurs. This is called the stimulated emission of radiation. The second photon has the same direction, energy, phase, and polarization as the first photon.

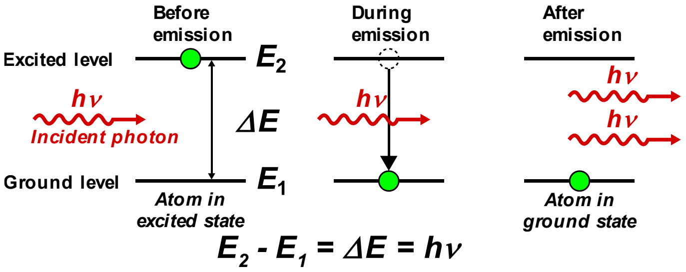


*Figure 2-8: Stimulated emission of radiation.*

A system with more atoms in an excited state than in a ground state is called a system with population inversion.

### Boltzmann distribution

The numbers of atoms/molecules of a system at temperature *T*, with two energy states (the ground state with energy $E_1$ and an excited state with energy $E_2$) $N_1$ and $N_2$ obeys the Boltzmann distribution

$$\frac{N_2}{N_1} = e^{-(E_2 - E_1)/_{kT}}$$

where *k* is the Boltzmann's constant and *T* is the temperature. At room temperature, $N_2$ is close to zero. At higher temperatures, $N_2$ increases. When trying to obtain $N_2$ higher than $N_1$ using different types of excitations e.g. by increasing the temperature of the system or by pumping light with the required wavelength into the system, the probability of absorption becomes equal to the probability of emission. At some point, the system will reach saturation and the number of atoms absorbing energy is equal to the number of atoms emitting radiation. At this point $N_2 = N_1$ and the temperature of the system is infinite. No population inversion can be obtained in a system with two levels of energy.

Population inversion can be obtained in a system with 3 or more states (see section 3.1).

The stimulated emission of radiation can be an exponential process. If in a medium with population inversion, a photon is emitted and this photon passes near an excited atom, it will stimulate the de-excitation of that atom. As part of the de-excitation process, a second photon will be emitted. This second photon will be in the same quantum state as the first one. As a result, two photons in the same quantum state are present in the medium. These two photons can create four photons and so on. This cause an exponential increase in the number of photons in the same quantum state.

Such stimulated emission of radiation in a medium in which the population inversion is obtained is the basic functioning principle of the laser.

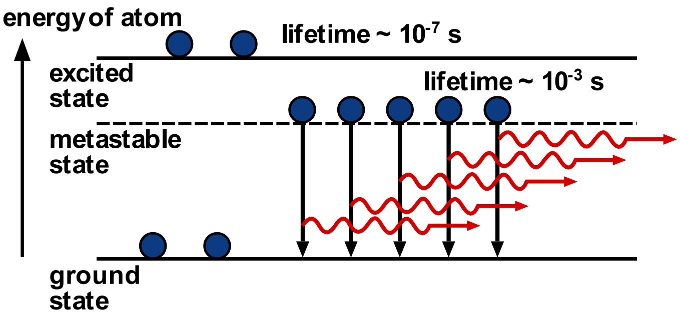


Figure 2-9: Population inversion and stimulated emission.

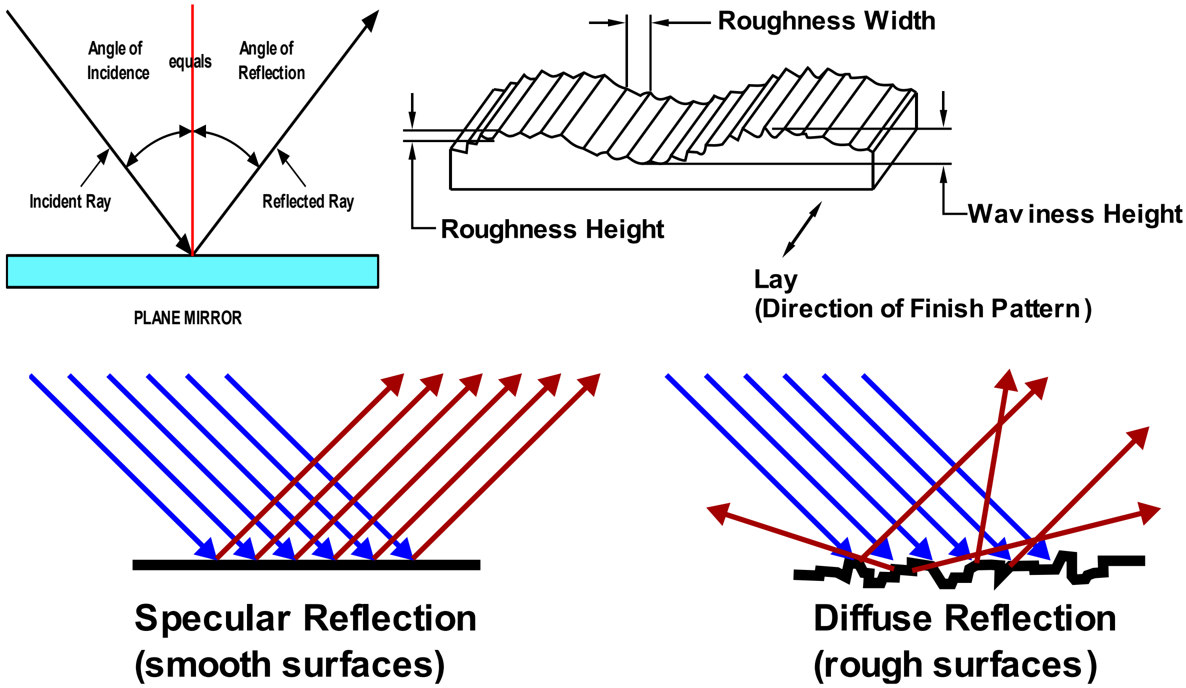


*Figure 2-10: Example of specular reflection. The angle of reflection is equal to the angle of incidence (top-left). Roughness of the surface (top-right). Comparison of specular and diffuse reflection. After a diffuse reflection the beam is not preserved (bottom).*

## 2.3 Properties of light

To understand the functioning of mirrors, lenses, prisms, beam splitters, optical fibres, and other optical instruments used in a laser laboratory, laser users must understand some fundamental properties of light.

### 2.3.1 Reflection of light

When light hits a plane mirror it is reflected at an angle of reflection equal to the angle of incidence. This type of reflection is called specular reflection. In specular reflection, the laser beam is preserved.

When light hits a rough surface, the reflected light travels in different directions. This type of reflection is called diffuse. Following a diffuse reflection, the laser beam is replaced by a luminous spot.The type of reflection (specular or diffuse) depends on the type of material and the roughness of the interface. For example, a shiny metal surface is more likely to cause specular reflection while a marble surface will cause a diffuse reflection.

The roughness $R_a$ of a surface is defined as:

$$R_a = \frac{1}{n}\sum_{i}^{n} |y_i|$$

A specular reflection happens when λ is greater than $R_a$ and a diffuse reflection when λ is comparable or smaller than $R_a$. A He-Ne laser (λ = 633 nm) will produce a specular reflection on a metallic surface with a roughness of 100 nm, and a diffuse reflection on a wall with a roughness of 1000 nm. A $CO_2$ laser (λ = 10,600 nm) will create mostly a specular reflection on a surface with a roughness of 1000 nm.

### 2.3.2 Refraction of light

As mentioned in 2.1, the index of refraction of a transparent material “n” is a dimensionless number greater than 1. When light passes from one transparent material with an index of refraction $n_1$ to another material with the index of refraction $n_2$, the direction of the propagation of light changes. This process is called refraction. Refraction

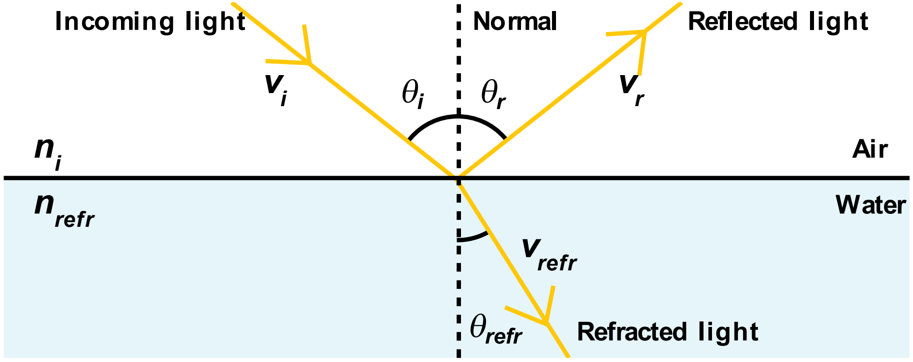


*Figure 2-11: Reflection and refraction.*

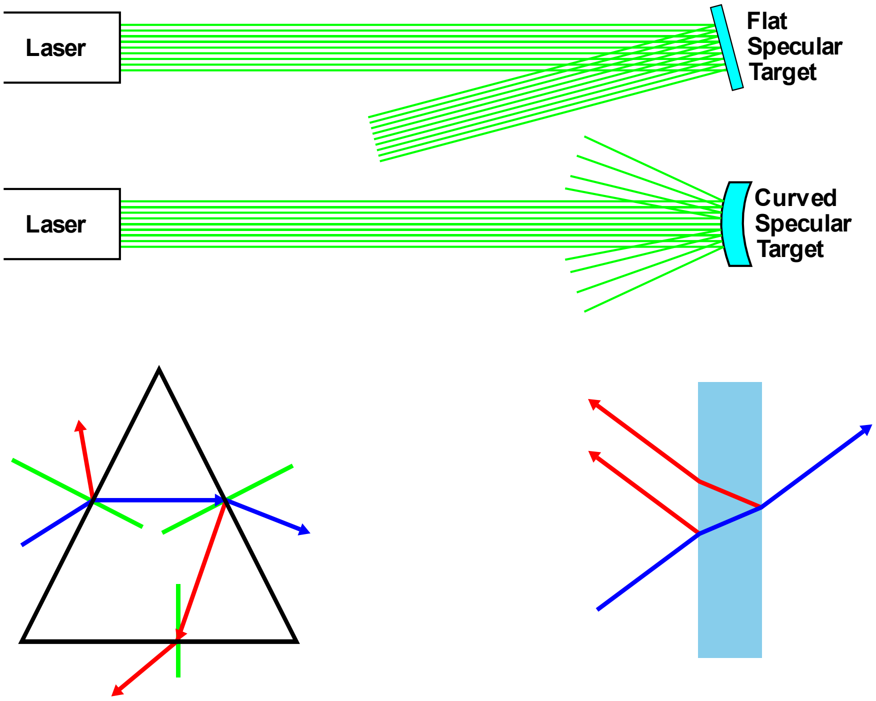


*Figure 2-12: Stray beams from flat and curved surfaces (top). Stray beams from prisms and windows (bottom).*

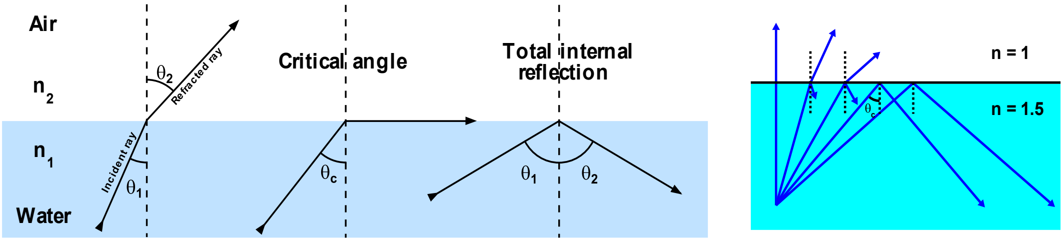


Figure 2-13: Total internal reflection.

is always accompanied by reflection. The amount of light that is reflected depends on the two materials, the polarization of light and the angle of incidence.

At the interface between air and glass, when the incident ray is normal (angle of incidence = 0°), 4 % of the light will be reflected. When the light passes perpendicular through a window approximately 8 % is reflected. When the angle of incidence is greater than 0°, more light will be reflected. Windows in a laser laboratory, if any, must be covered to protect not only individuals from outside the laboratory but also individuals inside because of reflecting properties.

When the reflected ray of a laser beam is undesired, it is called a “stray beam”. Most laser eye accidents are caused by stray beams.

A user may pay attention to the main beam and may not think about stray beams. Stray beams often get neglected because they are, in general, less intense. However, these can carry enough energy/power to create a significant hazard. Stray beams from a flat surface are particularly dangerous.

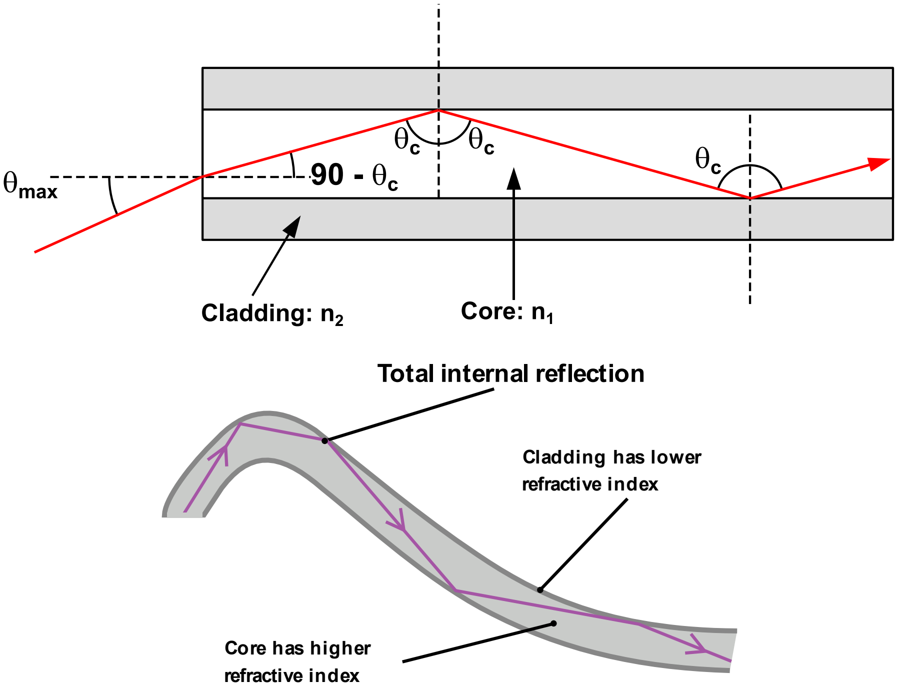


Figure 2-14: Optical fibre core and cladding. The index of refraction of the core is greater than the index of refraction of the cladding ($n_1 > n_2$).

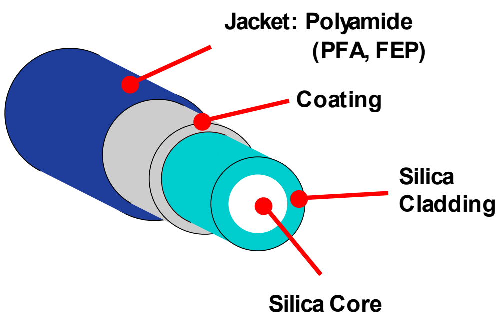


*Figure 2-15: Cross-section of an optical fibre showing the different parts. Silica core, Silica classing, coating, and jacket.*

When light travels from a material with a higher index of refraction $n_1$ to a material with a lower index of refraction $n_2$, the angle of refraction is greater than the angle of incidence.

If the angle of incidence is increased above a certain critical value, all light is reflected in the first medium, and no light passes to the second one. This phenomenon is called total internal reflection. The value of the critical angle $\theta_c$ can be calculated used the following equation:

$$sin\,\theta_c = \frac{n_2}{n_1}$$

Total internal reflection is the basic principle used in fibre optics to transmit laser light.

The refractive index of the fibre core must be bigger than the refractive index of the cladding.

A coating and a jacket cover the optical fibre core and cladding to protect from physical damage.

To maximize the amount of light entering the optical fibre the laser beam must be within the acceptance cone of the fibre. Based on the use, the optical fibres have jackets made of different materials.

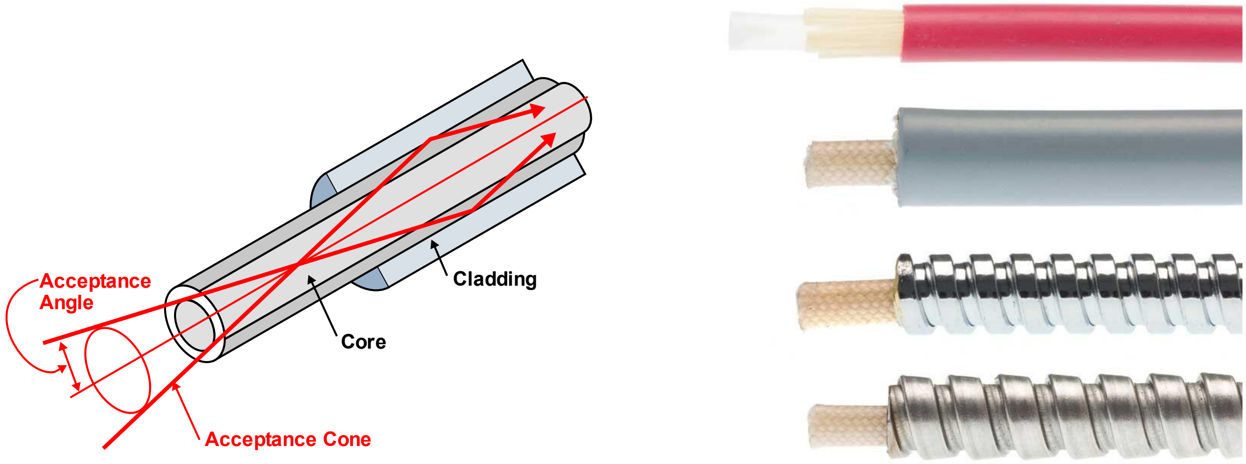


*Figure 2-16: Optical fibre acceptance cone (left). Different types of optical fibre jackets (right).*

### 2.3.3 Absorption of light

When radiation passes through a transparent material it is partially absorbed.

$$OD = -\log_{10}\left(\frac{I_1}{I_0}\right)$$

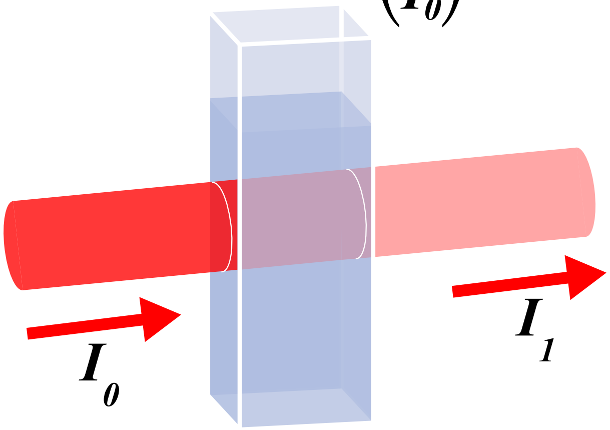


Figure 2-17: Absorption of light by a semi-transparent material.

Transmission T is defined as the ratio between the intensity of light that is transmitted and the incident light.

$$T = \frac{I}{I_0}$$

The colour of the objects is given by the scattered light. When white light is directed to a blue object, for example, only blue light is reflected, and the rest of the colours are absorbed.

### 2.3.4 Scattering of light

Transmitted or reflected light can be scattered. The process in which the wavelength of the incident light and the scattered light are the same is called elastic or Rayleigh

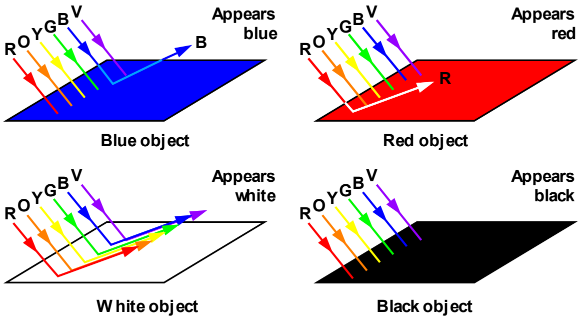


Figure 2-18: Reflection of multiwavelength (white) light in surfaces of different colours.

scattering. Inelastic scattering is the process in which the wavelength of the scattered light is different from the incident light's wavelength (Raman effect – see section 2.4.1)

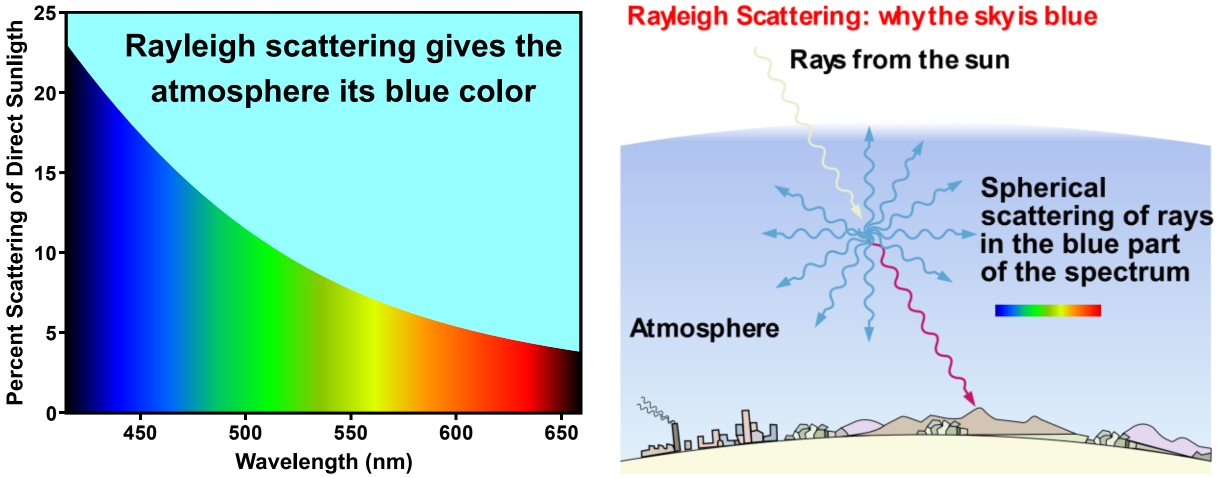


*Figure 2-19: The efficiency of the Rayleigh scattering depends on the wavelength (left). Rayleigh scattering is the reason why the sky is blue (right).*

Rayleigh scattering is predominant when the wavelength is much greater than the dimension of the particles causing the light scattering. Since the light scattering in the air is caused by its constituent i.e. water molecules, $O_2$, $N_2$, and $CO_2$ (with sizes smaller than 1 nm), the scattering of light coming from the Sun is mostly Rayleigh. Rayleigh scattering is inverse proportional to the $\lambda^4$. Therefore, light with a shorter wavelength (like violet and blue) will be scattered more than light with a longer wavelength (like yellow or red). This explains the blue colour of the sky.

As a result of the interaction of light with a medium, the following phenomena are possible: reflection, transmission, absorption or scattering. All these phenomena can occur at the same time and the efficiency of each phenomenon will depend on the interaction between the material and the light which also depends on the properties of the material and the wavelength of the light.

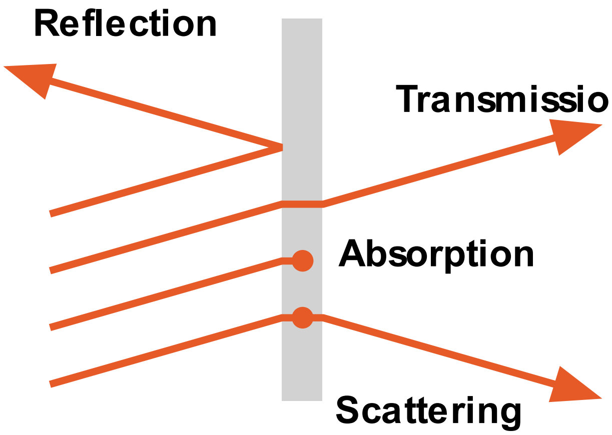


*Figure 2-20: Different types of interactions between light and matter.*

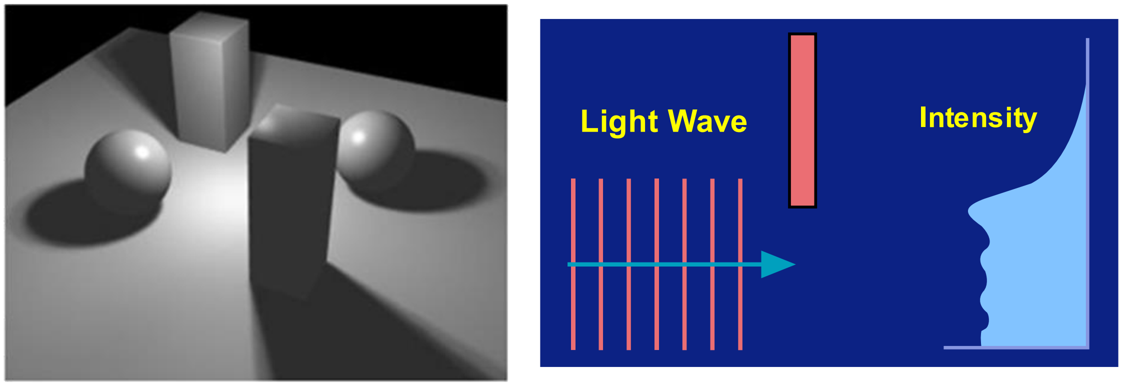
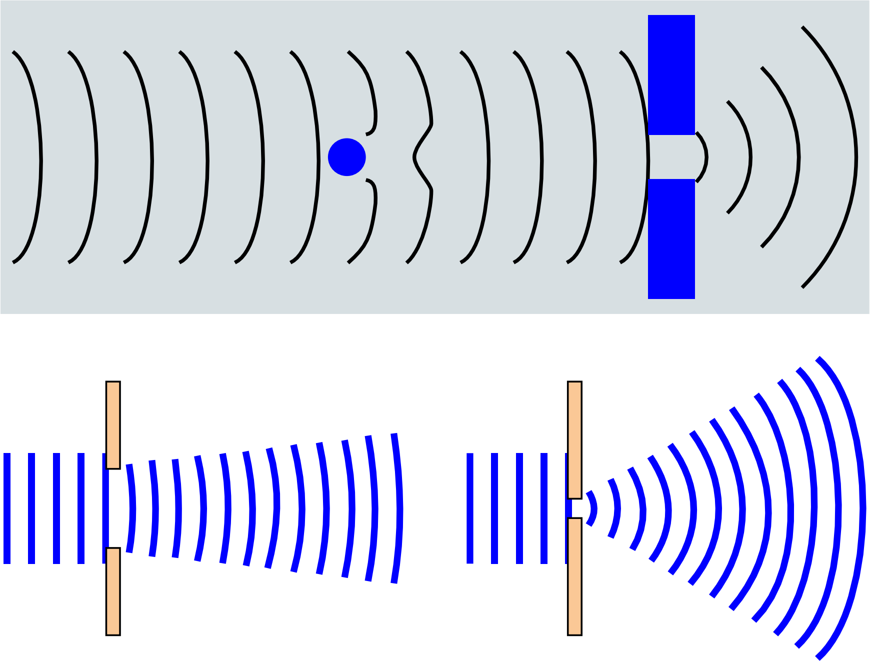


Figure 2-21: Diffraction of light around objects.

### 2.3.5 Diffraction of light

In the wave theory of light when light approaches an obstacle or a slit, light can bend and reach into the region of the geometrical shadow.

The intensity of light into the shadow region decreases further from the obstacle. Light can go around a small obstacle.The smaller is the slit, the greater is the diffraction effect.



**Wide gap - small diffraction effect** **Narrow gap - large diffraction effect**

Figure 2-22: Diffraction of light around small obstacles (top). Effect of the slit width in the diffraction of waves. A wider slit produces a smaller distortion of the wavefront (bottom-left). A narrower slit produces a greater distortion of the wavefront (bottom-right).

### 2.3.6 Interference of light

The interference of light is the phenomenon in which two coherent (with the same wavelength) waves combine to form a resultant wave with an amplitude equal to the combination of the two original amplitudes. The resultant amplitude depends on the phase difference between the original waves.

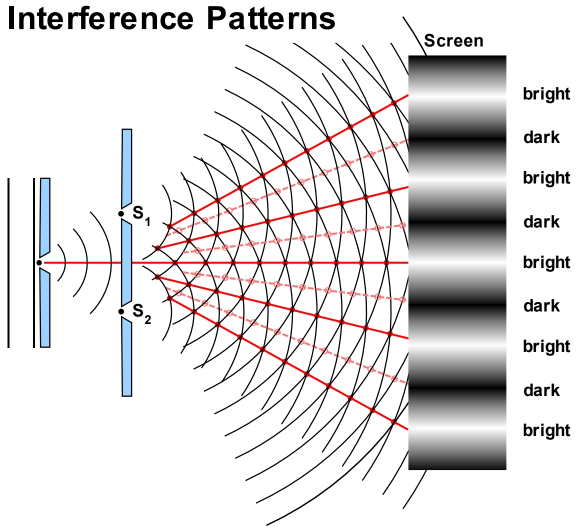
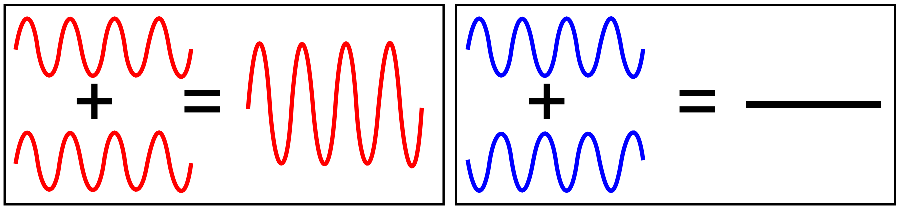


*Figure 2-23: Interference pattern created by two slits. Similar configuration to Young's double-slit experiment.*

In the Young double-slit experiment light with a certain wavelength passes through a small opening resembling a point source. Two small slits are located in front of the point source, creating two identical light sources $S_1$ and $S_2$. The light coming from sources $S_1$ and $S_2$ interact with each other and create an interference pattern. This pattern is a succession of bright and dark light fringes.

When the two waves interference in phase, the resulting wave will have an amplitude equal to the sum of the original amplitudes (constructive interference).



**Constructive Interference** **Destructive Interference**

*Figure 2-24: Constructive (left) and destructive (right) interference of an electromagnetic wave.*

If the two waves interfere out of phase, the resulting wave will have zero amplitude (destructive interference).

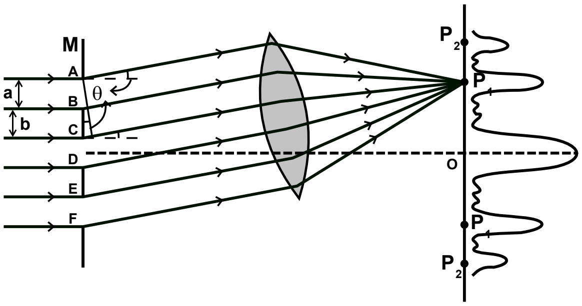


*Figure 2-25: Diffraction pattern created by a transmission diffraction grating and a lens.*

An interference pattern like the one obtained in a Young double-slit experiment can be also obtained with a grating. A grating is a succession of grooves or slits at equal distances.

In grating diffraction, the central maximum is surrounded by smaller maximum fringes.

The interference of light is also possible when light is reflected by a thin layer of transparent material.

In Figure 2-26, if A and B are two rays from the laser beam, the reflection of ray A passes twice through the thin layer and creates a phase change compared with ray B. When the reflection of ray A interferes with the one of ray B, the result can be a maximum or a minimum (or something in between), depending on the thickness of the layer.

If the layer thickness is such that produces a shift phase of 180° a minimum interference is obtained. This happens when the thickness of the film is equivalent to λ/4.

The thin film layer destructive interference is used in laser safety to protect the user against stray beams (see section 2.3.2).

Constructive interference occurs when the thickness of the thin layer is the equivalent of λ/2. Using optics covered with a thin layer intended for a different wavelength can increase the dangers of stray beams.

$$n_0 < n_f < n_s$$

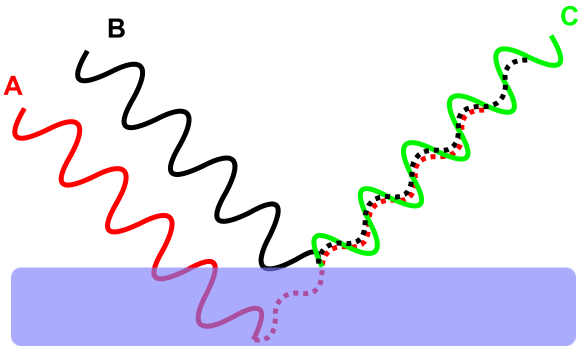


*Figure 2-26: Interference by reflection in a think layer.*

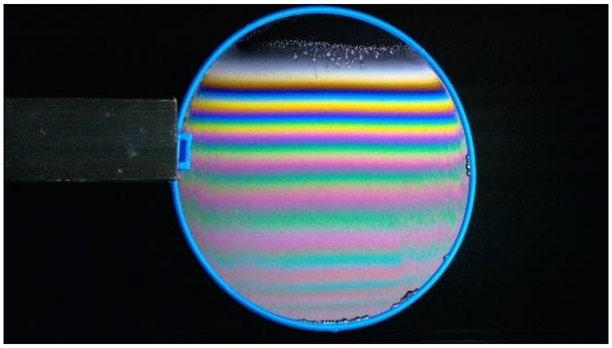


*Figure 2-27: Interference pattern created by a thin film.*

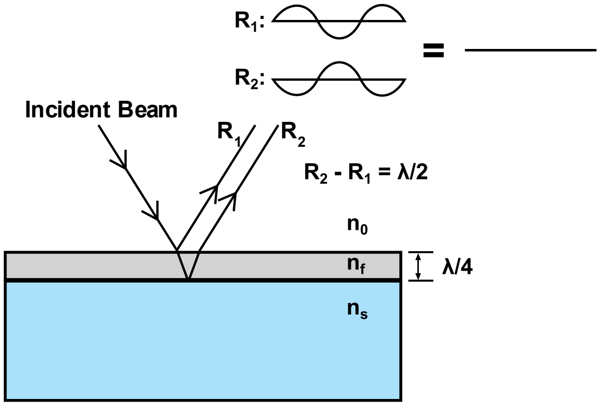


*Figure 2-28: A thin layer of a dielectric material of the proper thickness can create a total destructive interference. Antireflex coatings for optical elements are based on this phenomenon.*

Interference produced by thin layers is also used to make dielectric mirrors (also called Bragg mirrors). Multiple layers of thin dielectric material are used to create mirrors with ultra-high reflectivity (>99.9%) for certain wavelengths (by using constructive interference). These mirrors can be transparent or show very low reflectivity for wavelengths for which there is not constructive interference.

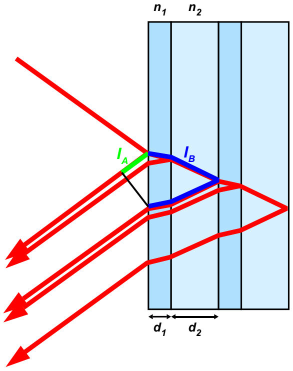


*Figure 2-29: A thin layer of a dielectric material of the proper thickness can create a total constructive interference. High reflectivity Bragg mirrors are based on this phenomenon.*

### 2.3.7 Dispersion of light

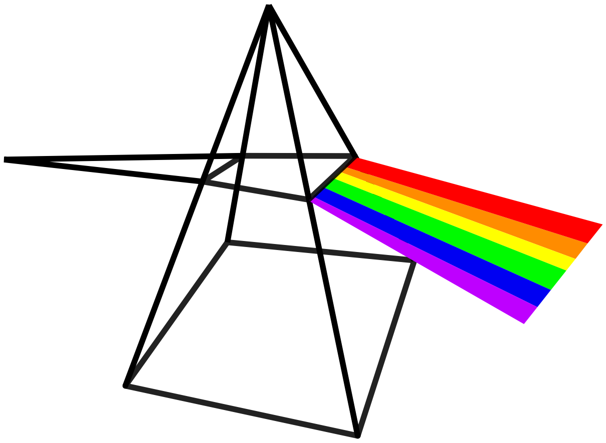


*Figure 2-30: Dispersion of light in a prism.*

The light coming from the Sun, from an incandescent bulb, or a flame, is a combination of different wavelengths. Indices of reflection of materials in the visible light range spectrum slightly depend on the wavelength of the light. During the refraction process, the angle at which the light bend depends on the wavelength. This creates the effect called light dispersion. Light dispersion is the spatial separation of the white light beam into its components of different wavelengths.

The same process happens during the diffraction of light. If a grating is illuminated with a white light the pattern described in section 2.3.6 will have a succession of maxima with different colours. The diffraction on a grating can also be obtained through reflection (Figure 2-31).

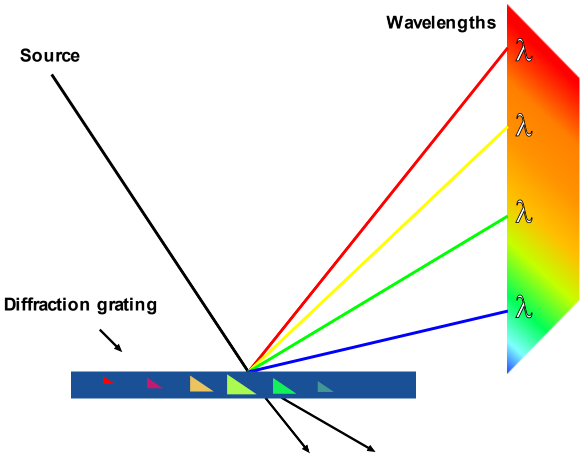


*Figure 2-31: Light dispersion by reflection in a diffraction grating.*

### 2.3.8 Polarization of light

Polarization is the property of waves to oscillate in more than one direction. Longitudinal waves are not polarized (the oscillations can only move in the direction of the transmission of the wave). Transverse waves can be polarized (oscillations are forced to move in one direction).

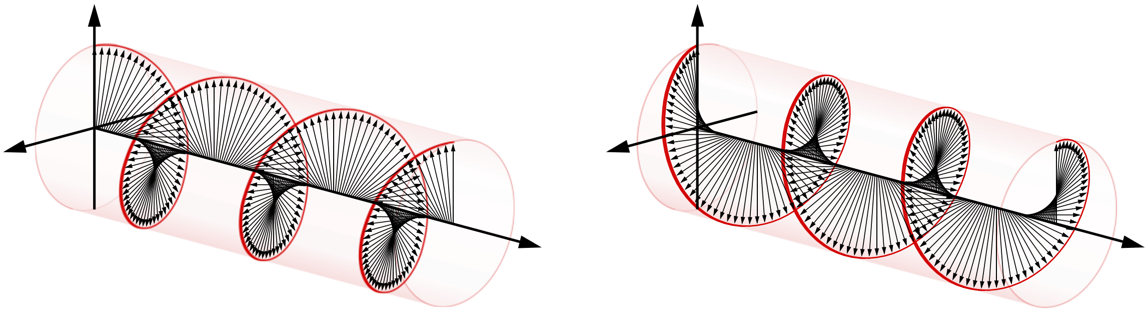


Figure 2-32: Left-handed circularly polarized light (left) and right-handed circularly polarized light (right).

A polarizer is a device that forces a transverse wave to oscillate only in one direction by blocking all other directions of oscillation. After an unpolarised transverse wave passes through two perpendicular polarizers the wave is completely stopped. This type of polarization is called linear polarization since, after the wave passes through the polarizer, the vector oscillates in one direction.

When the oscillating vector of the wave rotates only in one direction (counterclockwise or clockwise), the wave is called circularly polarized. If the oscillating vector rotates counterclockwise the waves are called left hand polarized, if it rotates clockwise the waves are called right-hand polarized.

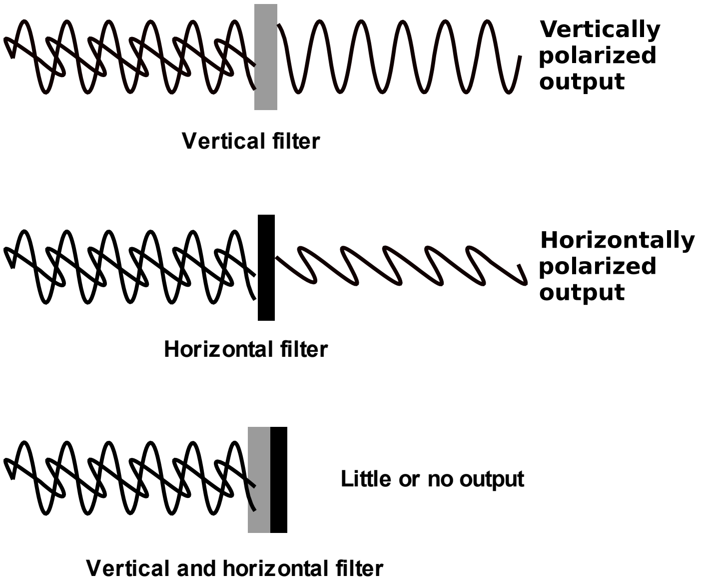


Figure 2-33: Polarizers can filter light based on their orientation with respect to the incident polarization. Polarizer filtering out horizontal polarization (top), vertical polarization (center). No light passes through two polarizers oriented perpendicularly (bottom).

Light is a transverse wave that can be polarized linear, circular or a mixture of both (elliptical). In quantum mechanics, the polarization of light is a manifestation of the spin of the photon. The polarization of light can be obtained by transmission. In this case, the dumped light is absorbed in the polarizer.

Polarization can also be obtained by reflection. In this case, the light oscillating in one direction penetrates in the second medium and the one oscillating in perpendicular direction returns in the first medium. The light coming back in the first medium is transmitted in a different direction. When working with a polarizer, the laser user must understand how the polarizer works and where the light goes.

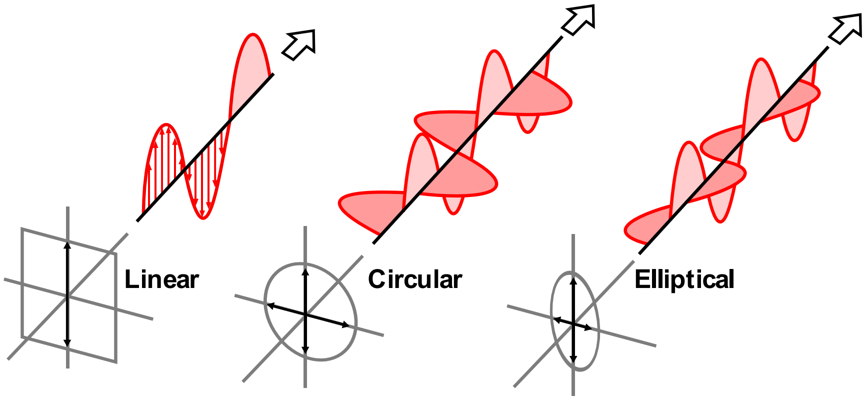


*Figure 2-34: Examples of linearly polarized light (left), circularly polarized light (center) and elliptically polarized light (right).*

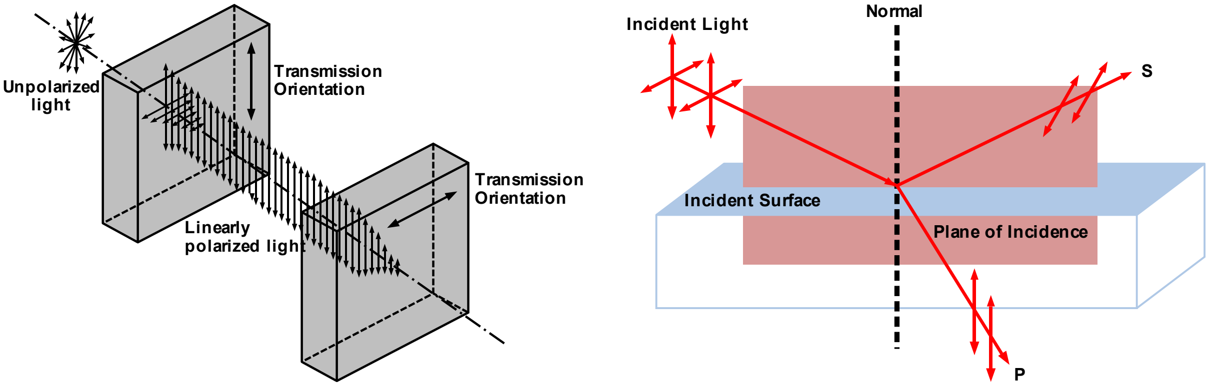


*Figure 2-35: Polarization of light can be achieved by transmission though a polarizer(left) or by reflection on a dielectric material at some particular angle (right).*

### 2.3.9 Brewster’s Angle

Brewster's angle (also known as the polarization angle) is an angle of incidence at which light with a polarization parallel to the incident plane is completely transmitted through a transparent dielectric surface, with no reflection.

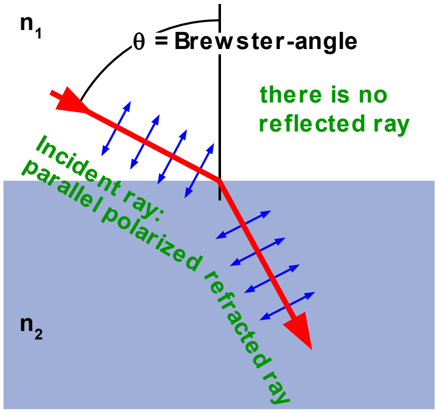


*Figure 2-36: Light polarized parallel to the plane of incident hitting the interface of two transparent media at Brewster's angle. No reflected beam is created. All the energy is transmitted to the second medium.*

When unpolarised light is incident at the Brewster angle, the light that is reflected from the surface is therefore perfectly polarized. In this case, the reflected and refracted rays are perpendiculars.

If the indices of refractions are $n_1$ and $n_2$, the Brewster angle $\theta_B$ can be found with the equation:

$$tan\,\theta_B = \frac{n_2}{n_1} \qquad\qquad \theta_B = arctan(\frac{n_2}{n_1})$$

The Brewster's angle at the interface between air and glass with refraction index n = 1.5 is around 56°.Two mirrors arranged at the Brewster angle (the first will act as a polarizer and the second as the analyzer) will completely stop unpolarised light.

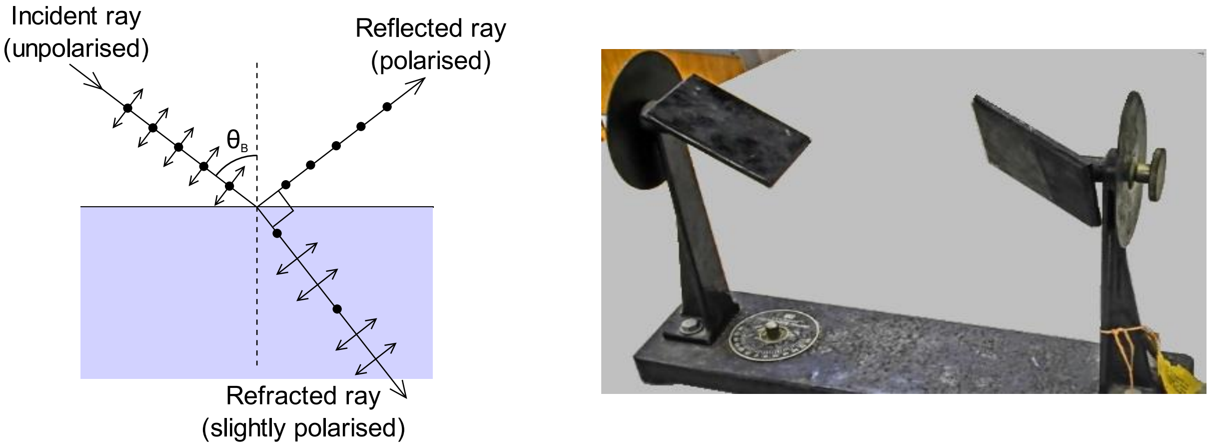


*Figure 2-37 : Reflection and refraction of an unpolarized beam hitting the interface at Brewster's angle (left). : Two mirrors mounted at Brewster's angle (right).*

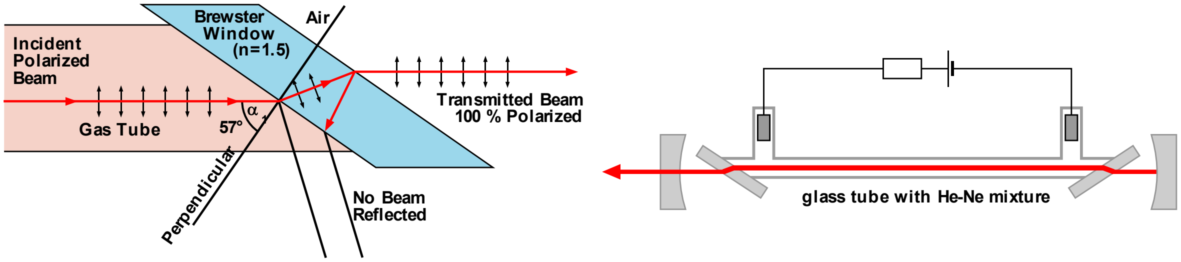


*Figure 2-38 : Examples of windows mounted at Brewster's angle. The beam exiting the laser medium is polarized parallel to the plane of incidence.*

When the incident ray is polarized and hits the glass at Brewster angle there is no reflection (there is no stray beam). This is used in some lasers to reduce losses in a laser cavity.

*Figure 2-39: Optical mount for Brewster's angle windows.*

### 2.3.10 Beam splitter

A beam splitter is an optical device, which can split an incident laser beam into two beams, which may or may not have the same optical power or polarization. When the direction of the incident beam changes, the direction of the reflected beam also changes. If a flat optic (like a mirror, window, or prism) is located after the beam splitter, the stray

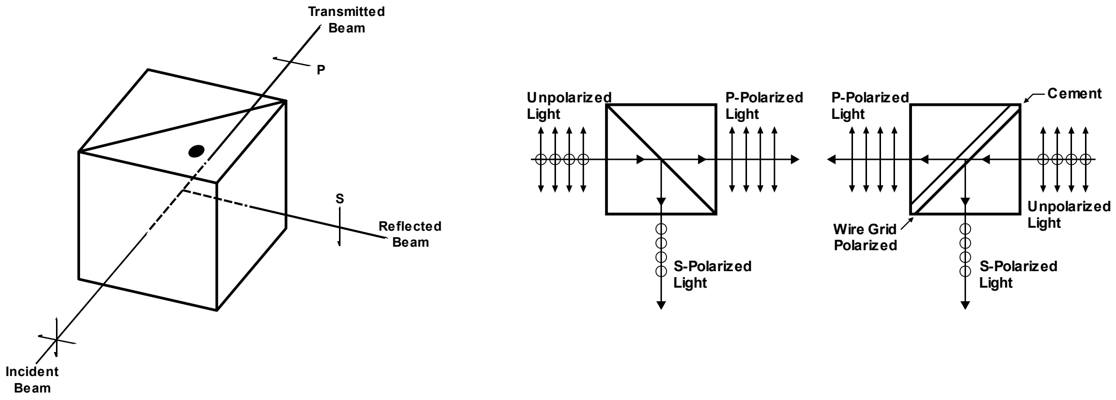


*Figure 2-40: Principle of functioning of beam splitter (left). Incident light from opposite directions (right).*

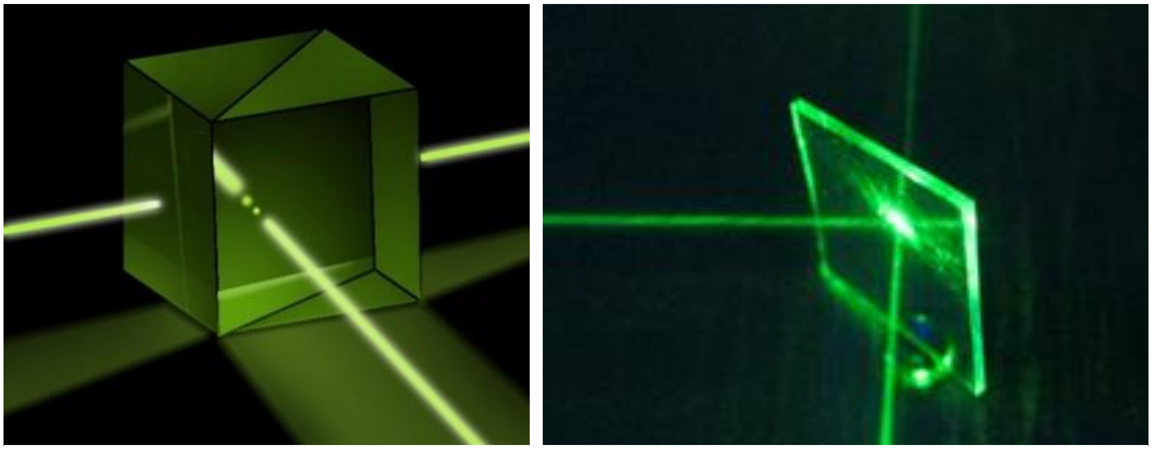


Figure 2-41: Cube beam splitter (left). Window beam splitter (right).

beam coming back will be separated from the reflected beam in the opposite direction of the first reflected beam. The user must block both reflected beams when they are not used.

If two polarizer beam splitters are used one after another, they form an attenuator that can be used to control the power of the transmitted beam. By rotating the second beam polarizer the user can replace light filters.

## 2.4 Non-linear effects

Some non-linear optical effects are important in laser manufacturing, experiments, applications, and laser safety. When light interacts with a material, linear effects (effects proportional to the beam's intensity I) are most likely to happen. Other effects that are proportional to higher powers of the intensity ($I^2$, $I^3$, $I^4$, etc.) happen with much lower probability. These are called non-linear effects. In certain conditions, the probability of non-linear effects can be increased.

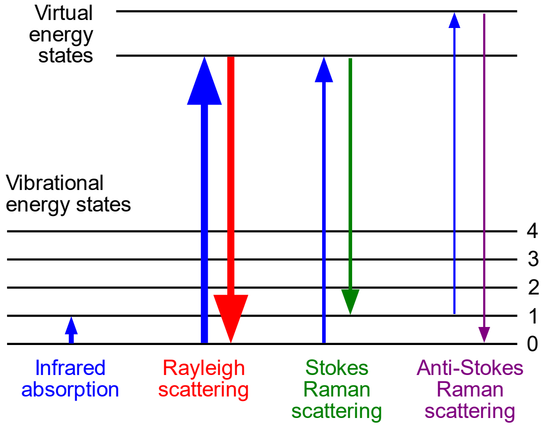


Figure 2-42 Energy levels involved in IR absorption, Rayleigh scattering and Raman scattering.

### 2.4.1 Raman Effect

When the dimension of the object on which light scattering occurs is much smaller than the wavelength (e.g. when scattering happens on molecules or atoms), most of the scattered light will have the same wavelength as the incident light. This is an example of a linear effect and is called Rayleigh scattering. During the Rayleigh scattering, the excitation and de-excitation energies of the atoms or molecules are equal.

With a much lower probability, another effect happens. When the incoming photons induce intra-molecular vibrations and rotations inside the molecules, the scattered light will have a different wavelength. This non-linear effect is named the Raman effect. When the energy of the scattered photons is reduced by the energy of excited states, there is a Stokes Raman scattering, and when is increased by the energy of the excited states, there is anti-Stokes Raman scattering. Since the energy of the excited states depends on the molecule, the Raman effect is successfully used in chemical analysis.

### 2.4.2 Harmonic Generation

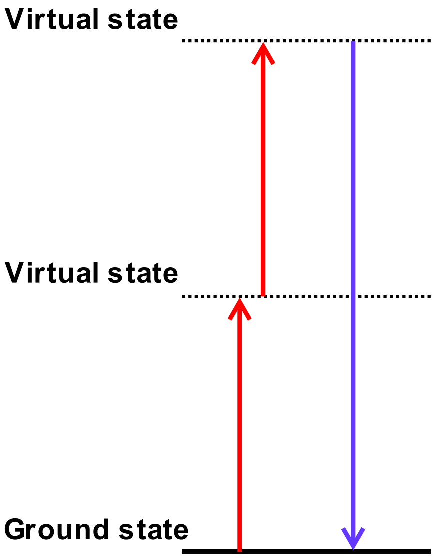


*Figure 2-43: Energy levels in a second-harmonic generation.*

Harmonic generation is a non-linear process in which two or more photons with the same frequency interacting with a non-linear material are “combined” and generate a new photon with energy twice (second harmonic generation SHG) the energy of the incoming photons. This is the energy level scheme for a second harmonic generation process.

Since this non-linear effect is significant only at high power densities of light, generating the second harmonics became possible only after the invention of lasers in 1961. The process of generating the second harmonic depends on the material and the square of the power of the laser beam.

$P_2 = \gamma P_1^2$, where $P_2$ is the power of the double frequency beam, $P_1$ is the power of the pump, and $\gamma$ is a coefficient that depends on the crystal.

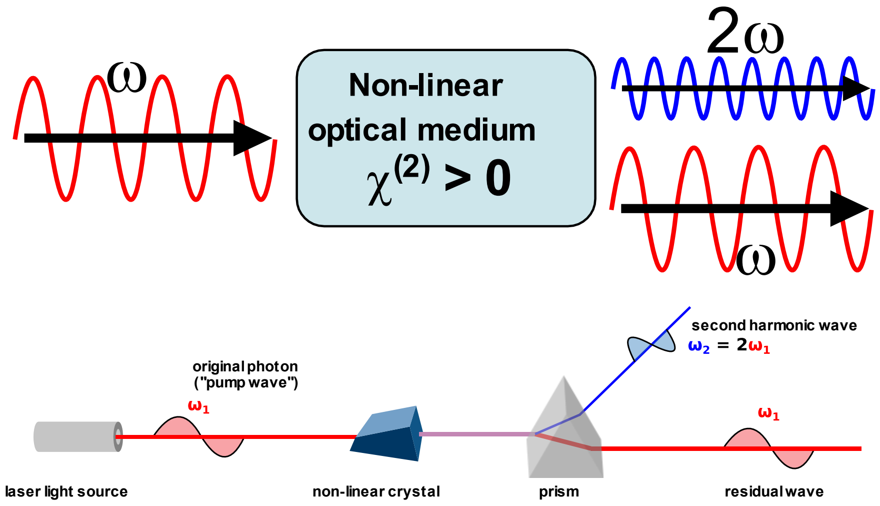


*Figure 2-44: Light of frequency $\omega$ (fundamental) incident to a non-linear optical medium. The generated light of frequency $2\omega$ (SHG) exits medium mixed to the residual of the fundamental (top). The fundamental and SHG lights can be separated by a prism (bottom).*

Harmonic generation in the perturbative (weak-field) regime is characterized by rapidly decreasing efficiency with increasing harmonic order. This behaviour can be understood by considering an atom absorbing n photons then emitting a single high energy photon. The probability of absorbing n photons decreases as n increases, explaining the rapid decrease in the higher harmonic intensities.

The SHG is used, for example, to produce a 532 nm beam from a 1064 nm beam of Nd:YAG lasers. Many materials show relatively high efficiency in non-linear processes. When these materials are crystals, they are called non-linear crystals. Examples of these crystals are lithium niobate ($LiNbO_3$), potassium titanyl phosphate (KTP = $KTiOPO_4$), lithium triborate (LBO = $LiB_3O_5$), etc. The crystals need to be oriented at some particular angle with respect to the beam to fulfil the phase-matching condition. For high-intensity beams, especially for picoseconds (ps) and femtoseconds (fs) pulses where the peak power is very high, almost 100 % of energy can be converted to double frequency. For lower powers (longer pulses) or when the phase-matching condition is not good, the conversion can be much less. In these cases, an important amount of laser power at the fundamental wavelength is present in the beam after the conversion. When laser radiation at the fundamental wavelength is not filtered out by the laser manufacturer or the user, the laser goggles must provide protection against the SHG wavelength and also the fundamental one. If the goggles only protect the user from the SHG wavelength, serious laser eye injuries can happen.

Since the generation of higher harmonics generation is even less efficient than SHG, direct third or fourth harmonic generation is not very common. In the case of the Nd:YAG laser ($l_1$ = 1064 nm), the third harmonic wavelength of 355 nm ($l_3$= $l_1$/3 = 1064 nm/3 = 355 nm) is obtained by using a sum-frequency mixing between the 1064 nm and 532 nm beams. For the same laser, the fourth harmonic wavelength ($l_4$ = $l_1$/4 = 1064 nm/4 = 266 nm), is obtained by doubling the frequency of the 532 nm beam. A higher harmonic generation (HHG with frequency five times or higher than the original laser beam frequency) was first observed in 1977 with a $CO_2$ laser.

### 2.4.3 Electro-Optic Effects

A birefringent material has two different indices of refraction, one for each of the two perpendicular components of polarization. When unpolarized light passes through a birefringent material, two different components of polarization travel in two different directions.

Some materials (like quartz or calcite) exhibit birefringence naturally, without the application of an electric voltage. The birefringence is present all the time.

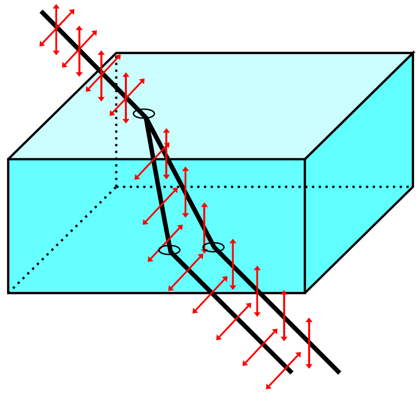
The change in the birefringence properties of the materials under the influence of the electric field is used in the electro-optical Q-switch to create short laser pulses (see section 3.2.3).

When an electric field is applied to an electro-optic material, the indices of refraction and polarization properties of the material change. The Kerr or quadratic electro-optic effect is a second-order effect that is a change in the index of refraction of a material that is proportional to the square of the electric field intensity.

When the electric field oscillates rapidly, as in the case of visible light frequency, it is called the optical Kerr effect. This causes a local variation in the index of refraction, which is proportional to the square of the irradiance of the beam. This refractive index variation is the basis for the functioning of Kerr-lens mode-locking (see section 3.4.4). The effect only becomes significant with very intense beams such as those created by very short pulses (ps or fs).

### 2.4.4 Saturable absorption

Saturable absorption is a property of materials where the absorption of light decreases with increasing light intensity. Most materials show some saturable absorption, but often



**The two refracted rays passing through the Iceland Spar crystal are polarized with perpendicular orientations**

*Figure 2-45: Two different polarization travel different paths in a birefringent material as Iceland Spar.*

only at very high optical intensities, close to the optical damage of the material. The decreased absorption at the high light intensity competes with other mechanisms like an increase in temperature or the formation of colour centers.

For pulsed operation, when the pulse duration “t” is smaller than the relaxation time of the medium, the absorption can decrease very fast and increase back after the pulse ends. In some situations, for very short pulses and relaxation times, the material can look unchanged after the laser pulse passes through the material.

Saturable absorption is used in creating very short laser pulses. Also, when the front mirror of the laser cavity is made of the saturable absorber to let pass the very high intensity, short laser pulses and return to reflectivity when the intensity of the light is lower. Saturable absorption can be a challenge for the laser goggles used for ps and fs lasers (see section 7.3.5).

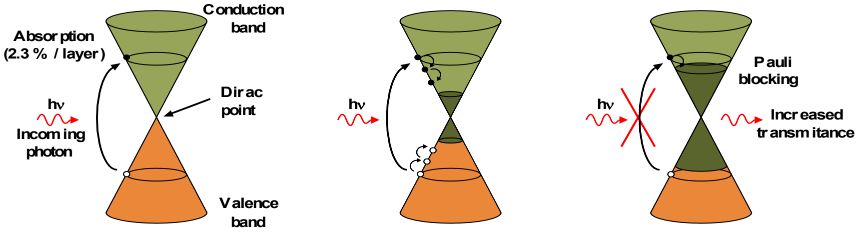


*Figure 2-46: Mechanism of increased transmittance in a saturable absorber.*

# 3 LASERS

## 3.1 Laser levels

As mentioned in section 2.2 population inversion is required to produce the lasing effect. Theoretically, this can be obtained only in atoms or molecules with three or more levels of energy involved in the laser operation.

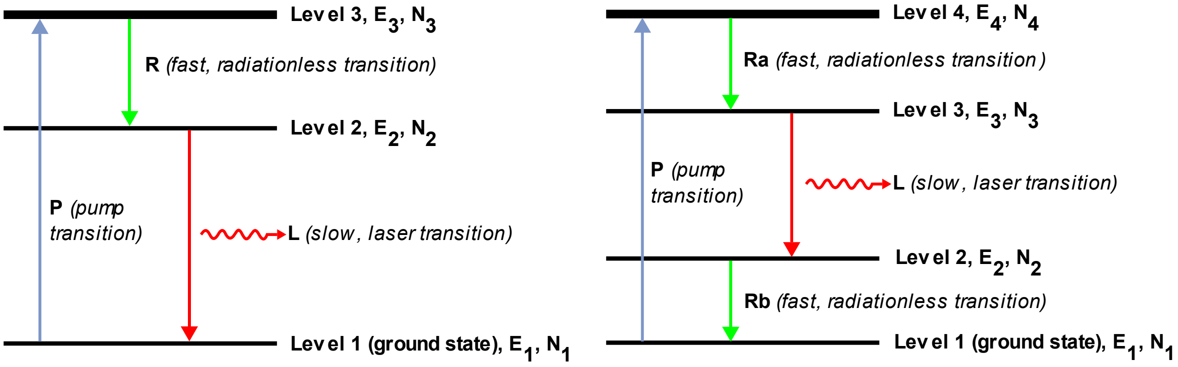


*Figure 3-1: Energy diagrams of a three-levels laser (left) and four-levels laser (right).*

The transition from level 1 to level 3, in the three levels system, is called the pump transition. A fast transition from level 3 to level 2 is necessary to create the population inversion. This transition is radiationless and the energy is transferred to vibrational modes increasing the temperature of the system. The transition from level 2 to level 1 is called laser transition. To achieve population inversion, the number of atoms in the excited state, $N_2$; must be greater than the number of atoms in the ground state, $N_1$. The gain medium of the first laser was a Ruby rod, which is a three-level system. The laser was extremely inefficient. Since most atoms or molecules of systems at room temperature are in the ground state, it is very difficult to create population inversion with three energy levels.

A more efficient system is a laser with four levels. To have the population inversion $N_3$ must be greater than $N_2$. The transitions between levels 4 and 3 and between levels 2 and 1 are fast and radiationless. This process makes the populations $N_4$ and $N_2$ close to zero. Also, the transition from level 3 to level 2 is slow compared with the transitions from levels 4 to 3 and from levels 2 to 1. Therefore, it is easier to obtain $N_3$ greater than $N_2$. Most modern lasers have a four-level energy system.

More than four energy levels may be involved in the laser process, with complex excitation and relaxation processes involved between these levels. In particular, the pump band may consist of several distinct energy levels, or a continuum of levels, which allow optical pumping of the medium over a wide range of wavelengths.

The laser transition can also be considered between several energy sublevels giving the broad energy/wavelength range (bandwidth) measured in the laser emission. For some lasers, the emission can cover an extended energy/wavelength range, like the emission of a Ti:Sapphire which is between 660 and 1180 nm, and for others, a narrow range like the emission of a He-Ne laser which is 632.800 ± 0.001 nm.

It is important to understand that the energy of the pumping photons for any laser is higher than the energy of the lasing photons. As can be seen in the above pictures, in a 4-level energy laser, the energy between levels 4 and 1 is higher than the energy of the laser emission (the energy between levels 3 and 2). In a 3-level laser the energy between levels 3 and 1, is higher than between levels 2 and 1. For example a Ti:Sapphire laser emits in red and near IR range, but needs to be pumped by a green laser.

## 3.2 Laser components

The three main components of a laser are the lasing medium, the excitation source and the optical cavity.

### 3.2.1 Lasing medium

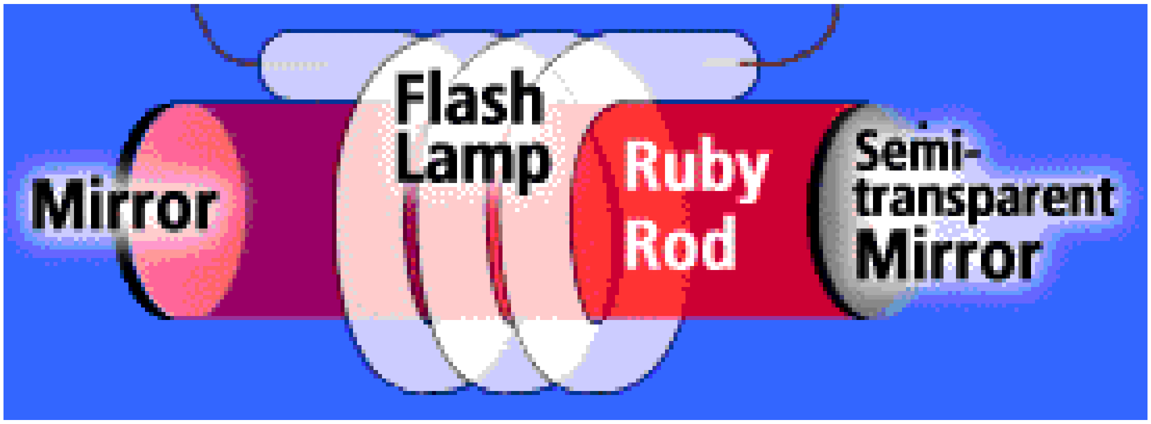


*Figure 3-2: Ruby laser including Ruby rod, helicoidal flash lamp and end mirrors.*

The material in which the population inversion is obtained is called lasing or gain medium. In the first laser (Ted Maiman – May 16, 1960) a ruby rod was used as a gain medium.

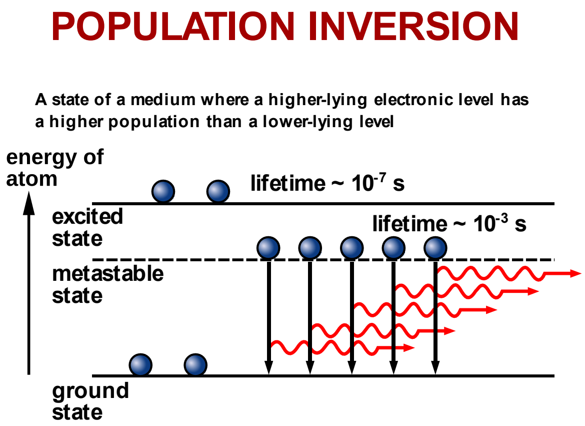


*Figure 3-3: 3 stages excitation of a Ruby laser.*

The ruby rod is made of $Al_2O_3$ crystals with 0.5 % Al replaced by Cr. The three levels of energy of the $Cr^{3+}$ ions are used for this laser.

Nd:YAG is a very common solid-state laser emitting in the near-infrared region of the electromagnetic spectrum (1064 nm). The gain medium of this laser is made of a crystal called Yttrium Aluminum Garnet doped with Nd. Nd replaces around 1 % of Yttrium from the YAG crystal. The YAG crystal can also be doped with Cr, Tm, Er or Ho to obtain other wavelengths.

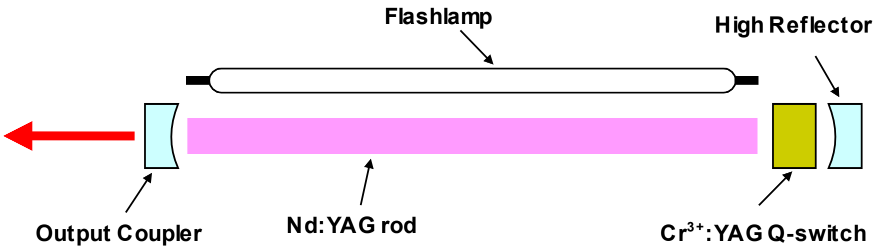


*Figure 3-4: Q-switched Nd:YAG laser.*

The lasing medium can also be a gas. A mixture of He (85%) and Ne (15%) is the gain medium for the first gas laser: HeNe laser. As explained in section 3.1 HeNe can have a complex energy level with many possible laser transitions. It can emit in different wavelengths, but the most common one is 633 nm.

*Figure 3-5: Helium-Neon laser.*

$CO_2$ is a very common gas laser. The gain medium is a mixture of gases (10–20 % $CO_2$, 10–20 % $N_2$, a few percent $H_2$ and/or Xe, and the remainder is He).

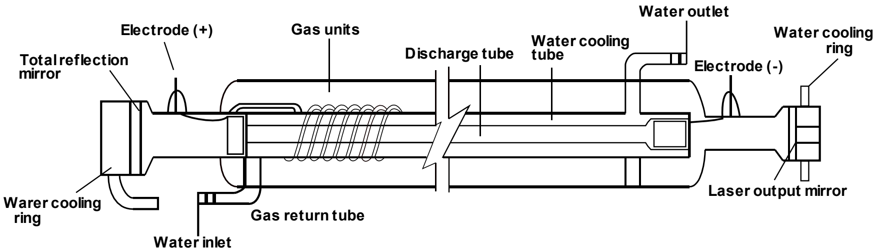


*Figure 3-6: Diagram of a $CO_2$ laser tube.*

The heart of the argon laser in the plasma tube. The design of the plasma tube must be such that it can sustain extremely high temperatures without damage while maintaining an excellent vacuum seal. The material of choice for the bore of an argon-ion laser plasma tube is BeO since it has a low vapour pressure and can be produced with a high chemical purity. Beryllium, however, is a carcinogen and the tube of the argon laser must be disposed of as hazardous material when the laser is decommissioned.

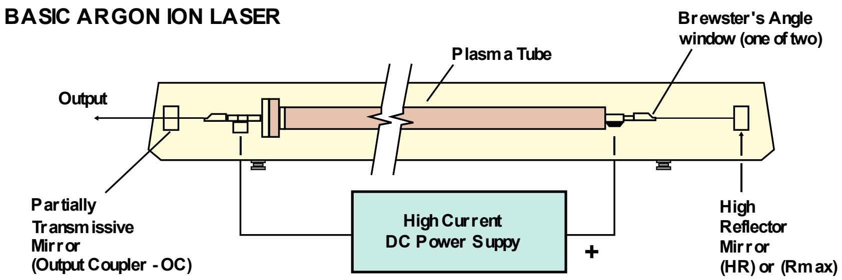


*Figure 3-7: Diagram of an Argon ion laser.*

Most of the lasers having liquid gain medium are dye lasers. A dye laser uses a gain medium consisting of an organic dye, which is a carbon-based soluble stain that is often fluorescent. The dye is mixed with a compatible solvent allowing the molecules to diffuse evenly throughout the liquid. Most of the dyes (like rhodamine or stilbene) are toxic or carcinogenic. For the diode lasers, the gain medium is the semiconductor itself (usually Silicon) in which different elements are used for the doping process.

The diode laser has, in general, an elliptical beam. Manufacturers normally mount a cylindrical lens in front of the laser to make the beam circular.

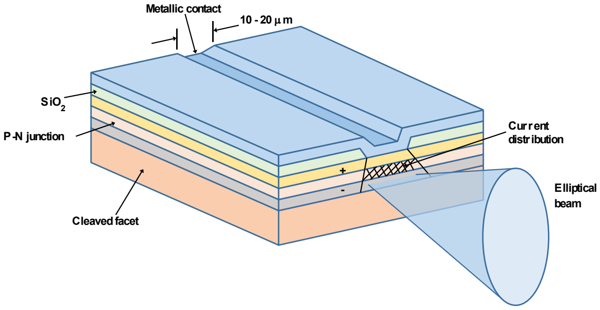


*Figure 3-8: Diode laser.*

A fibre optic in which rare elements are used for doping can be used as a gain medium for fibre lasers.

A Ti:Sapphire oscillator has a gain medium made of $Al_2O_3$ (Sapphire) doped with Titanium atoms. Ti emits at 800 nm with large bandwidth. Ti:Sapphire lasers are tunable from around 650 to 1100 nm. The pulse duration of a laser is inversely proportional to the

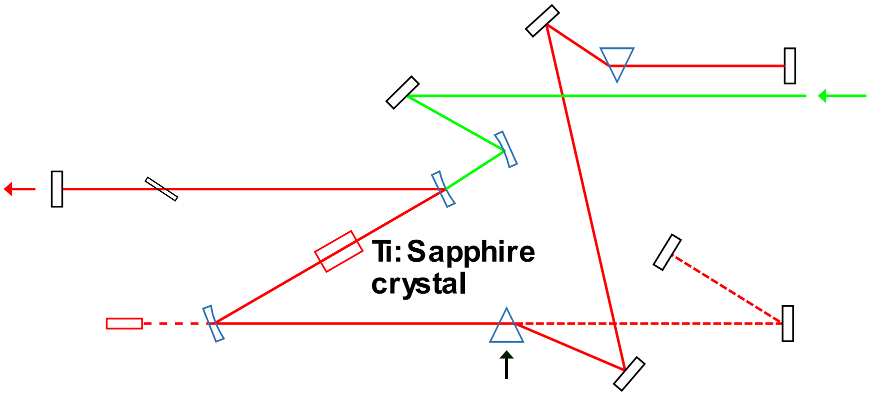


Figure 3-9: Diagram of a Titanium-Sapphire laser cavity.

bandwidth (see section 3.4.2). Having a large emission band this laser is suitable for obtaining very short pulses (ps and fs).

### 3.2.2 Optical cavity

In general, if photons of the proper wavelength pass just once through the lasing medium in the population inversion state, the stimulated emission and then the obtained amplification is not enough to produce an intense laser beam. An optical cavity is necessary to force the light to pass many times through the gain medium. The simplest optical cavity is made of two parallel mirrors. One mirror has 100 % reflectivity at the laser wavelength and the other mirror is just partially reflective. This second mirror is known as the output coupler. Depending on the laser, the reflectivity of the output coupler can be anywhere between 1 % to 99 %.

The mirrors can have different shapes. Inside the optical cavity, standing waves are created (see section 3.3.1).

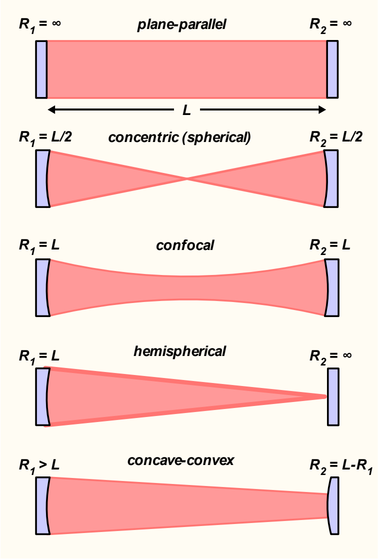


Figure 3-10: Different types of optical cavities used in lasers.

When the optical cavity can sustain the standing waves, it is said to have a large quality factor (Q). When, due to different reasons, standing waves cannot appear the optical cavity has a small Q. A “Q-switched laser” is a laser in which the quality factor can be changed between low and high values (see section 3.4.3).

Laser amplifiers are the type of lasers that don’t necessarily have an optical cavity. Low-intensity laser beams from a regular laser, normally called an oscillator, is injected in a laser gain medium that was previously activated by an excitation source. This low-intensity beam acts as a “seed” inducing stimulated emission in the exciting medium. After just one pass on the medium, the beam is amplified several orders of magnitude.

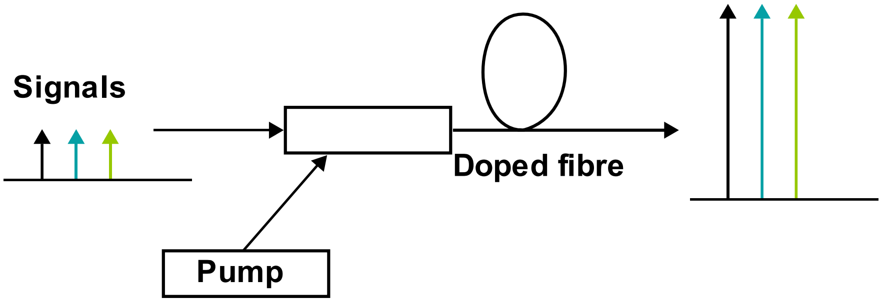


Figure 3-11: Fiber laser amplifier.

Examples of amplifiers are Doped Fiber Amplifiers (DFA), Erbium-Doped Fiber Amplifier (EDFA) with a wavelength in the range 1525-1565 nm or 1570-1610 nm, Thulium (1450-1490 nm), Praseodymium (1300 nm region), Ytterbium (1000 nm region), or Semiconductor Optical Amplifiers (SOA).

### 3.2.3 Energy pump

To create the population inversion in the gain medium a source of energy is necessary. The energy pump is dependent on the lasing medium and other characteristics of the laser.

In optical pumping, a source of light such as a flash lamp with broad emission bandwidth is used to excite a medium with an excitation band extremely narrow. The disadvantage of this type of excitation is its low energy yield. Most of the energy emitted by the flash lamp is lost as heat. These types of lasers need to have a cooling system (usually water) to remove the excess heat. Ruby and Nd:YAG lasers use optical pumping.

Electrical pumping is the most common energy pump for gas lasers. In this kind of laser pumping a high voltage, alternative current (AC) or direct current (DC) is used to create a discharge in the gas. The discharge will create ions inside the lasing medium, these ions will be accelerated, collide, and excite other components of the gain medium.

Arc lamps are used for pumping some solid-state lasers that can operate in continuous wave mode (CW). The voltage must be high enough to create a current around 20 to 50 A. Arc lamps must also be cooled by water.

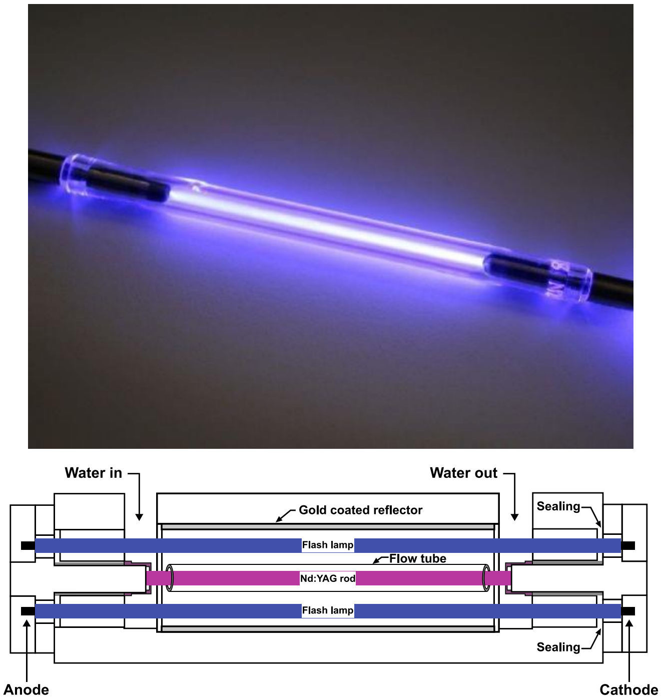


*Figure 3-12: Flash lamp used to excited Nd:YAG laser media (top). Diagram of a Nd:YAG laser excited with two flash lamps (bottom).*

The diode laser is pumped by passing a high-density current through the p-n junction. This type of laser diode is called an injection laser diode (ILD). Laser diodes can also use the optical pump. Optically pumped semiconductor lasers (OPSL) offer some advantages over the ILD for some wavelengths.

Chemical pumping is also used to excite chemical lasers. Infrared lasers based on the vibrationally excited products of a chemical reaction was first proposed by John Polanyi in 1961. These types of lasers can reach MW power in CW operation.

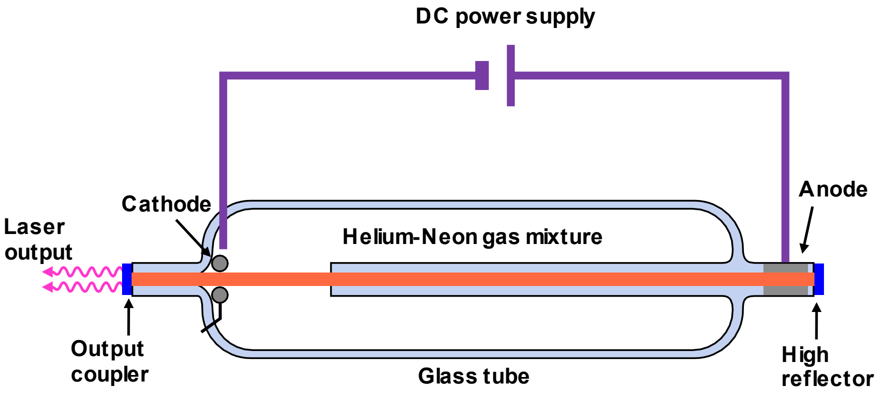


*Figure 3-13: Diagram of electrical excitation of He-Ne laser.*

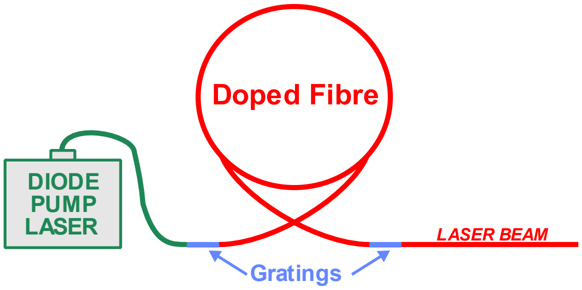


Figure 3-14: Laser diode used to excite a fibre laser.

A much more efficient photoexcitation is obtained when a laser is used to pump another laser. The pump laser must have an emission band that overlaps with the absorption band of the gain material of the pumped laser. The mirrors used for the optical cavity of the pumped laser are transparent to the excitation wavelength but reflect the wavelength of the pumped laser. The most common laser used as a pump is a diode laser.

This type of energy excitation is used in fibre and solid-state diode pump (SSDP) lasers. For fibre lasers, gratings are used to create the optical cavity.

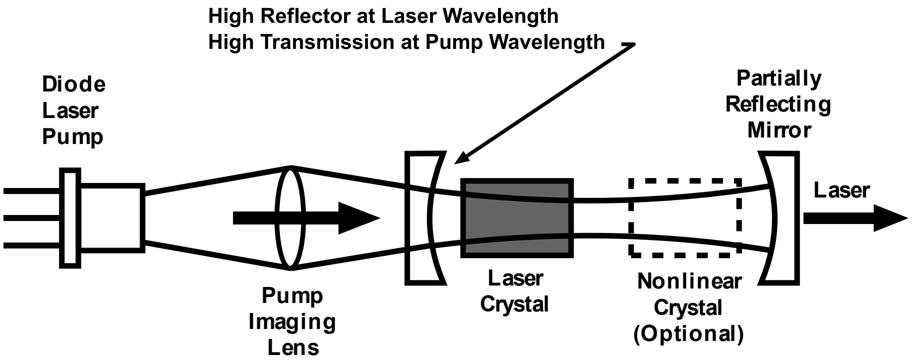


Figure 3-15: Diode laser used to excite a solid-state laser (DPSSL).

Using this type of pumping powerful lasers could be obtained with small dimensions and low energy consumption.

## 3.3 Laser Modes

The laser cavities can have two types of modes: axial (longitudinal) and transverse modes.

### 3.3.1 Axial modes

Inside the optical cavity, waves of different frequencies can coexist. Just those whose electric field amplitude is zero at the surface of the mirror will be enhanced or amplified. That establishes a set of stable standing waves in the cavity as the ones shown in **Error! Reference source not found.**. The frequency of those waves depends on the length of the cavity.

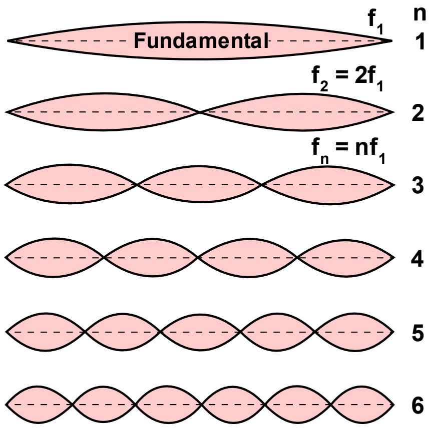


Figure 3-16: Longitudinal modes of a laser cavity.

The mode number “q”, the length of the cavity “L”, the wavelength “λ” and the frequency “f” of the standing waves that can be produced in the optical cavity is connected. If ‘n’ is the index of refraction of the gain material, the following formulae are valid:

$$L = q\frac{\lambda}{2} = q\frac{c}{2f} \qquad f = q\frac{c}{2nL} \qquad \Delta f = \frac{c}{2nL}$$

Δf represents the difference between the frequencies of two successive modes.

For a cavity, with L = 0.3 m, and with n ≈ 1 (in case of air or a low-density gas) the frequency difference will be 0.5 * $10^9$ Hz = 0.5 GHz. The equation for Δf is more complex when the cavity consists of multiple materials.

Out of all possible axial modes for a given optical cavity length, only the modes with frequencies within the material gain response will be amplified. The number of modes can be obtained by dividing the gain bandwidth (Df) of the particular laser by the frequency difference (Δf).

For a typical He-Ne laser with a length of the cavity 0.3 m and a Full Width at Half Maximum (FWHM) gain bandwidth Df =1.5 GHz, using the Δf = 0.5 GHz, we obtain 3

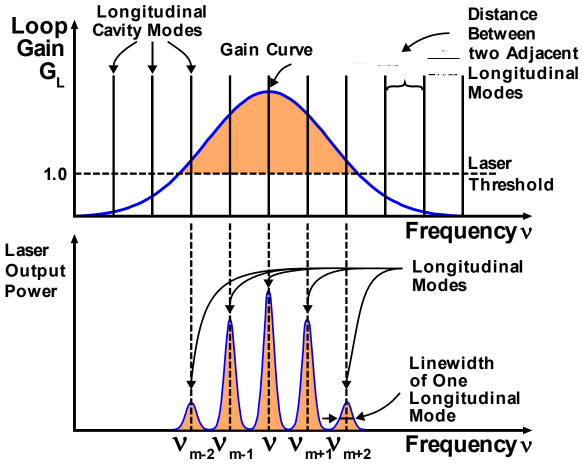


Figure 3-17: Gain curve of laser medium and all possible longitudinal modes for a given cavity length (top). Only the cavity modes with frequencies within the laser gain curve are amplified.

modes. Since the He-Ne has a very narrow bandwidth and few axial modes, this laser is ideal to be used as a standard for wavelength calibrations.

For a Ti:Sapphire laser, the FWHM gain bandwidth is Df = $10^{14}$ Hz = $10^5$ GHz. For a cavity length of 1.5 m and neglecting the optical path in the Ti:Sapphire crystal, the frequency difference is $\Delta f$ = 0.1 GHz. Using these values, the number of amplified modes in this laser will be 1,000,000.

The number of longitudinal modes can be reduced by reducing the length (L) of the cavity. In this way, the $\Delta f$ increases and the number of possible modes are reduced. This procedure will reduce the power of the laser.

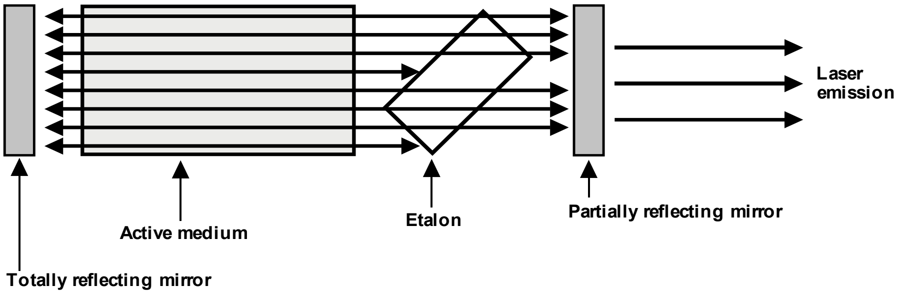


*Figure 3-18: Etalon used to reduce the number of longitudinal modes in a laser cavity.*

Another way of reducing the number of modes is by adding Fabry-Perot etalon (a crystal with parallel flat surfaces) inside the optical cavity.

The etalon will act as an additional mirror. The number of longitudinal modes will be reduced because the laser must satisfy the condition for both “mirrors”.

The etalon can be fixed or rotating. By rotating the etalon, the user can tune the transmission to the desired frequency.

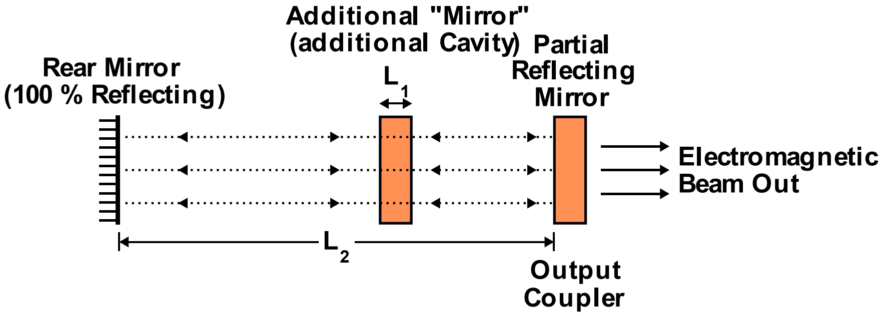


*Figure 3-19: Etalon as additional cavity mirror.*

### 3.3.2 Transverse modes

Transverse modes are modes in the cross-section of the beam, perpendicular to the optical axis of the laser. They are created by the width of the cavity, which enables a few diagonal modes to develop inside the laser cavity. A little misalignment of the laser mirrors causes different path lengths for different rays inside the cavity.

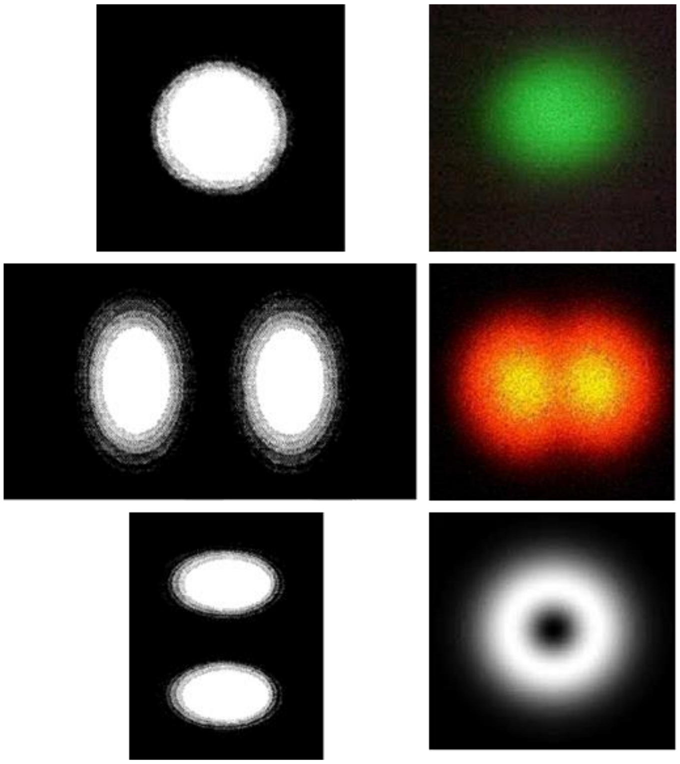


*Figure 3-20: Images of different tranverse modes. TEM00 (top row), TEM10 (center row), TEM01 (bottom left) and TEM01 + TEM10 “bagel” (bottom right).*

Transverse modes are also called transverse electromagnetic modes, and the notation used is $TEM_{nm}$. Different transverse mode patterns exist inside the laser beam. The first letter (“n”) refers to the number of beams on the OX axis, and “m” on the OY axis. $TEM_{00}$ is the beam with the smallest diameter and beam spread

All other modes influence the beam quality factor, $M^2$. The beam quality factor of a laser is the ratio between the beam spread and the natural spread of light obtained by solving the Maxwell equations of an electromagnetic field. Beam quality factor of an embedded Gaussian beam with $TEM_{mn}$:

$M^2$ on x-axis = 2m + 1
$M^2$ on y-axis = 2n + 1

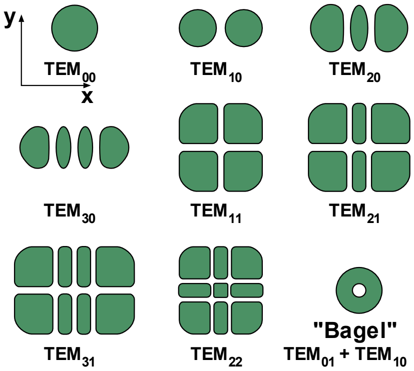


*Figure 3-21: Shapes of different transverse modes.*

$TEM_{00}$ will have a quality factor of 1. $TEM_{00}$ is a Gaussian and:

- Has the lowest divergence
- It can be focused on the smallest spot, for a given wavelength
- Has the best spatial coherence of all the other modes
- It stays with Gaussian distribution while passing through optical systems.

Beam quality can also be expressed as a percentage deviation from $TEM_{00}$ (e.g.: $TEM_{00}$ > 98%).

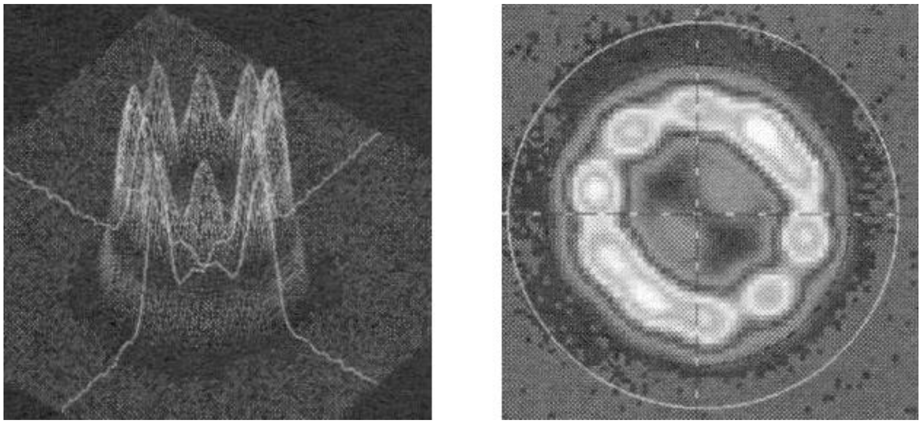


*Figure 3-22: : Low-quality real beam profile.*

In many applications, the number of transverse modes is not important. But if very small beam diameters are desired, the minimum diameter can be obtained if the beam is close to $TEM_{00}$ (high-quality factor).

To reduce the number of transverse modes intra-cavity diaphragms can be used. These diaphragms will reduce the power of the laser.

Transverse and longitudinal modes can coexist in a laser cavity. Some lasers can operate in a single longitudinal mode and single transverse mode. Other lasers operate with multiple longitudinal modes and multiple transverse modes.

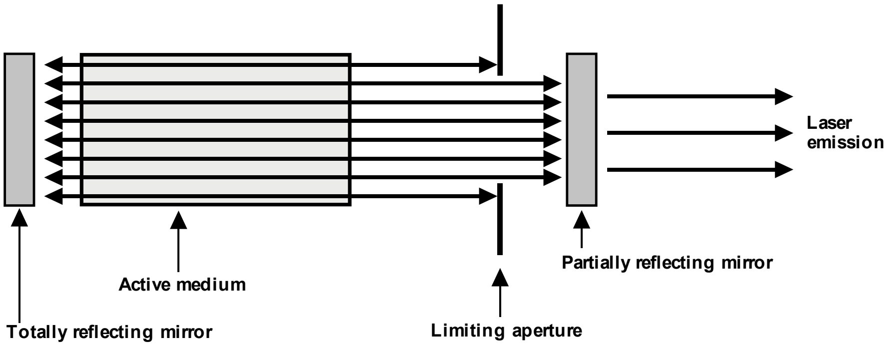


*Figure 3-23: Limiting diaphragm used to reduce the number of transversal modes.*

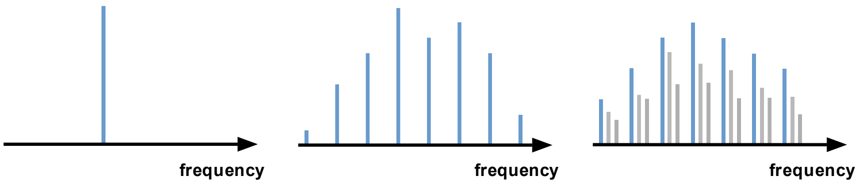


*Figure 3-24: Longitudinal and transverse modes.*

## 3.4 Laser Operation

### 3.4.1 Continuous-wave lasers

Lasers can deliver energy continuously or in pulses. From the laser safety point of view, if a laser delivers energy in pulses equal to or longer than 0.25 s, (including continuous delivery) the laser is called a continuous wave laser or CW. Lasers delivering the energy in pulses shorter than 0.25 s are considered pulsed lasers.

The duration of 0,25 s was chosen because it is the approximate time necessary for the eye to react to high-intensity visible radiation (light). This natural defence, the blinking of the eye, plays an important role in the definition of laser classes.

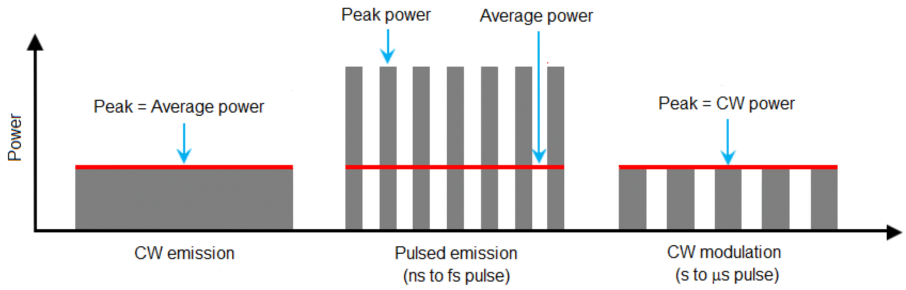


*Figure 3-25: Different types of laser operations.*

To obtain continuous emission, a steady-state must be reached inside the laser between the energy transferred to the gain medium by the pumping system, and the energy emitted by the laser. Diode lasers are the most common CW laser since the excitation is done by applying an electrical current through the diode. Other lasers can also be made to function in the CW mode. The first CW laser was a HeNe.

CW modulation can be obtained by blocking the beam of a CW laser to obtain the desired pulse duration and repetition. Even though the result of CW modulation appears similar to that of a pulsed laser the two processes are very different. In general, by using the modulation process the pulse duration is limited to microseconds, while the pulse duration in the case of a pulsed laser emission can be much shorter.

### 3.4.2 Pulsed Lasers

Pulsed lasers can be obtained by exciting the gain medium with a pulsed pumping source like a flashing lamp. The first laser in history was a pulsed ruby laser. Ted Maiman used a photographic flash lamp to create the excitation state in the ruby rod. In the past, some of these flashing lamps were connected to capacitor banks. These capacitors were charged first and then rapidly discharged, providing the energy for the flash lamp. As explained later in section 6.1.1, capacitors are an electrical hazard. The pulse duration is normally measured as the full width at half maximum (FWHM) of the laser pulse.

If a laser emits pulses at a certain interval the difference in time between two successive pulses is called pulse repetition time “PRT”. The number of pulses that a laser emits per second is the pulse repetition frequency “PRF”. PRF is equal to 1/PRT and is measured in hertz ( 1Hz = 1/s).

The pulse duration can vary many orders of magnitude from ms ($10^{-3}$ s) to fs ($10^{-15}$ s) range for lasers in the visible or infrared. Attoseconds (as = $10^{-18}$ s) can only be obtained with the centre frequency above the visible (UV and higher frequencies). The pulse duration is inversely proportional to the laser bandwidth. High harmonics generation (see section 2.4.2) allows the formation of $10^{-18}$ s pulses or pulse trains.

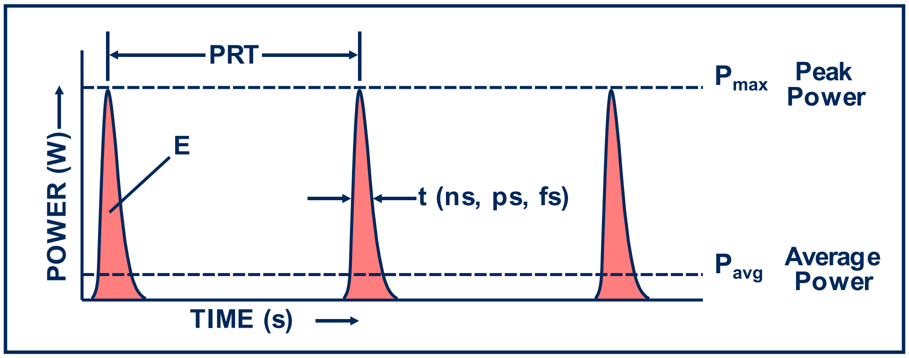


*Figure 3-26: Definition of pulse duration (t) and pulse repetition time (PRT).*

### 3.4.3 Q switched laser

As explained in section 3.2.2, the cavity quality factor Q is a number that tells how much an optical cavity can sustain the standing waves. When the Q of the optical cavity is low, the lasing does not occur. The process of rapidly changing the quality factor of the optical cavity from low to high and *vice-versa* is called Q-switching. This process is used to make laser emitting pulses with duration in the nanosecond range. The energy from the excitation source brings atoms to a high energy level. Since at low Q there is no stimulated emission, to produce the de-excitation of the atoms the energy stored in the gain medium increases. Then Q is rapidly switched to a high value and all the stored energy is released in a very short time creating a high peak power nanosecond laser pulse. The total energy emitted by the laser is not greater than a similar laser operating in CW mode, but because is released in a very short time the peak power can reach hundreds of MW.

The cavity quality factor can be switched actively or passively.

In passive Q-switching, the Q-switch is a saturable absorber—material that transmission increases when the intensity of light exceeds a threshold. After the short pulse of large energy is emitted from the laser, the Q-switch will block again the transmission of light causing a low-quality factor in the optical cavity.

The active Q-switch can be a mechanical device such as a shutter, a chopper wheel, or a spinning mirror/prism placed inside the cavity. Other devices used for active Q-switching are acousto-optic, magneto-optic or electro-optic devices.

Some properties of an optical crystal can be changed by applying an electric or magnetic field to it. For example, the crystal can act as a quarter waveplate changing the polarization from light to left. In this way, the crystal will block the transmission of light creating a low Q inside the laser cavity.

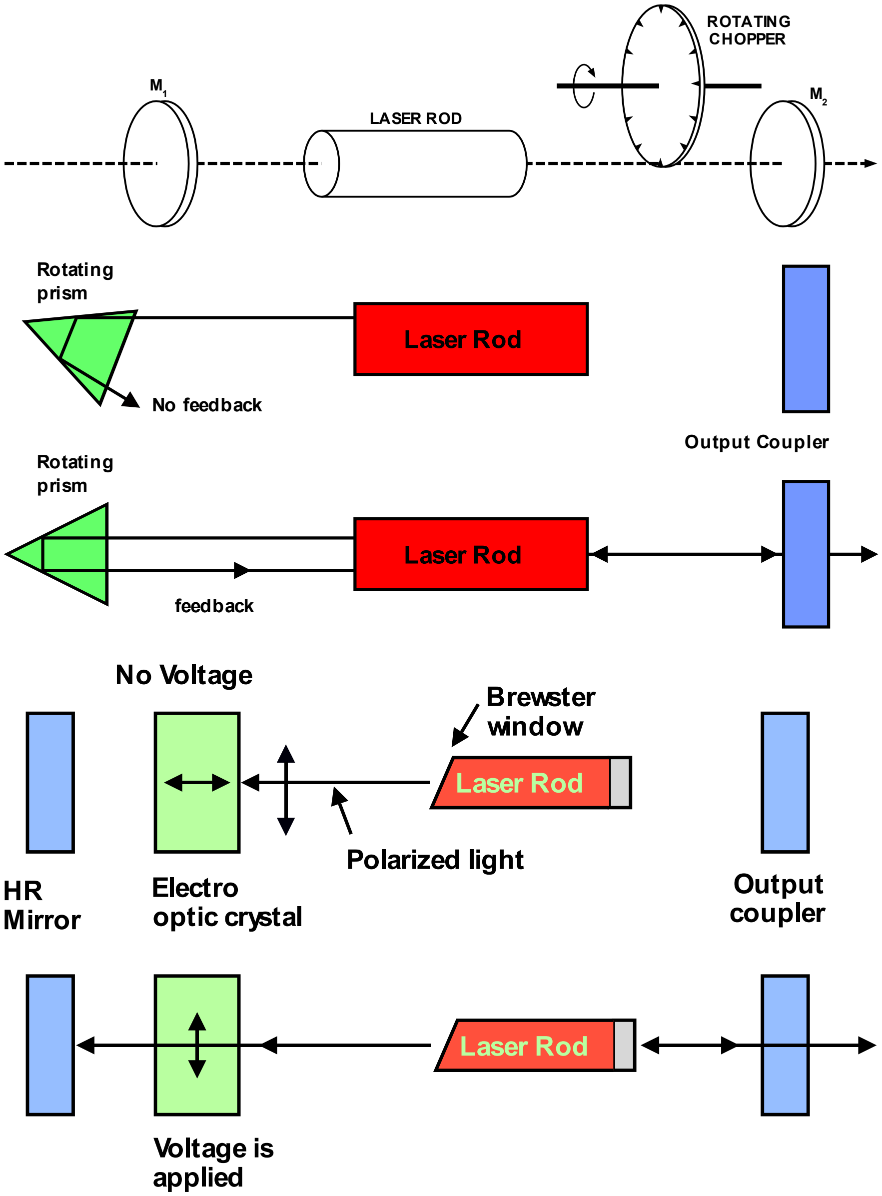


*Figure 3-27: Different techniques to achieve Q-switch. Rotating chopper (top), rotating prism (center) and electrooptical device (bottom).*

### 3.4.4 Mode-locked laser

As it was mentioned before, Q-switching can produce laser pulses in the nanosecond range but not shorter than that. To produce laser pulses in the picoseconds or femtoseconds range another method needs to be used. This other method is called mode-locking and it is based on combining several longitudinal cavity modes with a fixed phase relation between them. The result of this is a series of very short and high peak power laser pulses. The pulse width of each mode-locked pulse is inversely proportional to the gain bandwidth of the laser cavity.

As in the case of Q-switch, there are active and passive methods.

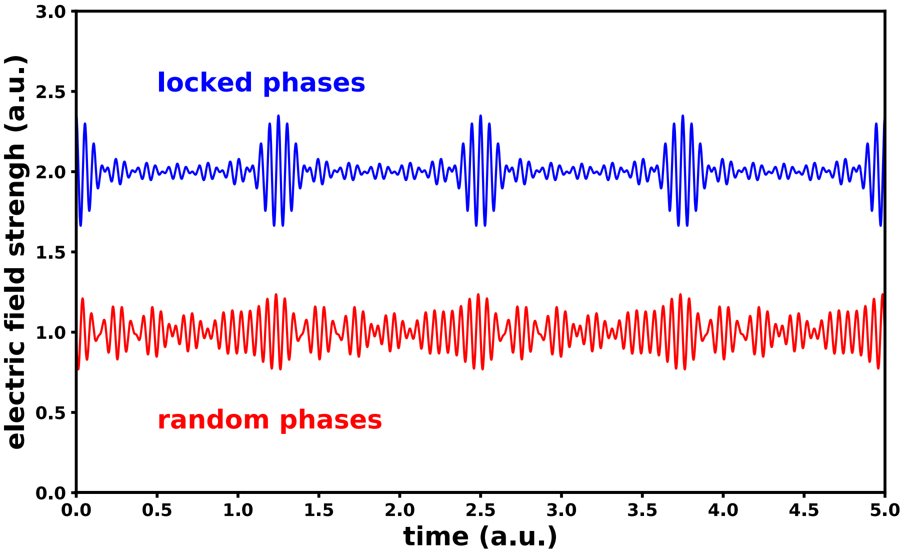


*Figure 3-28: Comparison of longitudinal modes locked in-phase (top) and with random phases (bottom).*

### Active mode-locking

Active mode-locking can be obtained by placing a standing wave acoustic-optic modulator in the optical cavity. This modulator is a semiconductor device and by changing the electric voltage applied to it, its energy bandgap changes which in turn will control the intensity of the laser beam. Driven by an electric signal the modulator creates sinusoidal amplitude modulation, acting as a shutter (when opened, the light passes, when closed, light is stopped). Typically, pulses with a duration of 0.5 to 5 ps can be obtained. One of

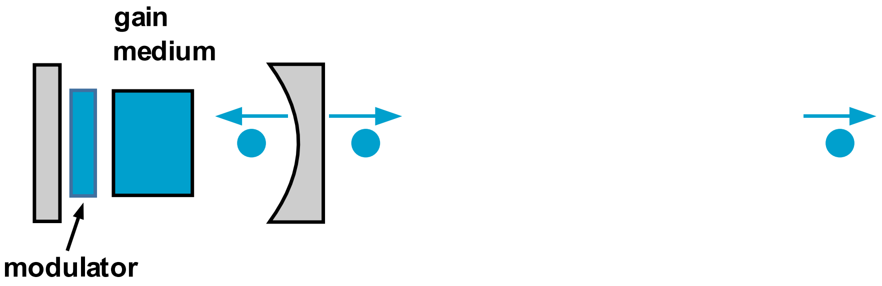


*Figure 3-29: A modulator used for active mode-locking.*

the disadvantages of active mode-locking is that precise synchronization must be kept at all times. Small jitter in the synchronization circuitry will make the laser have important fluctuations in pulse intensity.

### Passive mode-locking

One way the passive mode-locking can be obtained is by placing a saturable absorber in the optical cavity. The saturable absorber is a chemical compound that will absorb light when the intensity of the pulse is low, i.e. at the head and tail of the pulse. When the intensity of the pulse increases, the absorption transitions of the chemical saturate in a phenomenon normally called “bleaching”. At this point the chemical becomes transparent to the light, letting the full intensity pass unperturbed. This process effectively shortens the pulse duration.

Another way to achieve passive mode-locking is by taking advantage of Kerr lensing in the gain medium. The Kerr Lens Modelocking (KLM) is based on the optical Kerr effect, nonlinear optical process (electro-optic effects – see section 2.4.3). In this case, the index of refraction of the laser medium changes due to the high intensity of the short pulses. Short pulses get focused more tightly than CW beam. Adding an aperture to the cavity or adjusting the shape and diameter of the excitation beam to match the ones of short pulses will favour the mode-locking.

Passive mode-locking can have difficulties to start the mode-locking and relay on random fluctuations of the intensity of the light in CW mode. Modern lasers overcome this problem by mounting an extra mirror in the laser cavity on a piezoelectric actuator. Applying an oscillating signal to the actuator will produce vibrations in the mirror providing the random intensity fluctuations needed to start the mode-locking.

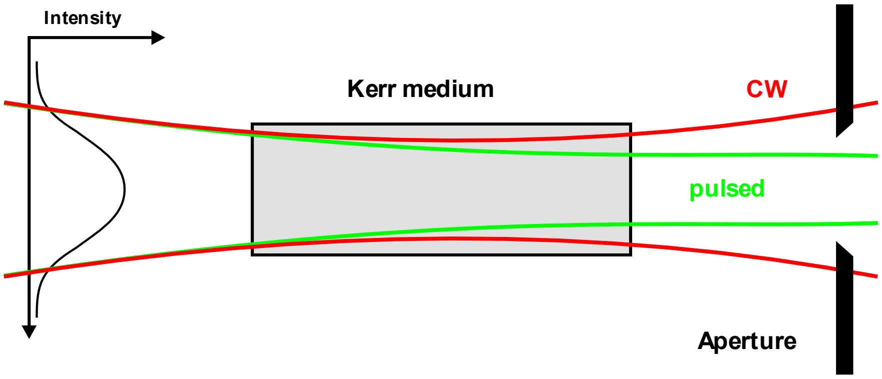


*Figure 3-30: Kerr lens mode-locking.*

### Hybrid mode-locking

The hybrid mode-locking is a combination of active and passive mode-locking. A saturable absorber is placed in the optical cavity and the injection current is modulated at the same frequency. In this way, it is possible to control the pulse timing externally, and also achieve a shorter pulse duration as in a passive mode-locking device.

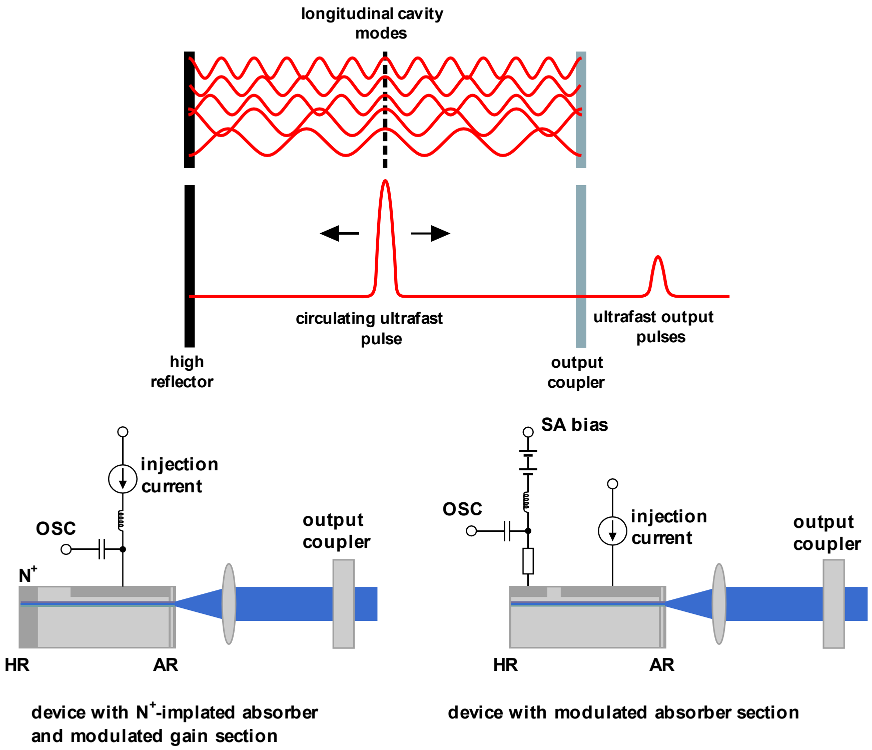


Figure 3-31: Ultrafast pulse circulating in an optical cavity (top). Hybrid mode-locking (bottom).

## 3.5 Laser safety properties

Two types of physical properties are used in laser safety. The first type is directly related to the laser itself and the second one laser interacting with the target.

### 3.5.1 Properties directly related to the laser

For a continuous wave CW laser, the most common property to measure the laser output is laser radiant power – P. Laser power is measured in watts – W.

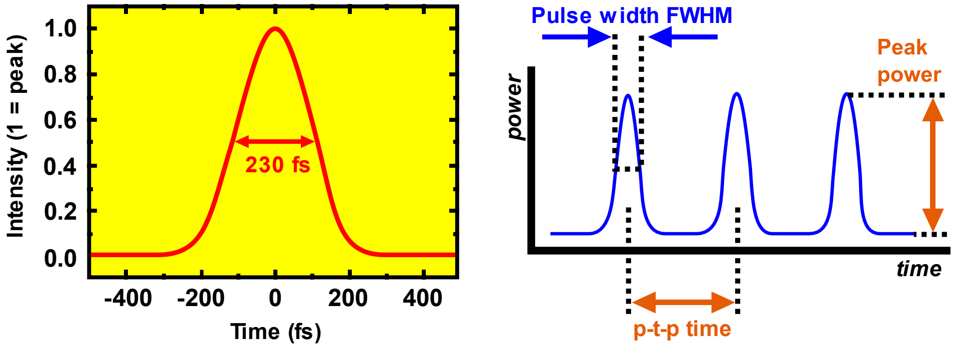


Figure 3-32: Pulse duration measured as full width at half maximum, FWHM (left) and pulse repetition time, PRT (right).

For a pulsed laser, the pulse duration is noted as *t* and is measured in s. The energy emitted per pulse, also known as the radiant energy is noted with E and is measured in joules – J.

The difference in time between two consecutive pulses is called the pulse repetition period (see section 3.4.2).

When more pulses are emitted the number of pulses per second is measured with the pulse repetition frequency - PRF. The pulse repetition frequency is measured in Hertz – Hz = $s^{-1}$.

To calculate the maximum or peak power of a pulsed laser, the energy per pulse is divided by the pulse duration.

$$P_{\max} = \frac{E}{t}$$

The average power of a repetitively pulsed laser is found by multiplying the energy per pulse by the pulse repetition frequency.

$$P_{\text{avg}} = E * PRF$$

The laser beam diameter is noted D and is usually measured in mm.

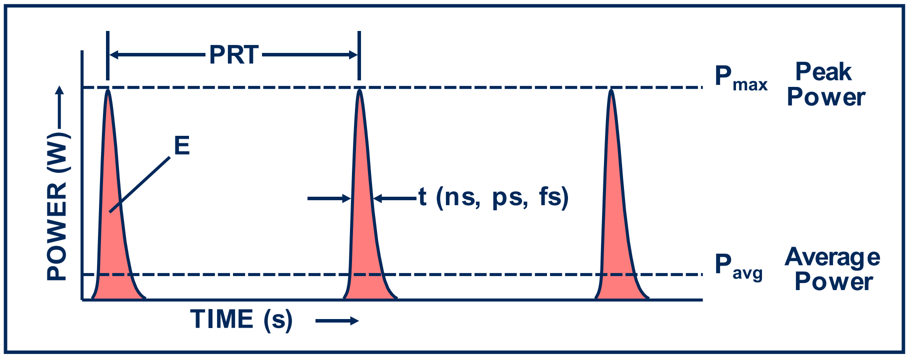


*Figure 3-33: Comparison of peak power $P_{max}$ and average power, $P_{avg}$. The area in orange represents the energy of the pulse.*

Usually, the symmetric laser beam profile (see section 8.2.2) can be fitted to a Gaussian function. The most common definition of the beam diameter is the distance between the points where the intensity of the beam decreases to $1/e^2$ of its maximum (e is the base of the natural logarithm).

In laser safety, the beam diameter is defined slightly differently and is the distance between the points where the intensity decreases at 1/e of the maximum. This definition conducts a safer calculation of the required laser goggles' optical density.

Assuming that the beam is Gaussian, only 63 % of the total energy passes through an aperture with the diameter defined at 1/e and 86 % when the diameter is defined at $1/e^2$.

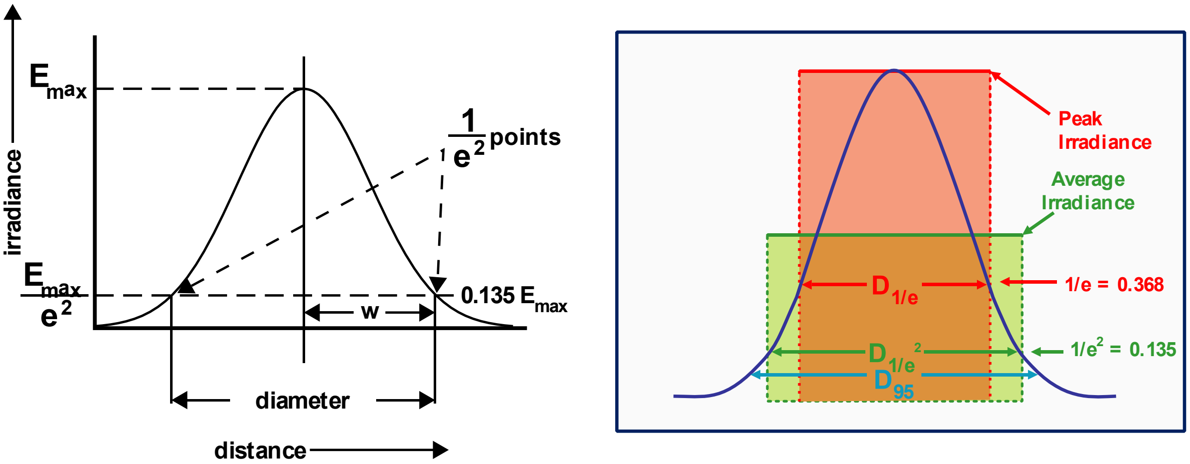


Figure 3-34: Definition of 1/e2 beam diameter (left). Other common definitions of the laser beam diameter

A third definition of the beam diameter is the diameter of an aperture through which 95 % of the beam's energy will pass.

The three definitions are related to each other. The following formula can be used to change from one to another:

$$D_{1/e} = \frac{D_{1/e^2}}{\sqrt{2}} = \frac{D_{95\%}}{1.7}$$

If the beam shape is elliptical the beam diameter can be estimated by averaging the diameter on OX and OY axis.

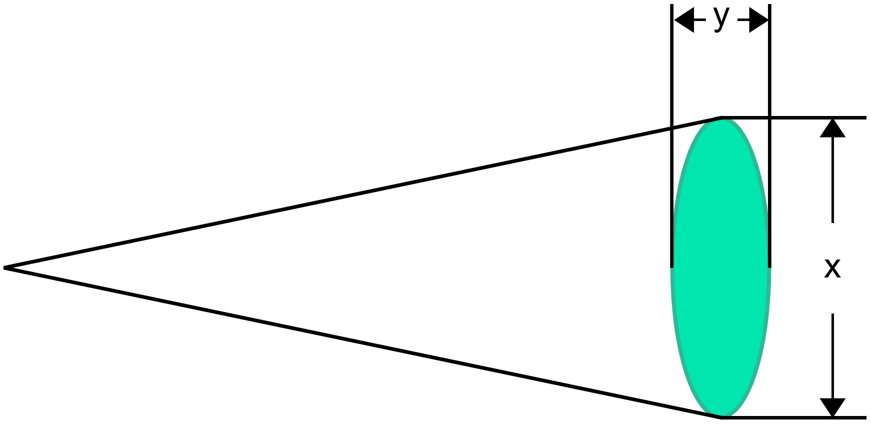


Figure 3-35: Beam diameter for elliptical beams.

The laser beam is, in general, very well collimated. However, small beam divergence is unavoidable. For small beam divergence, the angle of divergence is defined as the ratio between the beam diameter *D* at the distance *r* from the laser exit and the distance itself.

$$\phi = \frac{D}{r}$$

In the above formula, if the beam diameter is measured in mm and the distance to the laser exit is measured in m, the beam's divergence will be expressed in mrad.

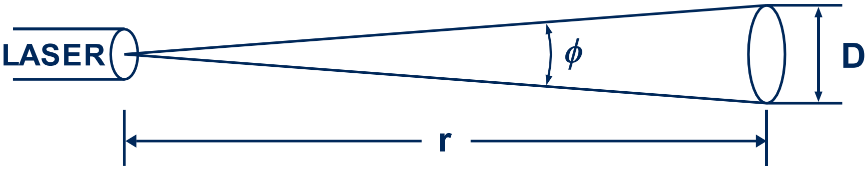


*Figure 3-36: Definition of laser beam divergence.*

The beam quality factor is noted as $M^2$ and is defined as the ratio between the real angle of divergence and the theoretical divergence of a perfect Gaussian beam. This ratio is always greater than one.

$$M^2 = \frac{\phi_{\text{real}}}{\phi_{\text{theoretical}}}$$

The quality factor of the beam is also defined as a measure of the beam's deviation from the transverse mode $TEM_{00}$.

### 3.5.2 Properties of the laser interacting with the target

When referring to the target or receiver of the laser beam, the interest switches from the energy or power of the laser beam, to energy or power density incident on a surface.

The energy density $E_d$ is defined as the total beam energy divided by the incident surface. The preferred unit for the $E_d$ is J/cm$^2$. The $E_d$'s is also called radiant exposure. Similarly, the power density $P_d$ is defined as the total power incident on the surface and is measured in W/cm$^2$. The $P_d$'s is also called irradiance.

For a 20 W laser, the power density where the beam diameter is 1cm is $P_d$ = 25 W/cm$^2$. If a lens is placed in front of the beam, the focused beam will have a higher $P_d$. If the $P_d$ is calculated where the beam diameter decreases to 0.01 cm, the calculated value is approximate 250,000 W/cm$^2$. Therefore, if the beam diameter decreases 100 times, the power density (or the energy density) increases 10,000 times.

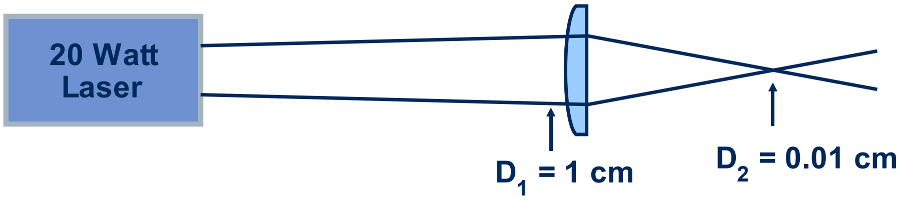


*Figure 3-37: Calculation of power density.*

Sometimes the $E_d$ or $P_d$ of a laser beam is loosely called the beam's "intensity – I". The Maximum Permissible Exposure (noted MPE) is the energy or power density of the laser beam to which a person's eye or skin may be exposed without hazardous effects.

As mentioned above, every laser beam has a divergence. Therefore, at a certain distance, the intensity of the laser beam is low enough to reach the applicable MPE. The distance at which the intensity of the laser beam is low enough for a person to look directly into the beam without sustaining any hazard is called Nominal Ocular Hazard Distance.

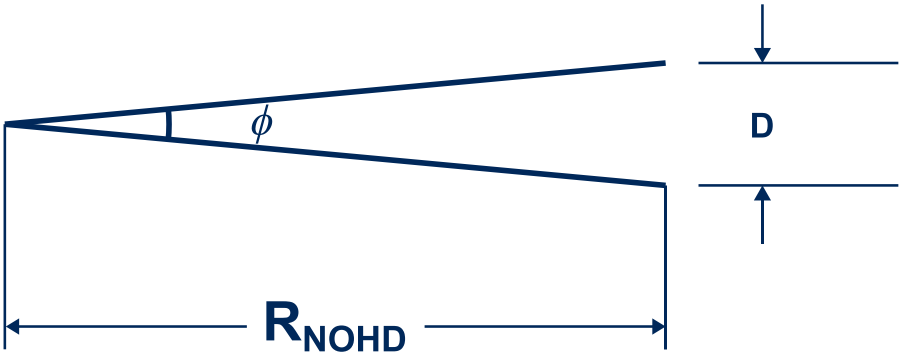


Figure 3-38: Nominal Ocular Hazard Distance (NOHD).

For some lasers used at the University of Toronto, this distance can be multiple hundreds of meters.

Similarly, the nominal skin hazard distance can be defined.

### 3.6 Point and extended light sources

Due to the type of image formed on the retina, a light source can be a point source or an extended source. Any type of light source can be considered a point source if they are at a very long distance from the observer, like a star.

If the observer is close to the light source, the source has a visible dimension and it is an extended source. If the observer is far from the source, the wavefronts are planes.

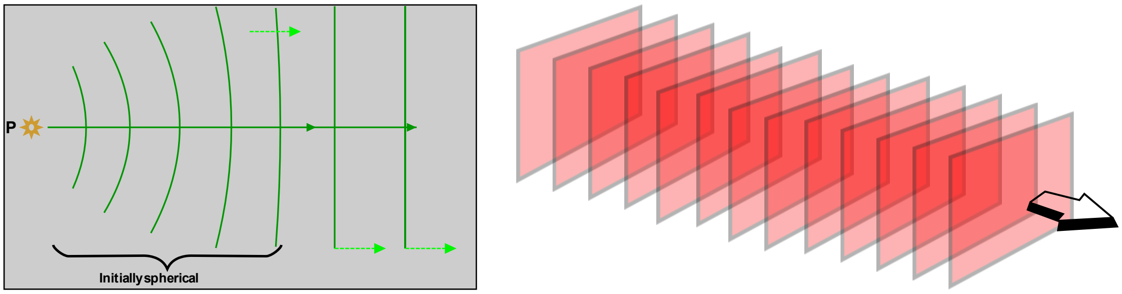


Figure 3-39: Wavefronts close to the point source and far from it (left). Plane wavefronts as they are seen by an observer far from the point source (right).

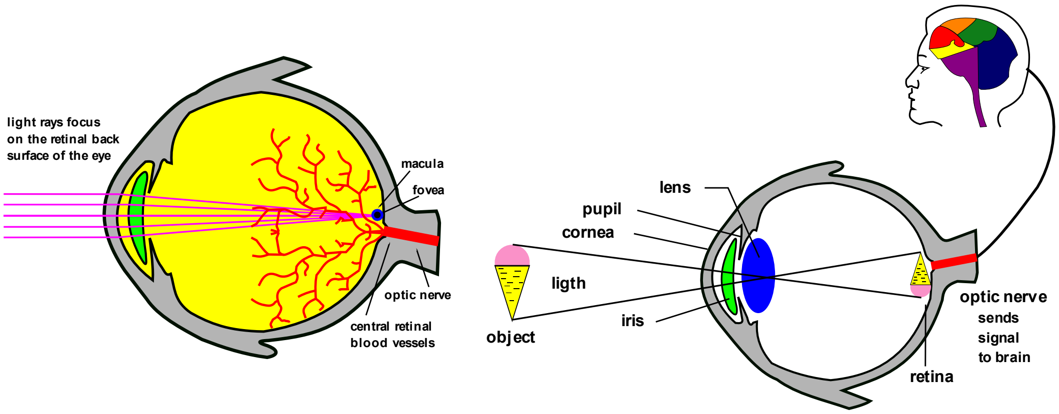


*Figure 3-40: Parallel light rays from a distant object. They form a point image in the retina (left). Light rays from a close object are not parallel. They form an extended image in the retina (right).*

The image on the retina depends on the type of source. If the source is a point source the image will be close to a point (a few micrometres – see section 5.2.3.3). If the source is an extended source the image on the retina is much bigger.

To distinguish between the two types of light sources, a physical quantity named apparent visual angle is defined. This angle is calculated with the help of the source size and the distance from the eye to the source.

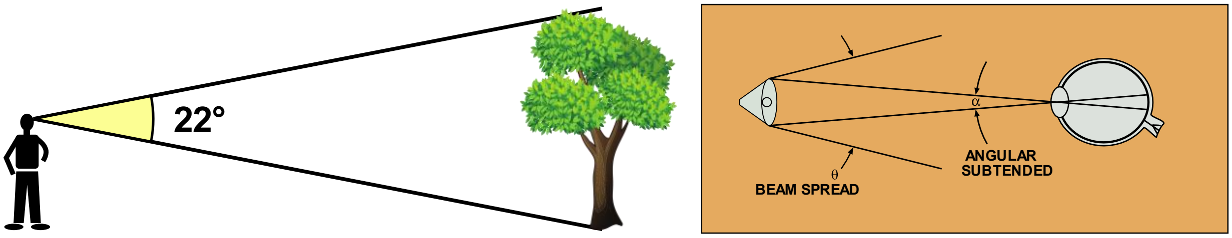


*Figure 3-41: Apparent visual angle of an extended source (left). Difference between beam spread ($\theta$) and apparent angle ($\alpha$) (right).*

The apparent visual angle is different from the angle of divergence (defined in section 3.5.1).

For small angles, the apparent visual angle can be defined as the ratio between the diameter of the object and the distance to the eye.

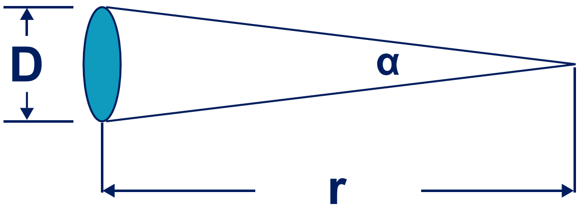


*Figure 3-42: Definition of apparent visual angle.*

For larger angles, a more precise definition involves the following formula:

$$\alpha = \frac{D}{r}$$

$$\alpha = 2\ \arctan\left(\frac{D}{2r}\right)$$

A light source is considered a point source if the apparent visual angle is smaller than 1.5 mrad.

$$\alpha \leq \alpha_{\min} = 1.5\ \mathrm{mrad}$$

The Sun is not considered a point source since the subtended angle of the Sun is approximately equal to 8.7 mrad.

Because the image on the retina from an extended source is larger than the one created by a point source, the safety analysis when using an extended source provides less restrictive results.

The light generated by a laser is coherent (the wavefronts are parallel planes and light rays are parallel) and generates on the retina an image similar to the image of a faraway star. Therefore, a laser is not an extended source, even when the subtended angle is larger than 1.5 mrad (e.g.: a laser with a diameter of 2 mm viewed from a distance of 0.5 m has a subtended angle of 4 mrad, but cannot be considered an extended source).

After a diffuse reflection, the beam loses coherence. The diffuse reflection spot on the rough surface can be considered an extended source for laser safety calculations.

An array of multiple diode lasers can also be considered an extended source since there is no coherence between different diode lasers.

In this case, the safety analysis must be made considering one diode as a point source, followed by calculations considering 4, 9, 16, 25, etc., diodes and the system being an extended source. The safest values must be used in the calculation of protective measures.

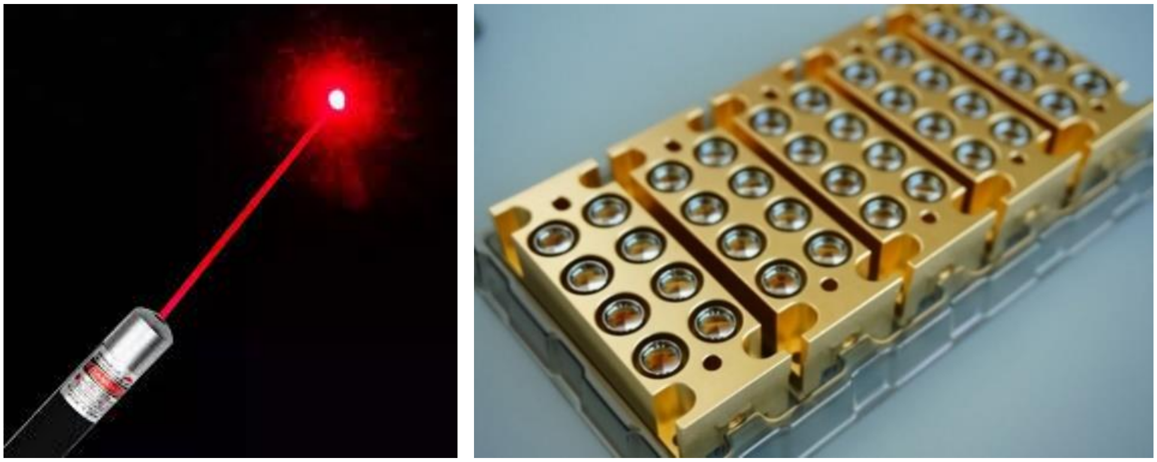


Figure 3-43: A laser spot on the wall (left) and laser arrays (right) are considered an extended source.

# 4 LASER SAFETY PRINCIPLES

## 4.1 General principles of health and safety

The philosophy of health and safety can be summarized in the following sentence: "Recognize and evaluate hazards, identify conditions of hazards occurring and try to eliminate these conditions". If the laser user can do this, he/she will ensure a high level of safe work with lasers.

To "recognize and evaluate hazards, identify conditions of hazards occurring" the user must: "know the laser he/she is working with". In chapters 2 and 3 of this manual, the fundamental notions necessary to understand laser hazards are presented. Laser technology evolves very fast. The user must read and understand the manual of the laser to be used; understand the type of laser; its physical principles and its construction.

Different types of lasers present different hazards. Continuous-wave lasers will pose a hazard different from very short pulses lasers (picoseconds or femtoseconds); a laser emitting in one wavelength is different from a laser emitting multiple wavelengths; a milliwatt laser will present a different hazard from a multi-kilowatt laser, etc.

The laser user must understand the differences between specular and diffuse reflections. The type of reflection depends on the wavelength and the roughness of the surface the laser hits. For a certain type of laser and laser applications, one or the other type of reflection can be more dangerous.

RISK = HAZARD x EXPOSURE

*Figure 4-1: Differences between Risk and Hazard.*

The user must also understand the properties of all-optical objects utilized in his/her laser experiments. Lenses or prisms can be hazardous because of stray beams created by back reflections; a polarizer can create a hazard in a direction that is different from the main beam; a beam splitter may create a beam in an unexpected direction, etc.

There is a difference between hazard and risk. Exposure to the Sun can cause skin burns, skin ageing or skin cancers. Blocking the Sun with a parasol or sunscreen can reduce the likelihood of the person having these effects.

A risk is a likelihood that a hazard harms a person exposed to that hazard. How can risk be mitigated when the hazard is known? Controlling a hazard to mitigate its risk of being the cause of an injury or illness is critical when the hazard can't be eliminated.

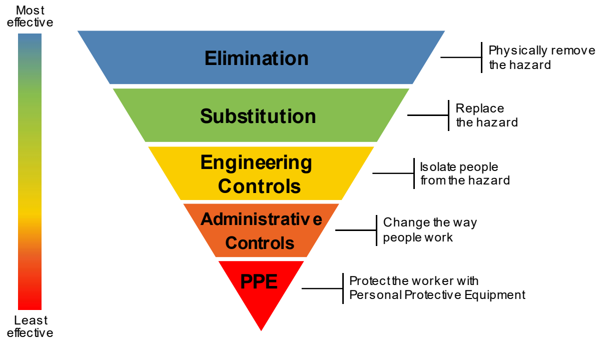


Figure 4-2: Effectiveness of controls.

Physically remove or replace lasers from a laboratory is not applicable in most research situations.

To eliminate conditions of a hazard occur, the laser user must implement engineering, administrative and procedural controls. The personal protective equipment, typically laser goggles, must be the last line of defence.

## 4.2 Engineering Controls

Engineering controls are physical barriers between the hazard and the user or other individuals that may be present. The user may be exposed to the hazard only if these physical barriers are: removed, disabled, or bypassed. In the case of a commercially available laser, engineering controls may be built around the laser allowing the hazardous beam to be emitted only in one direction. In this case, the user is protected against the other hazards present near the laser cavity, such as stray beams, electrical contacts, excitation sources, etc. In cases when the laser is used for one specific application, the manufacturer may also limit hazards by building an enclosure and limiting the access to the laser beam. This type of configuration where a higher-class laser is mounted inside an enclosure with interlocks is called a class 1 working environment.

For a laboratory-built laser, none of these controls is usually present. These types of situations are encountered in a laser lab when the user builds his/her laser for experimental/research purpose. In this case, it is up to the user to build engineering controls to reduce all risks related to its experimental setting. Besides, when a commercial laser (with built-in engineering controls) is used in new applications, the user is required to build the engineering controls adequate to control all hazards.

When assembling engineering controls, the user must understand all basic principles of the functioning of controls, the limitations of applicability, the necessity to build other controls when the current ones do not offer adequate protection.

The concept of “defence in depth” implies using more than one method to control a hazard. By applying this concept, the user is protected even when mistakes are made.

Examples of engineering controls are presented in section 7.3.2.

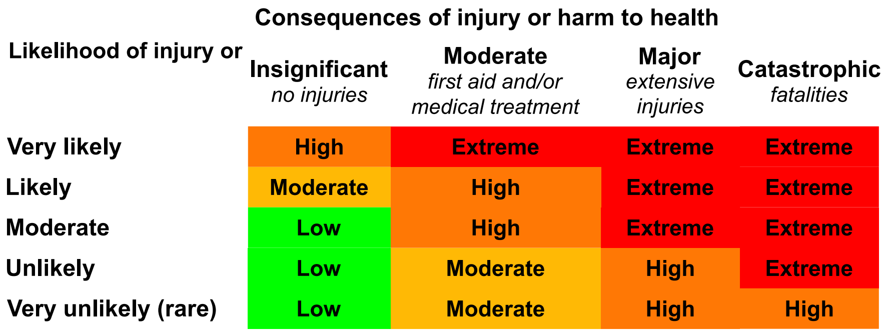
When physical barriers are not possible to be built, or not practical for a particular application, other controls must be put in place to mitigate risks and ensure the safe use of lasers. As requested by the applicable laws, regulations or standards, rules for the safe use of lasers must be followed. These rules may be in the form of standard operating procedures, alignment procedures, restrictions for operating the laser only by authorized trained people, defining the nominal hazard zones, controlling access, etc. Examples of administrative and procedural controls are presented in section 7.3.3.

Personal Protective Equipment (PPE) must be the last layer of defence. The PPE is meant to protect individuals when controls fail to prevent an incident or an accident.

An easy way to understand the principles behind the need for knowing your laser, introducing controls, and wearing the PPE is by comparing the use of a laser with driving a car. The first and most important condition for a person to drive a car is knowing how to drive, and especially how to stop the car safely. The manufacturer installs the turning wheel, the brakes, windshield, etc. The government establishes requirements for training, regulations and rules to drive on public roads. Finally, the last defence comes from the seatbelt, airbags, etc.

## 4.3 Principles of laser safety

When applying the general principles of health and safety to the use of lasers, it is important to understand that a laser is an important hazard with a low probability.



| | Consequences of injury or harm to health | | | |
|---|---|---|---|---|
| **Likelihood of injury or** | **Insignificant** *no injuries* | **Moderate** *first aid and/or medical treatment* | **Major** *extensive injuries* | **Catastrophic** *fatalities* |
| **Very likely** | High | Extreme | Extreme | Extreme |
| **Likely** | Moderate | High | Extreme | Extreme |
| **Moderate** | Low | High | Extreme | Extreme |
| **Unlikely** | Low | Moderate | High | Extreme |
| **Very unlikely (rare)** | Low | Moderate | High | High |

Extreme = immediate action

*Figure 4-3: Likelihood and consequences of injury.*

The probability of accident increases when the user does not know where the main beam and all stray beams are located. Unexpected reflections, either specular or diffuse from walls or objects around the laser are also increasing the likelihood of injuries. The same can happen when the user does not understand how optical elements are used in an experimental setting.

The user can reduce the probability of injury by controlling and containing the laser beam and stray beams. One way to control stray beams generated by back reflections on optical elements is to have an anti-reflective coating on those elements. Any type of beam can be controlled by enclosing the experimental setup, and if it’s possible by creating a “Class 1 working environment” (see section 4.5).

## 4.4 The objective of the ANSI Z136 standards

The American Standard for Safe Use of Laser ANSI Z136 is the most used laser safety standard in North America. The objective of this standard is "to provide reasonable and adequate guidance for the safe use of lasers".

The objective is achieved by classifying lasers according to their hazard, and by specifying appropriate controls for each laser class.

The Laser Safety Officer (LSO) is an individual nominated by the institution/employer to oversee the laser safety program implementation inside the institution/company. The LSO should be a person trained in laser safety, optical engineering, or a related field. In this case, the LSO can perform/verify the classification of lasers. When the LSO does not have the qualification, knowledge, or experience to do the classification, he/she can delegate this responsibility to a knowledgeable person.

The best way to ensure protection to laser users, bystanders, visitors, etc., is to develop a clear laser safety program. The program must support research and innovation and must establish a high level of laser safety across the institution. To ensure these objectives, the laser safety program must be adapted to the level of hazards within the institution. Some elements of the programs will be common, for example, the need for laser classification, alignment procedures, laser safety for contractors, etc. Other parts of the program must be specific to applications, for example, if the laser will be used for research, medical or industrial applications. The environment where the laser is to be operated is also specific. Lasers can be used indoors or outdoors, the beam can be completely open, or partially open, or enclosed.

The ANSI Z136 standard requires establishing hazard controls based on laser class. In some situations, the LSO may decide to ensure hazard controls based on the hazard zones. The "alternate control measures" must offer the same or better protection to the laser users, bystanders, and visitors.

## 4.5 Laser classes

Laser classification is the basis of installing the laser controls. The laser manufacturer must post the laser class on the laser label. If the laser is made in the institution or modified, or if there is a doubt about the laser class, the LSO must determine the laser class. The procedure for classifying the lasers is detailed in section 7.2.5.

### 4.5.1 Class 1

A class 1 laser is a laser that during any foreseeable exposure time emits power or energy at a level that poses no danger to the eye or the skin of a person. This type of laser is exempted from any control measures. It is safe for unrestricted use including be used by the general population.

A class 1 M (M stands for Magnification) is a class 1 laser where the level of irradiation is measured with a smaller aperture or at a greater distance from the apparent source.

*Figure 4-4: Class 1C laser.*

Therefore it is potentially hazardous when viewed using an optical instrument, such as lenses, microscope, binoculars, etc. This type of lasers is exempted from any control measures unless: optically aided viewing of the beam is expected and unattended operation in areas where the public is present.

Class 1 working environment is a laser system, which can contain a higher-class laser enclosed in a structure in such a way that is incapable of causing injury during normal operation. In general, such a structure has an interlocked door and a reset button. No additional controls are required for a laser used in a class 1 working environment. The system does not need to have high-class laser labels outside. If the system is opened and the safety interlock system is defeated; for example, during repair, maintenance, or service, all controls required for the actual laser class that is embedded, must be put in place. The label indicating the high-class laser must be visible after the system is opened.

A special case of class 1 working environment is a class 1C laser, as defined in the IEC 60825-1 or EN60825-1 standard. Class 1C (C stands for “contact” or “conditional”) is dedicated to commercial laser products like laser hair removal devices. The interlock system of this device monitors if a sensor is in contact with the skin. The laser will not operate when the skin is not in contact with the sensor.

### 4.5.2 Class 2

A class 2 laser emits higher energy/power than a class 1, but the protection comes from the natural aversion of the eye against high levels of illumination. The protection by the natural aversion can be obtained by blinking, moving the eyes or the head, which reduces the exposure time of the eye to the laser radiation. This natural aversion is only possible if the person can see the laser beam. Therefore, all class 2 lasers are in the visible range, from 400 to 700 nm.

Examples of class 2 lasers are laser pointers or laser scanners. If the laser is a continuous wave (CW) laser, to be considered class 2, its power must range between the maximum power of a class 1 laser and 1 mW. Class 2 lasers are exempted from any controls unless intentional direct viewing of the beam is expected. However, it is illegal for aiming a laser at an aircraft or into airspace. These lasers are not safe for children.

A class 2M laser is a class 2 laser where the level of irradiation is measured with a smaller aperture or at a greater distance from the apparent source, therefore is potentially

Figure 4-5: Class 2 lasers.

hazardous when viewed using an optical instrument. This laser is exempted from any control measures unless: intentional direct and optically aided viewing of the beam is expected; or when an unattended operation is probable in areas where the public is present.

### 4.5.3 Class 3

A class 3 laser is normally hazardous when direct viewing of the beam is expected. They can also be dangerous after specular reflections. Viewing diffuse reflections is normally safe.

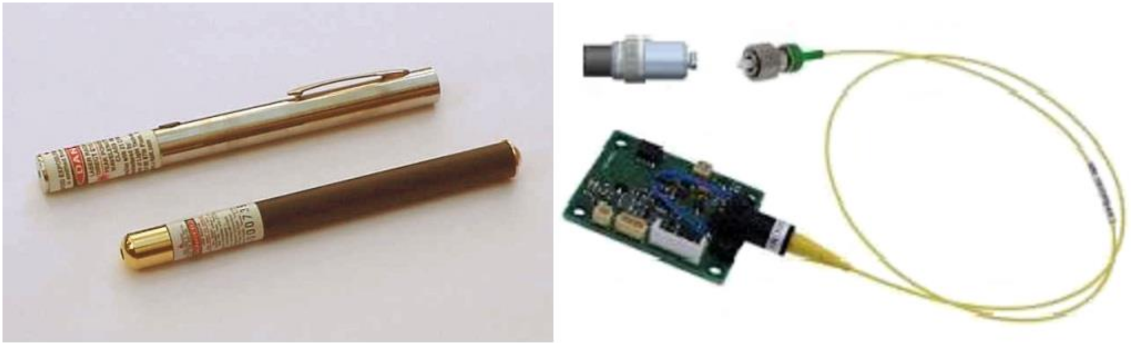


Figure 4-6: Class 3R lasers.

Class 3 was divided into two subclasses: class 3R (former 3a or 3A) and class 3B.

Class 3R (R comes from “reduce risk”) covers lasers with wavelengths in both visible and invisible ranges. Class 3R visible lasers (400 to 700 nm) have emissions between 1 to 5 times class 2 lasers. Therefore, in this wavelength range, CW lasers have emissions between 1 to 5 mW.

Class 3R lasers outside visible range (UV from 180 to 400 nm, and IR from 700 nm to 1 mm) have emissions between 1 to 5 times class 1 laser. Many low-power fibre lasers used for telecommunications are classified as class 3R.

A class 3B laser emits an average power/energy above class 3R but under class 4.

For the wavelengths in the UV (<400 nm) and FIR (>1400 nm) ranges, a class 3B emits more than 5 times Class 1 AEL, but less than 0.5 W for T > 0.25 s or less than 0.125 J total energy emitted in T < 0.25 s.

For the wavelengths in the visible (400 to 700 nm) and NIR (700 to 1400 nm) range, a class 3 B emits more than class 3R but:

- Less than 0.5 W for exposure time > 0.06 $C_A$ ($C_A$ from Table 6a ANSI Z136.1 – 2014)
- Less 0.03 J*$C_A$ per pulse for exposure time < 0.06 $C_A$ when 0.5 W peak power is exceeded (pulses separated by less than $t_{min}$ – Table 1 ANSI Z136.1 – 2014, are considered one pulse), and
- Less than 0.125 J total energy in 0.25 s

For continuous wave (CW) visible lasers, class 3B ranges from 5 mW to 500 mW.

The list of controls required to operate a class 3B laser is presented in chapter 7.

In Canada[1], you **cannot** possess a hand-held laser over 1 mW outside of a private dwelling within:

- municipalities within the greater Montréal, Toronto or Vancouver regions
- a 10-kilometre radius of an airport and certified heliports

You **may** possess a hand-held laser anywhere in Canada for any of the following reasons:

- The laser has 1 mW of power or less
- You own the laser for a legitimate purpose, such as for work, school or educational purposes
  - Learn more about enforcement and penalties
- You are a member of an astronomy society and own the laser for that purpose
  - Learn more about lasers for astronomy and laser light shows

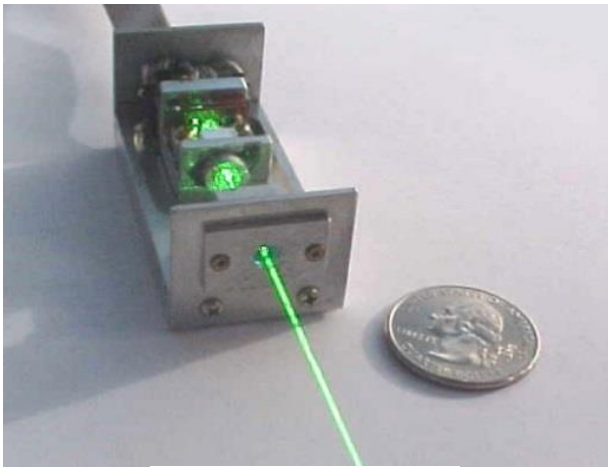


*Figure 4-7: Class 3B laser.*

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[1] https://tc.canada.ca/en/programs/non-funding-programs/transportation-security-clearance-program/transportation-security-clearance-program-aviation/use-hand-held-lasers-legally-safely

### 4.5.4 Class 4

The class 4 lasers are high power lasers in the UV, visible and IR regions of the spectrum (wavelength between 180 nm to 1 mm). They present an eye hazard for direct viewing of the beam and viewing of specular and diffuse reflections. They can also present a hazard to the skin, they can start a fire, can generate air contaminants, and hazardous plasma radiation.

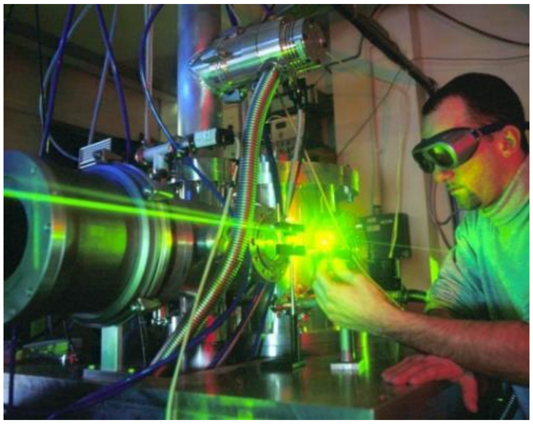


*Figure 4-8: Class 4 laser.*

A class 4 laser emits power or energy per pulse above the limits of a Class 3B laser. The controls associated with a class 4 laser are presented in chapter 7.

### 4.5.5 Overview of Laser Safety Classes

*Table 4-1: Laser classes chart**

| Class | Type of lasers | Meaning | Relationship to MPE | Hazard area | Typical AEL for CW lasers |
|---|---|---|---|---|---|
| Class 1 | Very low power or embedded lasers | Safe | MPEs are not exceeded, even for long exposure duration (either 100 seconds or 30000 seconds), even with the use of optical instruments | No hazard area (NOHA) | 40 µW for blue |
| Class 1M | Very low power lasers; either collimated with large beam diameter or highly divergent | Safe for the naked eye, potentially hazardous when optical instruments** are used | MPEs are not exceeded for the naked eye, even for long exposure durations, but may be exceeded with the use of optical instruments** | No hazard area for the naked eye, but hazard area for the use of optical instruments** (extended NOHA) | Same as Class 1, a distinction with measurement requirements |
| Class 2 | Visible low power lasers | Safe for unintended exposure, prolonged staring should be avoided | Blink reflex limits exposure duration to nominally 0.25 seconds. MPE for 0.25 seconds is not exceeded, even with the use of optical instruments. | No hazard area when based on unintended exposure (0.25 seconds exposure duration) | 1 mW |
| Class 2M | Visible low power lasers; either collimated with large beam diameter or highly divergent | Same as Class 2, but potentially hazardous when optical instruments** are used | MPE for 0.25 seconds not exceeded for the naked eye, but maybe exceeded with the use of optical instruments** | No hazard area for the naked eye when based on accidental exposure (0.25 seconds exposure duration), but hazard area for the use of optical instruments** (extended NOHA) | Same as Class 2, a distinction with measurement requirements |
| Class 3R | Low power lasers | Safe when handled carefully. Only a small hazard potential for accidental exposure | MPE with the naked eye and optical instruments may be exceeded up to 5 times | 5 times the limit of Class 1 in UV and IR, and 5 times the limit for Class 2 invisible, i.e. 5 mW | 5 times the limit of Class 1 in UV and IR, and 5 times the limit for Class 2 invisible, i.e. 5 mW |

| | | | | | |
|---|---|---|---|---|---|
| Class 3B | Medium power lasers | Hazardous when the eye is exposed. Wear Eye Protection within NOHA. Usually no hazard to the skin. Diffuse reflections usually safe | Ocular MPE with the naked eye and optical instruments may be exceeded more than 5 times. Skin MPE is usually not exceeded. | Hazard area for the eye (NOHA), no hazard area for the skin | 500 mW |
| Class 4 | High power lasers | Hazardous to eye and skin, also diffuse reflection may be hazardous. Protect Eye and skin. Fire hazard. | Ocular and skin MPE exceeded, diffuse reflections exceed ocular MPE | Hazard area for the eye and skin, hazard area for diffuse reflections | No limit |

* Chart courtesy of David Sliney

**Note for optical instruments: two classes of optical instruments are accounted for: such that increase hazard of the well-collimated beam with large diameter, i.e. telescopes and binoculars, and such that increase hazard of highly divergent beams (such as from fibres or LEDs), i.e. eye loupes and magnifiers. Generally, only one of the groups of optical instruments for a given laser product leads to an increase in the hazard.

### 4.5.6 Laser labels

All lasers must be labelled with a sticker indicating the laser hazard, laser class, the word “caution”, “warning’ or “danger”. For classes 3B or 4 also the wavelength and maximum laser power must be mentioned.

The international sign for laser hazard is black on a yellow background. Labelling the laser can be challenging when the dimensions of the laser product are very small. If you douth the accuracy of the information indicated on the laser, please consult the University LSO before using the laser.

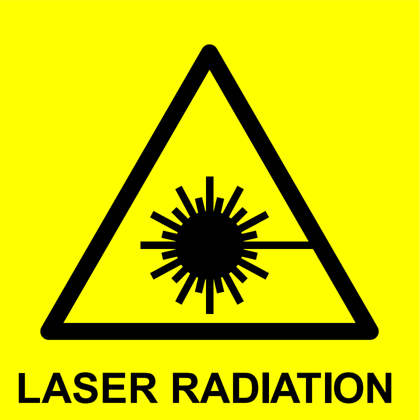


*Figure 4-9: Laser hazard warning sign.*

Some laser components do not emit laser radiation unless mounted in an electric circuit. In this case, the whole system is the laser.

Lower laser classes (class 1, 1M, 2, 2M and 3R) labels must have the word “caution”.

Commercial laser products are required to be labelled by the manufacturer. When a laser is built or modified at U of T (in-house laser product) the LSO must classify and label the laser. These laser products cannot be sold or lend to other institutions.

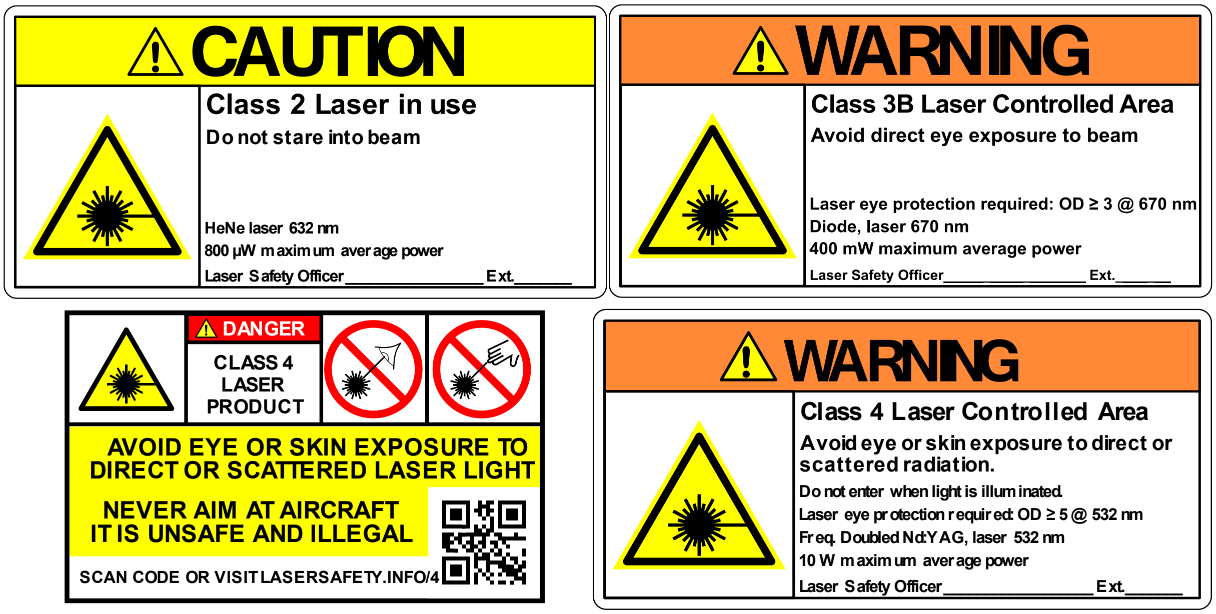


*Figure 4-10: Class 2 laser warning sign (top-left). Class 3B laser warning sign (top-right). Different types of class 4 laser warning signs (bottom left and right).*

What is wrong with this laser label in Figure 4-11? Firstly, the colour is not the standard colour for laser labels. The laser sign must be black on a yellow background or red on a white background. Secondly, the emission of a class 3A, or more accurate a class 3R, must be a maximum of 5 mW at 450 nm. A laser label like this indicates that the manufacturer does not follow the appropriate labelling and classification procedure.

Laser users at the U of T must inform the LSO when a wrong laser label is discovered. The LSO will classify the laser and install a correct laser label.

*Figure 4-11: Wrong laser label.*

# 5 LASER BEAM HAZARDS

Hazards associated with the use of lasers are separated into two categories: hazards that may result in human exposure to the laser beam (laser beam hazards) and all other hazards encountered while working with lasers but not related to exposure to the laser beam (non-beam hazards).

A laser beam can be hazardous to the eye and the skin of a person. To better understand the effects of a laser beam on the eye or skin, the following presents damage mechanisms to human tissue e.g. skin, cornea, retina.

## 5.1 Tissue damage mechanisms

The type of damage that a laser beam can cause to human tissue depends on wavelength, power density, energy density, exposure time and the type of tissue. A tissue is damaged only when the laser beam interacts with it. The interaction can be photochemical or thermal. The ablation of the tissue can also happen when the power density is very high (above 10 W/cm$^2$). This is most likely to happen when the laser pulse is very short (under ns).

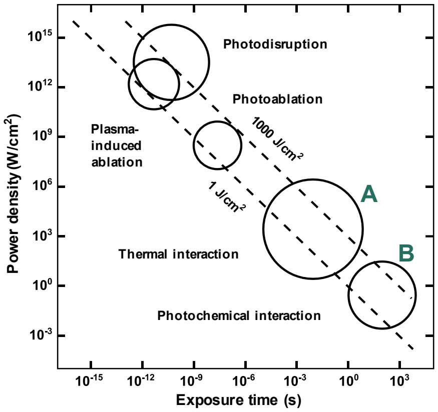


*Figure 5-1: Types of laser beam-tissue interactions.*

### 5.1.1 Photochemical interaction

This type of interaction is predominant at exposure times between 1 s and 1000 s. Photochemical interaction is characterized by the interaction between individual photons and molecules resulting in molecular bond breaking and chemical reactions.

Since molecular bond breaking and chemical reactions can happen only if the photon carries enough energy, a photochemical reaction only happens above a certain energy threshold. This is equivalent to a photon having a minimum frequency or a maximum wavelength. Some photochemical reactions are limited by an upper energy level. Therefore, this type of reaction is limited to a narrow wavelength range.

During photochemical injury, the tissue cells are destroyed one by one; the total energy absorbed by the tissue is more important than the beam power (the beam power can be interpreted as the rate at which the energy is delivered).

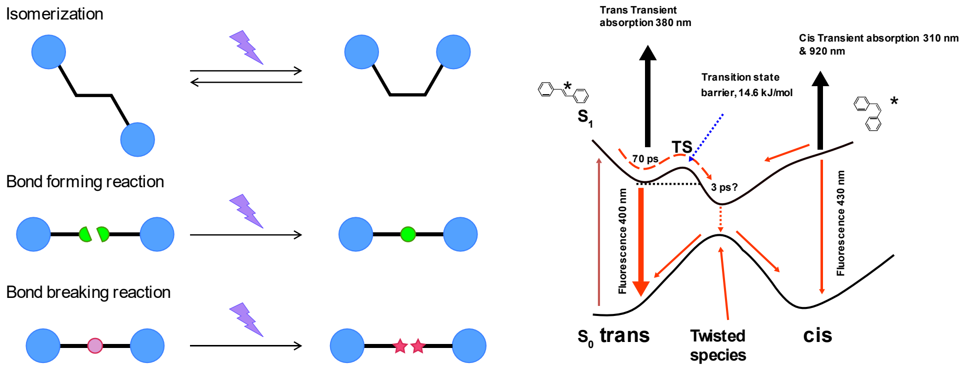
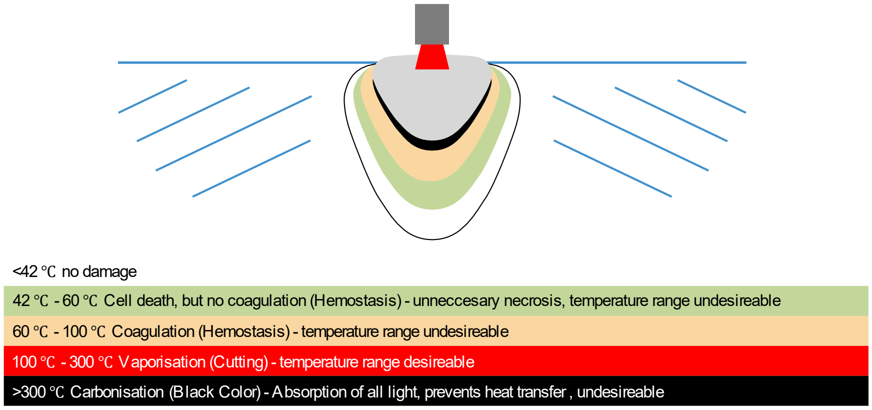


Figure 5-2: Photochemical interactions.

Since not all cells of human tissues will be affected immediately, photochemical effects appear with a delay—between a few hours to days—after the accident.

## 5.1.2 Thermal interaction

In this type of interaction, photons are absorbed in the tissue producing an increase in temperature.



<42 ℃ no damage

42 ℃ - 60 ℃ Cell death, but no coagulation (Hemostasis) - unneccesary necrosis, temperature range undesireable

60 ℃ - 100 ℃ Coagulation (Hemostasis) - temperature range undesireable

100 ℃ - 300 ℃ Vaporisation (Cutting) - temperature range desireable

>300 ℃ Carbonisation (Black Color) - Absorption of all light, prevents heat transfer , undesireable

Figure 5-3: Thermal interactions.

As opposed to photochemical damage, thermal damage is not limited by the photon's energy. The temperature increase is resulting from the rapid absorption of energy carried by photons in the tissue without enough time for heat dissipation. The thermal damage is predominant when the exposure time range between $10^{-6}$ s and 1 s. The thermal interaction is a rate process; the rate at which the energy is absorbed—the power of the laser—is more important than the total energy absorbed. Damages created by thermal interaction are instantaneous.

Thermal interactions are used in laser surgery. During surgery, a certain temperature is desired to be obtained. At other temperatures, the tissue will be damaged without obtaining the desired clean cut. If the temperature is too low the cells will die due to coagulation, but there will be no cut. If the temperatures are too high, carbonization occurs resulting in an unnecessary number of cell necrosis.

### 5.1.3 Tissue ablation

At high power densities (above $10^6$ W/cm$^2$) the tissue ablation is the prevalent damage process. Such power densities are obtained with very short laser pulses (under ns).

The photoablation process results in the excitation and dissociation of the molecules. This process is predominant in the ns laser pulse range.

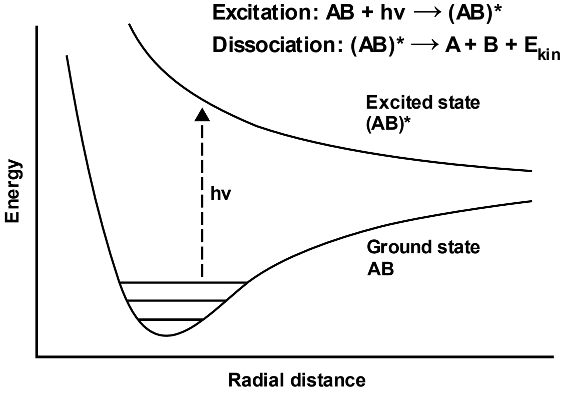


*Figure 5-4: Potential energy surface and energy transfer in the photoablation process.*

Photo disruption and plasma-induced ablation are predominant effects in the ps and fs range. Plasma, which is the state of matter in which atoms are separated into nuclei and electrons, is generated at extremely high power densities (above $10^{10}$ W/cm$^2$).

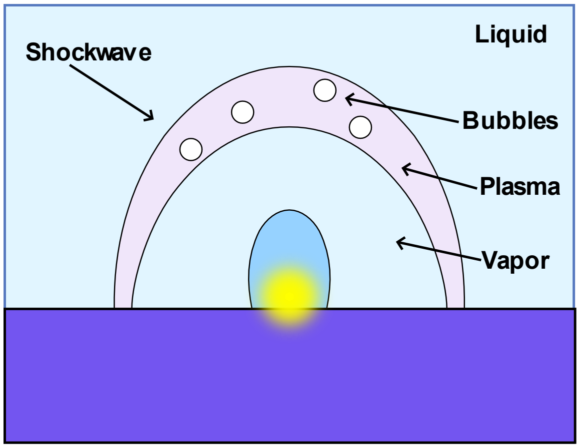


*Figure 5-5: Plume created by a plasma-induced ablation.*

## 5.2 Human eye

There is no “eye-safe laser”. This term was improperly used to refer to lasers outside the visible and near-infrared range (wavelengths shorter than 400 nm and longer than 1400 nm) where the laser radiation normally does not reach the retina.

Any part of the human eye can be damaged by a laser beam. To better understand the connection between the type of damage and the affected part of the eye, the laser user must understand the main components of the human eye and their role in the viewing process.

In this section, the anatomy and physiology of the eye are presented only to the level necessary to understand the type of precautions necessary to be taken against laser hazards.

### 5.2.1 The anatomy of the eye

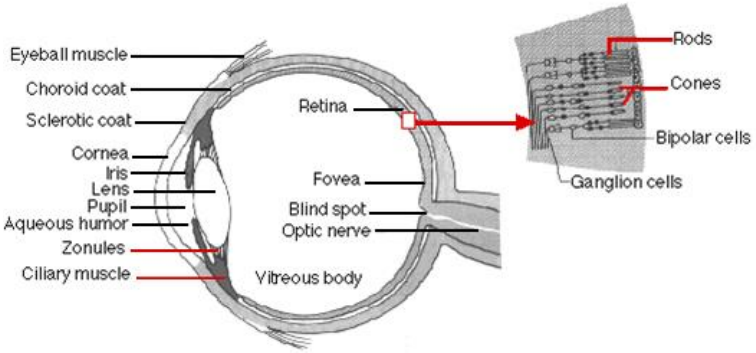


*Figure 5-6: Anatomy of the human eye.*

The cornea is the transparent skin that separates the eye from the environment. It has two main functions: protection from the environmental agents and focusing the light entering the eye. Due to its shape and curvature, the cornea acts as a lens focusing the light into the retina. Since the curvature of the cornea cannot be adjusted, focusing is not always perfect for every viewing condition. Other components in the human eye, to be discussed later, will do fine adjustments to create an image in the retina.

The epithelium is the outer layer of the cornea and is constantly regenerating. The eyelids remove the dead cells from the surface, which are replaced by new cells.

The iris, which is the coloured part of the eye, controls the amount of light that enters the eye. The iris is a ring-shaped tissue with a central opening, which is called the pupil. The iris has a ring of muscle fibres around the pupil, which, when they contract, causes the pupil to constrict and its diameter becomes smaller. This contraction is normally triggered

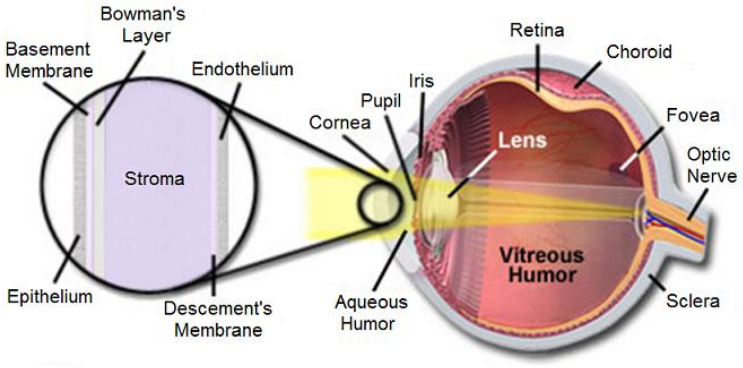


*Figure 5-7: Structure of the human cornea.*

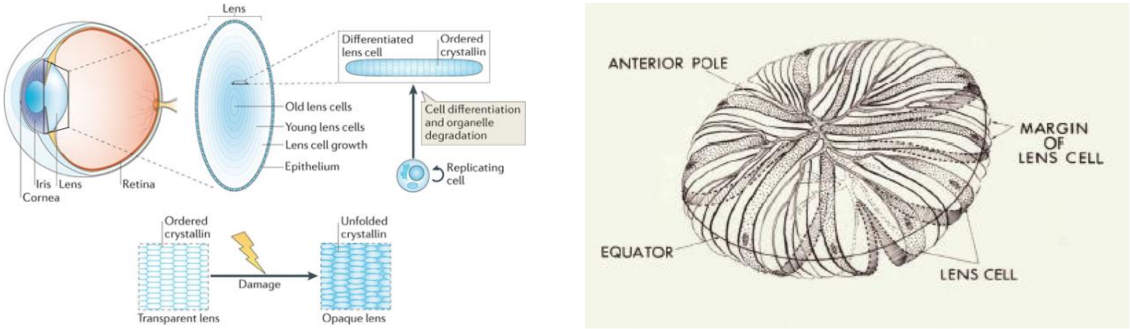


*Figure 5-8: Structure of the human lens and mechanism of cell replication (left). Old lens cells in the central part and young, stem cells in the equatorial region.*

when the eye is in a bright environment. The second set of muscle fibres are responsible to dilate the pupil. When these muscles contract, the diameter of the pupil becomes larger.

This happens when the eye is under reduced illumination or in darkness. The diameter of the pupil varies between 2-3 mm in bright conditions and 7 mm in the dark. Certain drugs, such as the ones used for fundoscopy, can dilate the pupil even more to a diameter of around 8 mm. The diameter of the pupil continuously changes to control the amount of light that can reach the interior of the eye.

Behind the iris and pupil is the lens of the eye. The role of the lens is to fine-tune the image on the back of the eye. As opposed to the cornea which can be compared to an optical lens with fixed focus, the lens of the eye is an optical lens with adjustable focus.

The lens is supported by the ciliary muscles. When these muscles contract or stretch, they change the shape of the lens, changing the focal distance to ensure that the image is formed on the right spot of the retina.

The eye lens has many stem cells that are responsible for making new corneal cells to replace damaged ones are located at the edge of the cornea closer to the equatorial part. When these stem cells are damaged, the regeneration process is affected. This is the reason why the oblique rays absorbed in the lens are more dangerous than the direct rays.

In the back of the eye is situated the retina. The retina is the extension of the optical nerve and consists of multiple layers.

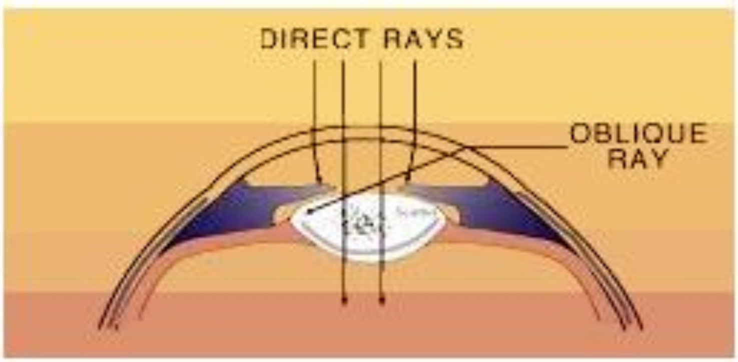


*Figure 5-9: Direct and oblique rays reaching different parts of the lens.*

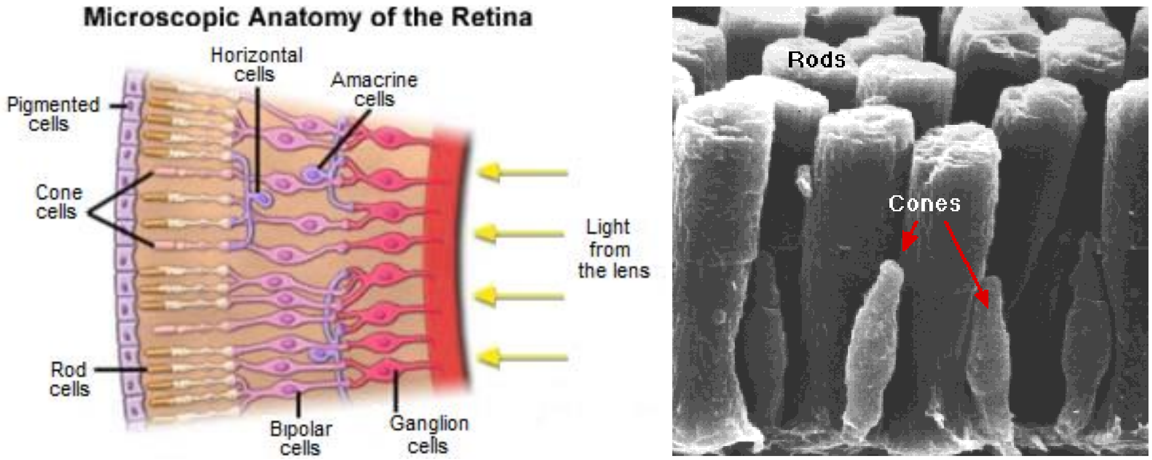


*Figure 5-10: Structure of the human retina (left). Electron microscope photography of human cones and rods (right).*

The last layer of the retina is formed by specific cells that are light receptors, the cones, and the rods. On the back of the eye, behind the rods and cones, there is a layer of cells called the retinal-pigmented epithelium. The main role of this epithelium is the absorption of light, which passes unabsorbed by the rods and cones. This absorption prevents the back reflections, which can result in the perturbation of the image formed in the rods and cones and is responsible for the black (dark brown) appearance of the pupil. When photography is taken using a flash, the absorption in the cones, rods and the epithelium is not complete, and the pupil appears red (the "red-eye"). This is due to the reflection of light from the epithelium cells on the back of the eye.

The human eye has approximately 6 million cones and there are three types of them corresponding to the main colours (blue, green, and red). They are mostly located in the middle of the eye, in a portion of the retina called fovea centralis. Fovea centralis is around 30 μm in diameter and is situated in the centre of the macula, which is around 0.6 mm in diameter. The cones are relatively insensitive to light and they need good illumination to form an image, but they can distinguish colours and fine details.

Rods are the other type of light-sensing cells in the human retina. They have high sensitivity to radiation and therefore, they can function with a low level of illumination. As

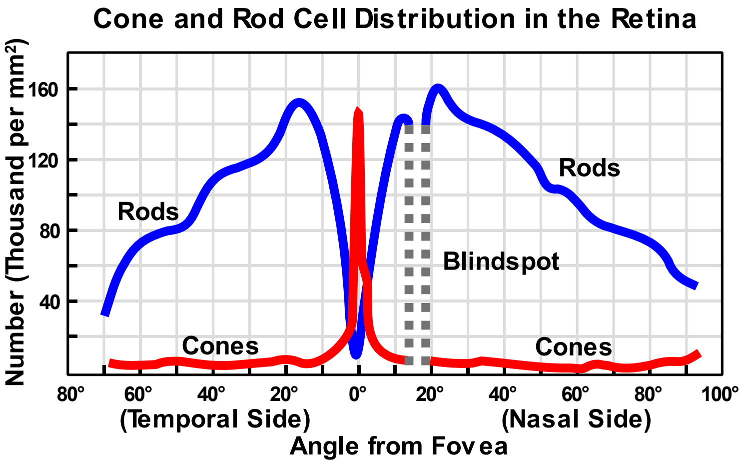


*Figure 5-11: Distribution of rods and cones in the retina.*

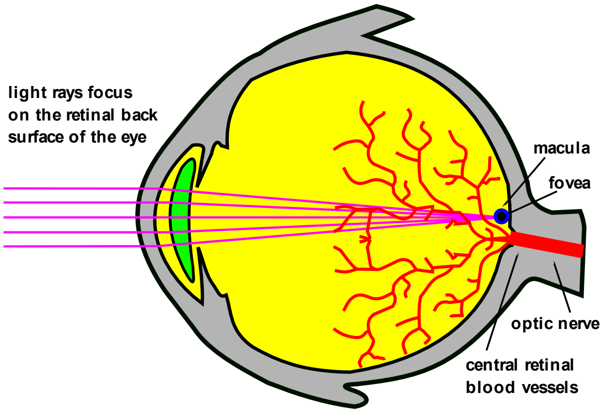


*Figure 5-12: Focusing of light on the macula.*

a difference to the cones, they cannot distinguish colours or fine details. They are distributed on the peripheral part of the retina except for the blind spot. The blind spot is the part of the retina that is connected to the optic nerve.

The optic nerve, a bundle of over 1 million nerve fibres, is responsible for transmitting nerve signals from the eye to the brain. These nerve signals contain information to be processed by the brain. The front surface of the optic nerve, which is visible on the retina, is called the optic disk or optic nerve head.

### 5.2.2 The physiology of the eye

How does the eye work? In a simplistic explanation, the light passes through the cornea (where visible light is focused), then through the pupil and the lens, and is absorbed in the retina. The iris controls the dimension of the pupil and therefore the amount of light reaching the retina. The cornea and the lens ensure that the focus of the image is on the right spot of the retina. The light absorbed in the cones and rods triggers a chemical reaction in these specialized cells. The chemical reaction will generate a signal that is transmitted through the optic nerve to the brain. In the brain, the information is processed and an image is interpreted. The image formed on the retina is upside-down. In the brain, the image is restored to normal. The brain needs time and training to interpret the signals received from the eye. A newly born child does not see the way an adult sees.

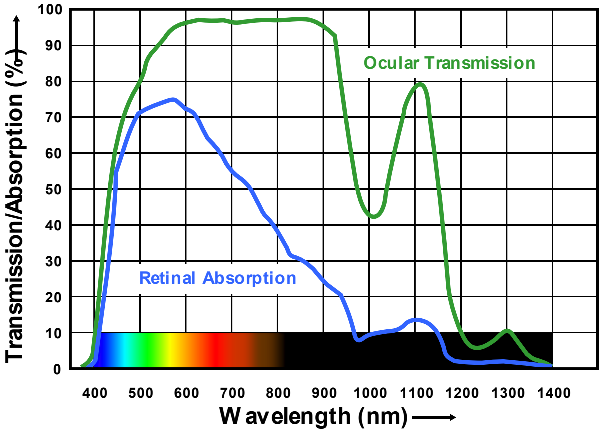


*Figure 5-13: Retinal absorption and ocular transmission of the human eye. Electromagnetic radiation between 400 and 1400 nm can reach the retina.*

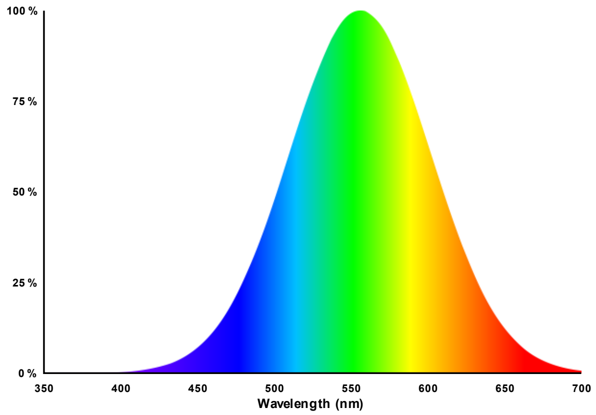


*Figure 5-14: Spectral luminous efficiency.*

It is important to understand that the eye is an organ and different parts of the eye are in continuous movement to ensure focus and stability of images received. The eyeball moves, the iris changes the dimension of the pupil, the lens changes the focal distance, etc. A laser accident can cause the melting of the cornea and iris together resulting in a person's incapacity to see, even if the optic nerve, the cones, and rods are not been affected.

In laser safety, only the electromagnetic radiation in the wavelength range between 180 nm and 1 mm is considered. Because of the eye's structure, different wavelengths affect different parts of the eye in different ways. Only the wavelengths between 400 and 1400 nm reach the retina.

Electromagnetic radiation between 400 and 700 nm is considered visible light. For lasers emitting in the region between 700 and 800 nm, the user may still distinguish a weak image on a white card, especially in a dark room.

Not all individuals perceive colours in the same way. For example, 8 % of the male population has a colour perception difference that is usually described as 'red-green colour blindness' due to the lack of the red or green retinal photoreceptor in their eyes.

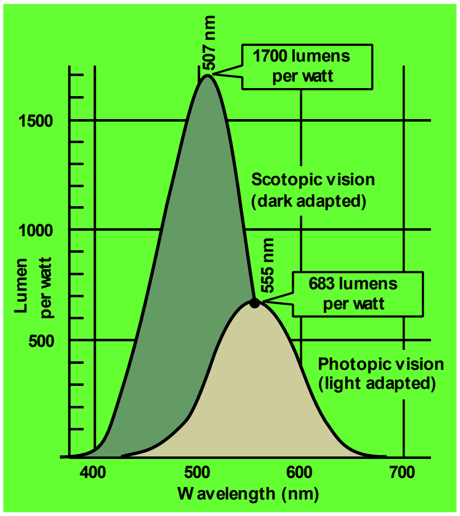


*Figure 5-15: Photopic and scotopic efficiency curves.*

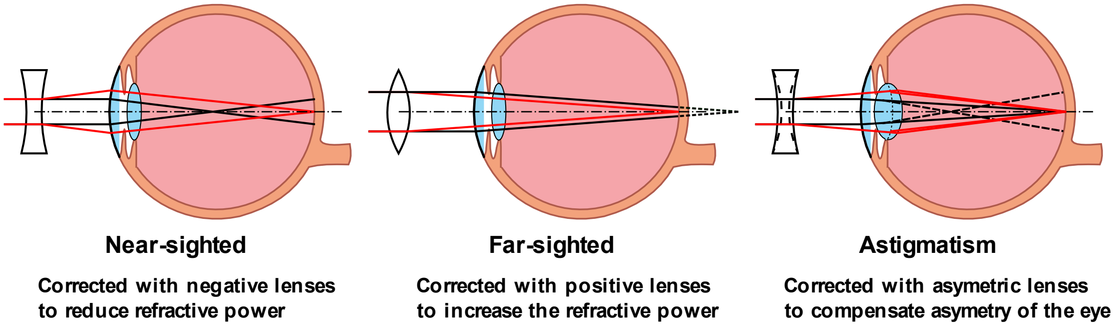


*Figure 5-16: Different refractive error conditions of the eye and its corrections*

The light with wavelengths on either side of the visible spectrum and near-infrared (i.e. ultraviolet, medium, and far-infrared) are absorbed in the front of the eye by the cornea, the iris, and the lens, and therefore never reach the retina. This absorption can damage the front of the eye.

Spectral luminous efficiency (luminosity efficiency function) connects the power/energy density that reaches the retina with the human perception of brightness and it is measured in lumens per watts. For the day vision (photopic vision) the maximum efficiency is at 555 nm, which is connected to the solar emission spectrum. For the dark-adapted vision (scotopic vision) the maximum is at 507 nm. The efficiency of scotopic vision is around three times higher than for photopic vision. This is related to the higher light sensitivity of eye rods compared to one of the cones.

An interesting feature of eye physiology is that parts of the cornea and the lens can regenerate themselves from damage in a few days (depending on severity), whereas the retina cannot.

Vision is measured by the Snellen Visual Acuity Chart. According to this chart, the 20/20 vision means the normal eye of a person can see clearly at 20 feet distance. A person with 20/40 vision at 20 feet away from an object will see what a normal eye sees when it is 40 feet away from the object. A person with a 20/15 vision at 20 feet away from an object will see what a normal eye sees when it is 15 feet away from the object. This means this person will see details more clearly than someone with 20/20 vision will.

There are many reasons an individual may not have 20/20 vision, some of which are not correctable such as amblyopia or better known as lazy eye, trauma to the eye, or even diseases such as diabetes or macular degeneration. There are causes of less than a perfect vision that is correctable; these are known as refractive errors. When light focuses accurately onto the retina, clear vision is achieved. The result is often 20/20 vision. However, millions of people in the world cannot focus clearly without a crutch such as (prescription eyeglasses) or contact lenses. This is because they have refractive errors. There are four main refractive errors; they are:

Hyperopia—also known as farsightedness—is a condition in the eyes that see objects better at long distances rather than short ones. Hyperopia occurs due to light not being bent enough and the image would hypothetically form behind the retina. Hyperopia must not be confused with presbyopia.

Myopia—also known as nearsightedness—is a condition in the eyes that sees objects better at short distances rather than long ones. This is due to light rays being bent too much and the image forms before the retina.

Astigmatism is a condition due to an irregularly shaped eyeball and causes light rays to bend erratically resulting in blurred vision at any distance.

Presbyopia is a condition in which the muscles of the lens (ciliary muscles) lose elasticity and can no longer focus on objects located at a short distance. It is connected to age. It is also common for people having both myopic and hyperopic problems, requiring reading and distance eyeglasses.

### 5.2.3 Laser eye injuries

Tissue damage is possible only when the laser radiation is absorbed. If there is no absorption in the tissue, there is no damage.

When a user of a medium power green laser has an injury to the cornea and no injury to the retina, it is most likely that the injury is not caused by the green laser. For a $CO_2$ laser (wavelength 10,600 nm) to cause injury to the retina, the laser beam must perforate first the cornea, iris (when not passing through the pupil), and the lens.

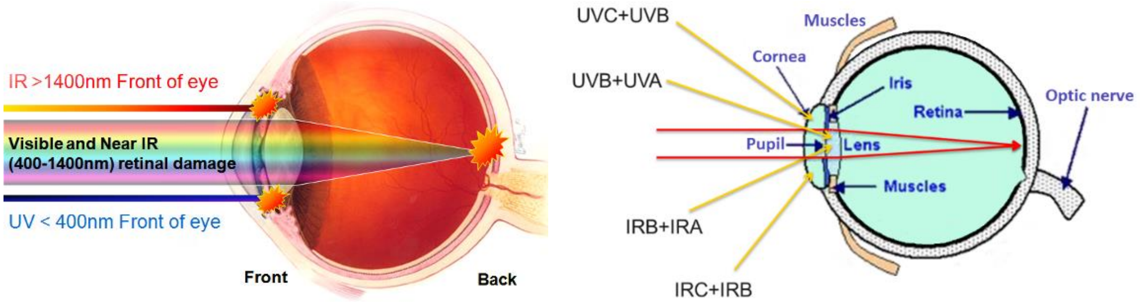


*Figure 5-17: Light absorption in different parts of the eye. Visible and near infrared reach the retina and are focussed on the macula.*

| Radiation | Wavelength | Predominantly absorbed in |
|---|---|---|
| UV C | 180 – 280 nm | Cornea |
| UV B | 280 – 315 nm | Cornea and lens |
| UV A | 315 – 400 nm | Lens |
| Visible | 400 – 700 nm | Retina |
| IR A | 700 – 1400 nm | Retina |
| IR B | 1.4 – 3.0 μm | Lens and cornea |
| IR C | 0.003 – 1 mm | Cornea |

#### 5.2.3.1 Corneal injury

Photochemical corneal injury is caused by UV B and UV C light. This type of injury has different names: photo-kerato-conjunctivitis, photokeratitis, welder’s flash or snow blindness (some connected with the origin of the injury). The pain starts hours after exposure. In photokeratitis, the corneal epithelium and the conjunctiva, which is the cellular layer covering the inside of the eyelids and the whites of the eye, are affected. It can be very painful with a sensation of sand in the eye. It is the equivalent of a skin sunburn but in the eye. By using eye drops for pain relief medication, by preventing inflammation, and by resting the eye in a dark room, the person may recover in a few days. For a deeper burn, the complete recovery may take longer.

Thermal burns on the cornea are caused by IR C and IR B. When the burn is superficial the symptoms, treatment and recovery are similar to photokeratitis.

*Figure 5-18: Corneal photochemical injury (left). Corneal treatment (right).*

A deeper burn may result in the formation of a scar in the cornea. If the scar is outside the pupil, the vision will not be impaired. Sometimes the scars move and can reach the pupil area interfering with the vision. A surgery involving corneal replacement may be necessary to correct the problem.

### 5.2.3.2 Lens injury

One of the most typical lens injuries is the cataract. As mentioned before, in a healthy eye, the pupil should look black. A sign of a cataract is when the pupil looks cloudy.

Cataract normally appears with old age and is caused by exposure to the Sun's natural light. In sunny tropical countries, especially on people working outdoors, the natural cataract will develop at an earlier age than in countries at higher latitudes. For example, in India people develop cataracts 20 years earlier than people in Canada (on average).

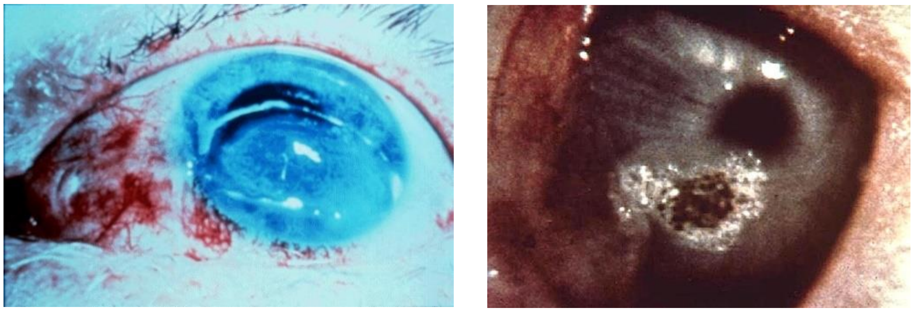


*Figure 5-19: Corneal burns by $CO_2$ laser.*

Another type of cataract is the one created by heat. It was common in glassblowers who did not wear eye protection after several years of exposure to high temperature due to the melted glass. It is produced by IR B wavelength in the range 1.4 – 3.0 μm.

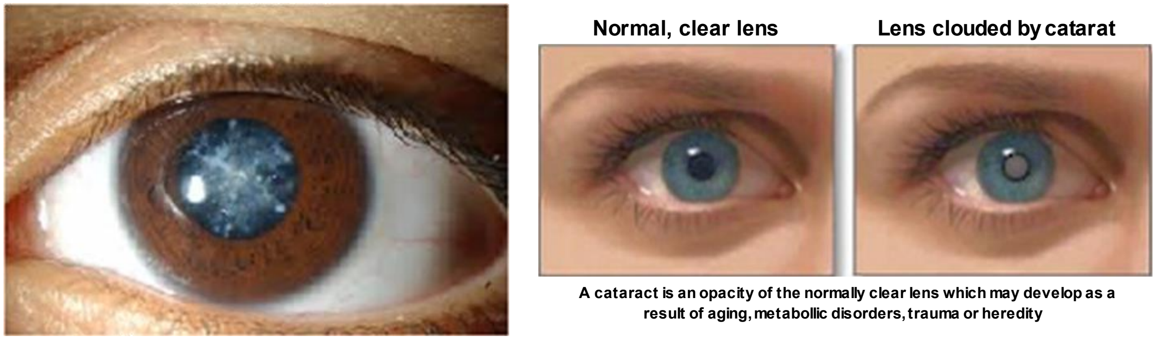


*Figure 5-20: Cloudy lens due to cataract (left). Comparison between a healthy clear lens and one with cataract (right).*

Cataracts can also be the result of exposure to ionizing radiation. There are specific limits for the ionizing radiation dose for the nuclear energy workers for the lens of the eye. These limits are lower than for other organs.

Cataracts will create a blur in a person’s vision. The only correction is lens replacement or removal.

Accidents involving a certain type of lasers can also produce cataracts. Excimer lasers emitting UV B radiation with a maximum around 300 nm are principally responsible for laser involved UV cataract. In laser jargon, Xe-Cl excimer laser, which emits at 308 nm, was nicknamed “cataract machine”. A laser emitting IR B radiation can produce heat cataract in the laser users.

### 5.2.3.3 Retinal injury

The most common and the most dangerous eye injury is retinal injury. As mentioned before some parts of the cornea or the lens can regenerate, can be removed, or replaced

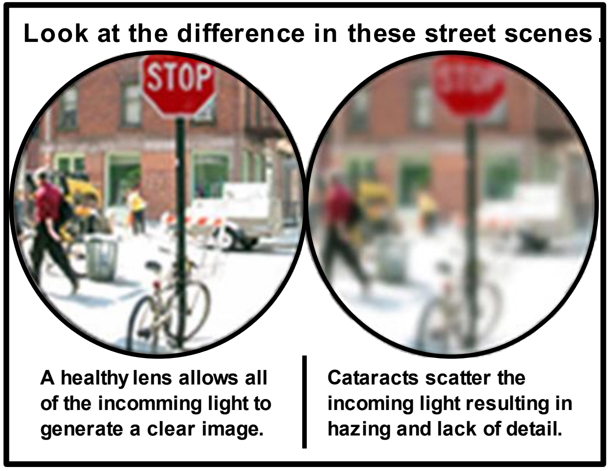


*Figure 5-21: Comparison of how the same image is seen by a healthy eye (left) and one suffering from cataract (right).*

*Figure 5-22: Fresh retinal injury (left). After a few days the scotoma will develop (centre). Multiple retinal scars (right)*

with surgery. The retina does not regenerate, and it is not possible to replace it. Damage to the retina results, in general, in permanent eye injury.

Factors that influence the laser damage to the retina are pupil size, amplification obtained by the cornea and lens, transparency of the cornea and lens for the particular wavelength, exposure time, total amount of energy entering into the eye, and the rate at which the energy enters to the eye.

The pupil size controls the amount of light entering the eye. The diameter can vary between 2 mm (at daylight), 3-4 mm indoor, and 7 mm in a dark-adapted situation. With special drugs, the pupil diameter can reach up to 8 mm.

As mentioned above the cornea has the most important part in the focusing of the light on the retina. The lens ensures a fine adjustment. The total concentration of laser light in the human eye can be up to 100,000. This means that the power density is 1 $mW/cm^2$ at the surface of the cornea it can reach, depending on the wavelength, up to $100W/cm^2$ at the surface of the retina. This increases the retinal injury hazard compared to corneal or lens injury hazards.

Image diameter on the retina is also an important factor in retinal damage. For point sources (most of the lasers are considered point sources) the instantaneous image is few microns in diameter. However, due to the continuing micro-movements of the eye, the image is in general around 20 microns (slightly smaller than the fovea centralis). For

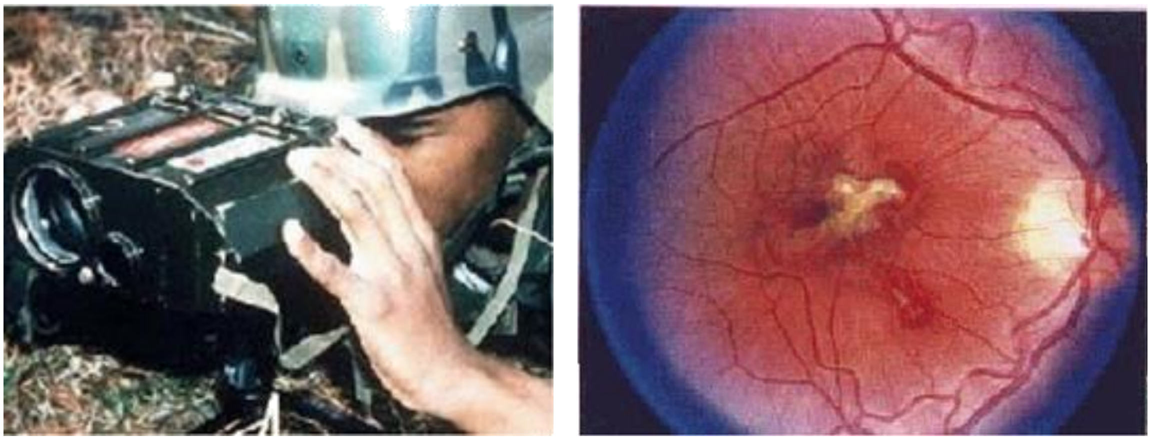


*Figure 5-23: Typical laser range finder used in the military (left). Retinal injury produced by a class 4 Nd:YAG laser range finder. (right).*

extended sources, (see section 3.6) the image is in general larger than the fovea centralis, resulting in a reduced hazard.

Photochemical injury of the retina is called photo retinitis. It is most likely to happen in the 400 to 600 nm range for exposures over 10 s long. The most common causes are by looking at Sun eclipse without protections (in this case is called eclipse retinitis), by the welding arc, and by laser. For a person having the lens removed, the retina can also be damaged by UVA (315 to 400 nm). Photo retinitis has a delay of 24 to 48 hours appearance after the exposure.

Retinal thermal burns are the result of photocoagulation of the retina because of brief exposure to intense light in the region from 400 to 1400 nm. The immediate result is an injury resulting in a haemorrhage causing pain, loss of vision due to the blood in the eye.

*"My vision was obscured almost immediately by streams of blood floating in the vitreous humour, and by what appeared to be particulate matter suspended in the vitreous humour. It was like viewing the world through a round fishbowl full of glycerol into which a quart of blood and a handful of black pepper has been partially mixed. There was local pain within a few minutes of the accident, but it did not become excruciating. The most immediate response after such an accident is a horror."*

*C. DAVID DECKER in "Laser Focus" August 1977.*

After the initial injury heals, a scar develops on the retina leaving a blind spot in the field of vision. This scar is called a scotoma. The scotoma can appear on the macula, resulting in the permanent loss of central vision. The person sees a black spot in the centre of the visual field. The person cannot read, distinguish faces, colours, or any details with that eye. The blind spot is the point where the optic nerve connects to the retina. If the laser hits the blind spot of the eye, the person loses total vision on that eye. When the scotoma develops in other parts of the retina, peripheral vision is lost. The person can still read,

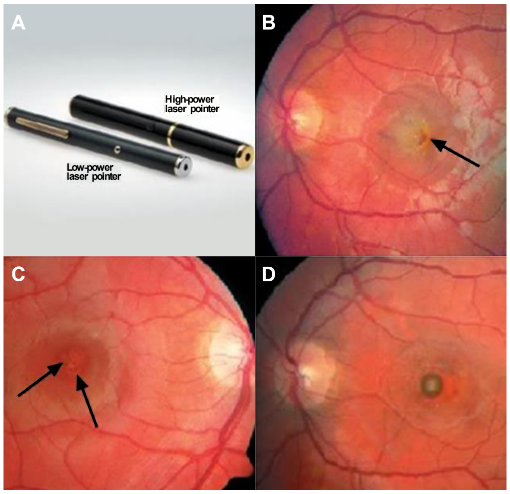


Figure 5-24: A 150 mW laser pointer (A). Subretinal hemorrhage created by the laser pointer (B). Scar in the foveolar area of the right eye (C). The left eye after four months (D).

see faces, identify colours or details, but will have problems with driving. When the eye is moving and a pulsed laser causes the injury, multiple retinal injuries can appear in different places of the retina.

## 5.3 Skin

The skin is the largest human organ. On average, an adult person's skin has around 3.6 kg covering a surface of approximately 2 $m^2$. The skin has an extremely important role in our survival. Among other roles, the skin ensures protection against external agents, such as extreme temperatures, sunlight, dangerous chemicals, biological agents, acting as a shield. It also prevents evaporation of water, produces vitamin D, which is essential in converting calcium into healthy bones, ensures the function of sensorial nerves. Damage to large portions of our skin can result in death.

Although the skin prevents the entry of water and many other substances into the body, it is not a complete barrier between the body and the outside world. Some medicines are absorbed through the skin, which is beneficial for us. Unfortunately, some toxic chemicals used in cosmetics can also be absorbed, and they may harm the body. The skin pores allow water to leave the body during perspiration. This process helps us to maintain a constant body temperature.

### 5.3.1 Structure of the skin

The outermost layer of skin is called the epidermis. The main constituent of the epidermis is keratinocytes cells, made from keratin (the same protein as hair and nails). Keratinocytes form several layers. The exterior layer dies and is constantly replaced by the internal layers. The layer of dead skin varies considerably in thickness in different parts of the body (on the soles of the feet or the palms can be 10 times thicker than around the eyes). The epidermis also contains Langerhans cells. These cells have the role to alert the immune system about the presence of viruses and other infectious agents. Merkel cells present in the epidermis help in the detection of light touches.

UV radiation absorbed in the epidermis induces the photoproduction of pre-vitamin $D_3$ in the skin and thus provides the major natural source for vitamin $D_3$ for humans. Our skin has not evolved as a mere sunblock, but also as a sunscreen. Vitamin D helps the absorption of calcium in the small intestine (to be used in the bones) and boosts our immune system. Melanocyte cells are located at the bottom layer of the epidermis. These cells make melanin, a pigment that gives colour to the skin. Melanin absorbs ultraviolet light, preventing it from damaging the body, and has an important role in preventing skin cancer.

The next layer of the skin is the dermis. This layer contains collagen and elastin fibres, hair follicles, sebaceous glands, the coiled sections of the sweat glands, blood and lymph vessels, nerves, sensory receptors, and cells from the immune system. The collagen and elastin fibres give firmness, flexibility, and elasticity to the dermis, enabling it to act as a supporting layer for the skin. The sebaceous glands produce an oily substance called sebum. Most sebaceous glands are connected to a hair follicle. Sebum lubricates and waterproofs the skin and hair.

Our skin contains two types of sweat glands. Eccrine glands are found over most of the body and release sweat directly to the surface of the skin. This sweat is watery and almost odourless. It contains many dissolved chemicals, including water, urea (a waste substance produced from protein metabolism), lactic acid, and sodium chloride. The other type of sweat glands, apocrine glands, are found only in certain areas, such as the armpits. Certain conditions, such as stress, stimulate the release of liquid from the apocrine glands. When the odourless liquid reaches the surface of the skin, bacteria break it down, producing odoriferous compounds.

Attached to each hair follicle is an erector pili muscle which causes the hair to become erect when the skin is cold or when we experience strong emotions. The erect hairs produce a "goosebumps" or "goose flesh" appearance on the surface of the skin. The dermis contains other sensory cells as well as a variety of chemicals. These chemicals include lipids and antimicrobial peptides (short chains of amino acids that fight pathogens). The epidermis does not contain blood vessels. Nutrients for the epidermal cells are supplied by the blood vessels in the dermis, which also removes waste substances made by the cells.

The subcutaneous tissue (also known as hypodermis or subcutis) is considered by some as not being part of the skin. The subcutis lies below the dermis. Its purpose is to attach the skin to underlying bone and muscle as well as supplying it with blood vessels and nerves. It consists of loose connective tissue, adipose tissue and elastin. The main cell types are fibroblasts, macrophages, and adipocytes (subcutaneous tissue contains 50 % of body fat). Fat serves as padding and insulation for the body.

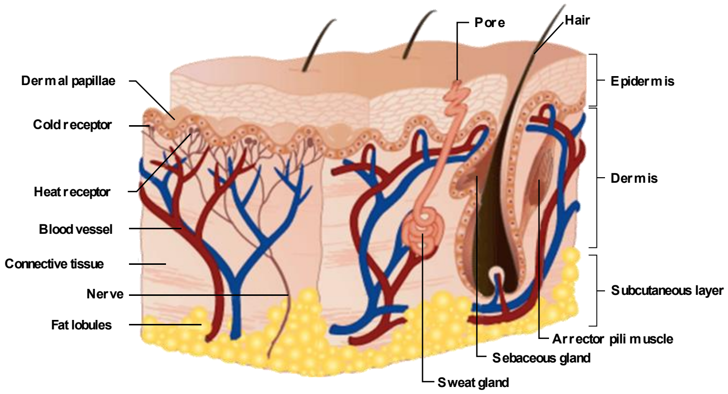


*Figure 5-25: Structure and physiology of the skin.*

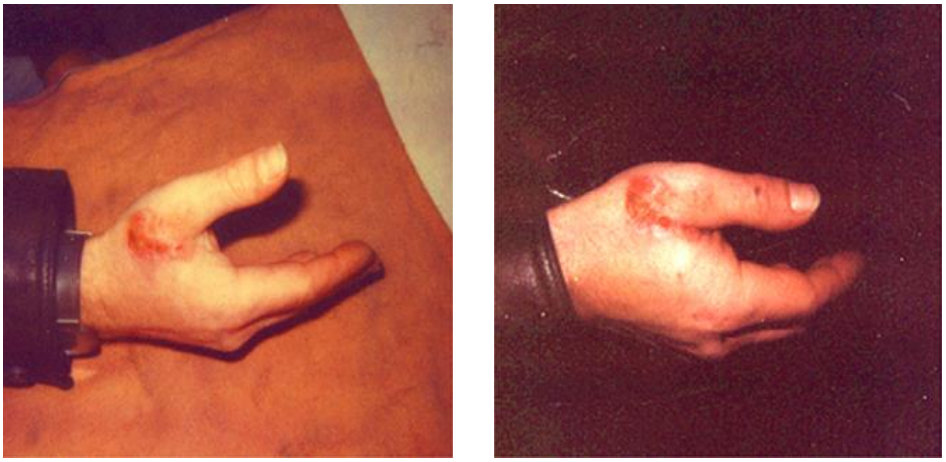
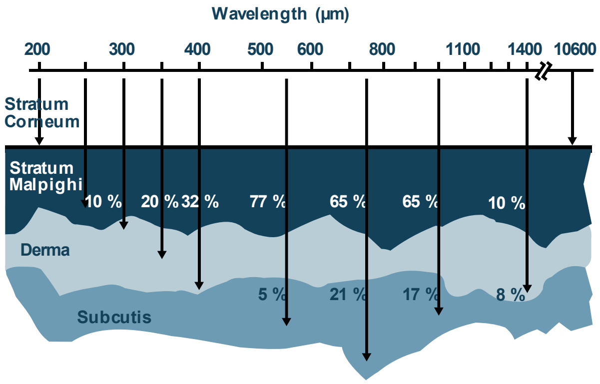


Figure 5-26: Accidental exposure of scattered radiation from a $CO_2$ kilowatt laser.

### 5.3.2 Laser skin injuries

The skin injury due to laser radiation depends on wavelength, radiation intensity and exposure time. The laser radiation penetration depends on the wavelength, skin colour and spot diameter. Laser radiation with wavelengths in the UV C range (180 to 280 nm) and far IR are absorbed in the epidermis. Visible and near IR may reach the subcutaneous layer and UV A, UV B and mid-IR reach the dermis. In various laser applications, such as hair removal, a spot size between 4 to 6 mm in diameter is used to reach the dermis. It has also been found that, although the penetration depth increases with spot size, there is a point at which the beam width has no further effect on the penetration depth. This is expected to be in the region of 5–12 mm in beam diameter.

Similar to eye laser injuries, the main skin injuries can be photochemical and thermal. Possible photochemical skin injuries are accelerated skin colouration (skin darkening), ageing, wrinkles, and skin cancer. Thermal injuries to the skin result in burns. When only the epidermis is affected, either due to photochemical or thermal effects, the healing may take a few days (similar to sunburns). If the base of the epidermis, the dermis or subcutaneous layers are affected, the injury may be permanent.



Values are percentages of incident radiation reaching a given layer of the skin
Source: WHO 1982.

Figure 5-27: Penetration of electromagnetic radiation of different wavelengths in the skin.

The exposure time is most important for the photochemical effects. Long-time exposure in the red and IR is less likely since the exposed person will feel the heat and move out of the beam. Short pulses in the ns or sub-ns range can cause explosive effects due to photoablation or plasma generation in the tissue. Exposure in the range of milliseconds to a few seconds predominantly result in thermal effects, while exposures above 100 seconds produce mostly photochemical effects. Chronic exposure to UV radiation will cause the other photochemical effects mentioned before (skin ageing, wrinkles, and potentially skin cancer). Thermal burns are classified as first, second, and third-degree burns.

A **first-degree** burn affects only the epidermis and causes pain and redness in the burned area, but usually heals within a few days and does not cause scarring. A typical sunburn is a first-degree burn. A **second-degree** burn affects all layers of the epidermis and often part of the dermis. A **third-degree** burn affects the full thickness of both epidermis and dermis, and often the skin appendages, such as hair roots and glands, as well.

Second- and third-degree burns require much longer healing and usually leading to permanent scars. Second and third-degree burns to major portions of the body can result in death.

*Figure 5-28: Skin injury after improper laser hair removal.*

# 6 NON-BEAM HAZARDS

As mentioned earlier laser beam hazards to the eye and the skin are not the only hazards present in a laser lab. These hazards can be classified as physical, chemical, biological and other hazards (ergonomic, electrical, mechanical, noise, nanoparticles, fibre optics fragments, sharp objects, etc).

## 6.1 Physical hazards

### 6.1.1 Electrical hazards

Electrical harms are, after eye damages, the most encountered injuries in a laser laboratory. A laser beam can blind a person, but electrical shock can result in a fatality.

The main sources of electrical hazards in the laser labs are power supplies and capacitors. Under normal operation, if the laser is certified according to the applicable laws and regulations, the user should not have access to the power supplies or the capacitors. When the laser housing is open (for repairs, adjustments, maintenance, tests, etc.) contact with high voltage supplies (especially for gas lasers) or capacitors (used to feed the energy pumping system of the laser), creates an electrical hazard. Besides, if the laser is laboratory-made and not intended for commercialization, access to power supplies or capacitors may be possible.

Factors determining the extent of the electrical hazard include current intensity, frequency, voltage, the path through the body, body size, and body impedance. The impedance of the human body varies from individual to individual and in general, is larger for men, is different in different parts of the body and varies with the frequency of the current. The impedance of the skin drastically decreases when the skin is wet, or damaged (cuts, abrasions, etc.), reducing the total impedance of the body.

The following table presents the physiological phenomena and the person's sensations for different intensity ranges for a 60 Hz current.

| Current (60 Hz) | Physiological phenomena | Feeling or lethal incidence |
|---|---|---|
| < 1 mA | None | Imperceptible |
| 1 – 10 mA | Perception threshold | Mild to painful sensation |
| 10 mA | Paralysis threshold of arms | Cannot release hand grip |
| 30 mA | Respiratory paralysis | Stoppage of breathing, frequently fatal |
| 75 mA | Fibrillation threshold 0.5 % | Heart action disco ordinated (probably fatal) |
| 250 mA | Fibrillation threshold 99.5 % | Heart action disco ordinated (probably fatal) |
| 4 A | Hearing the paralysis threshold | The heart stops for the duration of the current passage |
| > 5 A | Tissue burning | |

*This data is approximate and based on a 68 kg person*

Figure 6-1: Fuses and circuit breakers are normally used to protect equipment and buildings.

***Ref**: R. H. Lee," The Other Electrical Hazard: Electric Arc Blast Burns," IEEE Trans. Industrial Applications, 1A-18 (3): p246, 1982*

It is important to understand that an ordinary fuse or circuit breaker cannot protect the user from an electric shock.

The over-limit protection device (a fuse or a circuit breaker) will not break the circuit until the current exceeds the pre-established value (15, 20, 25 or 30 A), while currents as low as 30 mA can be fatal. The role of this device is to protect the instruments or the building against fire from over-heating electrical wires.

Figure 6-2: Ground-fault circuit breaker.

The ground-fault circuit interrupter (GFCI) interrupts a circuit when there is a difference in the currents in the live and neutral lines. Such a difference indicates an abnormal diversion of current either through the ground line or through a person's body who is in contact with the live wire and is being electrocuted. The device activates with a minimum current difference of 5 mA. This keeps the person safe. When a circuit functions normally, the difference in current is always zero.

GFCIs are required to be used in bathrooms, swimming pools, and some kitchen receptacles. The GFCIs have a "Test" button which causes a small difference between the live and neutral lines.

The arc-fault circuit interrupter (AFCI) is a device intended to protect from the effects of arc faults by recognizing characteristics unique to arcing (integrated processors) and by functioning to de-energize the circuit when an arc fault has occurred. It clears the fault in a very short time. For a 60 Hz alternating current (AC) power system, the clearing time is less than 8.3 milliseconds. It is recommended that AFCIs should be used in most rooms and other places in all new constructions.

Figure 6-3: Arc-fault circuit interrupter.

The barrier system (enclosure) must be the primary methodology to prevent electrical shock. Electrical hazards warning and safety instructions and procedures especially during maintenance, repairs, testing (all actions requiring the opening of the laser housing) must complete the barrier system.

Resistive heating (the increases of the conductor resistance when the temperature increases) can cause damage to the equipment or start a fire. Electric sparks can be generated by equipment malfunctions. When flammable vapours are present, this can generate fire. Besides installing a GFCI or an AFCI, the laser users must follow all precautions to mitigate electrical hazards:

- For new lasers - have the laser connected by a qualified electrician
- For old lasers - verify that the laser is properly grounded
- Work on de-energized parts only
- “Power-up” warning lights and labels must be visible
- Use an instrument to verify an electrical contact before touching
- Cover and properly insulate all electrical terminals
- Remove excessive wires/cables from the floor to mitigate trip hazards
- When necessary, follow lockout/tag-out procedures
- Never handle electrical equipment when the hands are wet or when standing on wet ground (regard all floors as conductive unless a special insulating dry rubber mat is used)
- ‘buddy system” or equivalent safety measures must be taken when performing maintenance, service, etc.

- Restrict access until capacitors are discharged
- Conduct manual discharging of capacitors before touching
- Avoid wearing metallic items (rings) when working with electrical equipment

### 6.1.2 Fire and explosions

In a laser laboratory, a fire can start because of interaction between the laser beam and flammable or combustible materials, as well as faulty electrical circuits or flammable laser dyes. Any beam that can reach irradiance of 10 W/cm$^2$ can start a fire if it is not properly enclosed. Laser beam enclosures must be built of flammable resistant materials, and laser beam stoppers used for high power lasers must be built of ceramics or metal with proper air or water-cooling.

*Table 6-1: Irradiance dependency of specific non-beam hazards.*

| Non-Beam Hazard | Approximate minimum irradiance (W/cm$^2$) | Recommended control measures |
|---|---|---|
| Ignition if easily ignited materials | 1 to 10 | Non-combustible barriers |
| LGAC production (the irradiance required greatly increases with atomic number-Z of the target material) | • $10^3$ (low z material)<br>• $10^3$ – $10^6$ (plastics)<br>• $10^6$ – $10^7$ (high Z materials, composite metals, tissue) | • Adequate building ventilation required<br>• Local exhaust ventilation (LEV)<br>• LEV or respiratory protection |
| Plasma production | • $10^{12}$ (metals)<br>• $10^{14}$ (dielectrics) | Limit personnel exposure to plasma radiation |
| Production of X-rays | $10^{16}$ (depending on wavelength, target materials) | Monitoring, shielding, radiation training, restrict access to authorized personnel |

As mentioned in section 6.1.1, faulty electrical circuits can cause sparks and over-heating of the circuits and start a fire. Invisible beam lasers interacting with unprotected wire insulation can also be the cause of fires.

The cause of explosions in a laser lab can be:

- High-pressure arc lamps
- Filament lamps
- Capacitor banks
- Interaction between the laser beam and targets or optical components
- Explosive chemical reactions
- Ignition of dust

To prevent explosion hazards, the components that have the potential of causing explosions must be enclosed in a housing that can withstand the maximum explosive pressure.

Figure 6-4: Skin burns due to contact with Cryogenic liquids.

### 6.1.3 Cryogenic fluids

Liquid nitrogen and liquid helium are the most common cryogenics in laser labs. If during the handling of cryogenics, large amounts are released in the room, this can create an oxygen-deficient atmosphere and may result in asphyxiation. Improper handling of cryogenic can result in burns on fingers, face, eyes, etc. To prevent accidents when handling cryogenic fluids, the users must follow appropriate procedures and wear protective equipment (cryogenic gloves and face shield). Specific training on handling cryogens is available through EHS.

### 6.1.4 Radiation (X-rays, UV, visible, EMF and plasma)

Dangerous levels of X-rays can be produced in experiments involving high-energy electrons that are slowed down in a metallic target, or when a current leakage exists in high voltage sources (above 15 kV). Besides, in experiments with class 4 lasers, plasma, X-rays, UV, visible and other electromagnetic radiation can be produced when the laser beam hits the target (see Table 6-1 for approximate irradiance values).

The flashing lamps used to pump solid-state laser (e.g.: Nd:YAG) can be a source of intense visible light. This can cause retinal damage when the eyes are not protected.

The best control for the radiation and plasma hazards is enclosing the components that can produce the hazard. The users must not remove the existent shielding of the power

Figure 6-5: Cryogenic hazards (left). Gloves used when handling cryogenic liquids (right).

sources and build an additional lead or other metal shielding around the areas where X-rays can be produced.

When X-rays are generated, the users must have X-ray safety training and learn how to measure the level of X-rays. The X-ray safety program may also require wearing personal radiation badges or installing area radiation badges.

In some experiments, high intensity static electric and magnetic fields or high-intensity electromagnetic fields (EMF) may be involved. Applicable EMF limits for each frequency must be followed. If the fields are close or possible above the public limits, the area must be marked, access must be restricted, and adequate EMF shielding must be installed.

### 6.1.5 Mechanical hazards

In many applications involving robots or moving equipment, since the laser user may have reduced visibility due to laser goggles and darkness in the workplace, accidents are possible. Some accidents happen when the laser user is pinned between a moving robot or piece of equipment and a confining object ("pinch effect"). Measures must be taken to reduce this type of hazard by the use of surface interlock mats, interlock light curtains, non-rigid walls, and barriers. Besides, robots safeguarding measures against malfunction and improving the work illumination (when possible), are necessary.

In many laser labs, compressed gas cylinders are used for different reasons. All compressed gases are hazardous because of the high pressures inside the cylinders. Gas can be released deliberately by opening the cylinder valve, or accidentally from a broken or leaking valve or a safety device. Even at relatively low pressure, gas can flow rapidly from an open or leaking cylinder. Handling, storage and use of compressed gas cylinders must comply with the applicable guidelines. When stored in the laser lab the compressed gas cylinders must be:

*Figure 6-6: Moving equipment at workplace (left). Moving robots (right).*

- Secured in an upright position
- The control valve (other than a cylinder connected to a regulator, supply line or hose) should be covered by a protective cap that is secured in its proper position

*Figure 6-7: Correct way to storage compressed gas cylinders (left). Damage caused by a compressed gas cylinder (right).*

- Store empty cylinders outside the building

If possible, do not store gas cylinders containing flammables in the laser room.

### 6.1.6 Other physical hazards (noise, nanoparticles, fibre optics fragments, sharp objects, etc.)

Excessive noise produced by the laser, vacuum pumps, power supplies, the ventilation system can be a cause of fatigue and a source of accidents in a laser lab. Most of the laser accidents happened during alignment. In general, alignment is a long and tedious process. If the work area is also noisy, the conditions for an accident are created. Measures to reduce the noise by appropriate shielding, repairing the defective vacuum pumps or ventilation system, or moving the noisy equipment to a different room, must be implemented.

More and more laser experiments involve the use of nanoparticles. Special precautions to avoid inhalation or ingestion must be taken when preparing the samples containing them. Special attention must be paid when cutting fibre optics to avoid glass splinters.

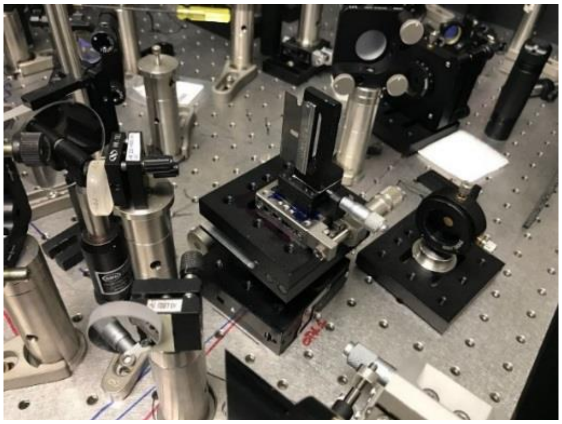


*Figure 6-8: Razor blade used in beam profiling left on the optical table.*

Wear appropriate protection equipment (gloves, face and eye protection, long sleeves, etc.) and clean the workplace of any residual glass. Accidents happened when blades used for beam characterization, needles used for experimental work, are left on the optical table. Reduced visibility during laser experimental work combined with sharp objects on the table create conditions for an accident.

To prevent injuries, sharps must be removed from the optical table.

## 6.2 Chemical hazards

### 6.2.1 Laser generated air contaminants

The interaction between the laser beams of high-class lasers with certain materials can generate air contaminants. The amount of laser-generated air contaminants (LGAC) depends on the composition of the target and the irradiance (see Table 6-1 for approximate irradiance levels). If the laser beam is mostly absorbed on the surface of the material, the amount of LGAC is larger.

Special optical materials used for far infrared windows and lenses (like CaTe or ZnTe) can burn in the presence of oxygen. During experiments involving Te and Te compounds (like $TeF_6$), or CaO, additional controls must be implemented.

### 6.2.2 Compressed gasses chemicals

The compressed gases used in the laser labs may contain toxic gases (as $Cl_2$, $F_2$, HCl, or HF) or inert gases (as He or $N_2$). When toxic gases are used, all users must have the WHIMIS training, read and understand the Safety Data Sheet (SDS) for each hazardous material, and implement the applicable control measures. All compressed gases having a hazardous material information system (HMIS), flammability or reactivity rating 3 or 4 (see the SDS) must be stored in an approved cabinet with the appropriate exhaust. These cabinets must have sensors to indicate the potential leakage that will trigger an alarm.

### 6.2.3 Laser dyes and solvents

Certain dyes and solvents used as a lasing medium are potentially hazardous. Rhodamines can be mutagenic or carcinogenic, and polymethine compounds are toxic. Lasing dyes must be prepared in fume hoods or glove boxes. Storage of chemicals must be on separate shelves or in double containers to prevent spills and unwanted reactions.

Other toxic or flammable solvents may be used to clean optical components. Handling, storage and disposal of these chemicals must be performed according to the applicable rules and procedures.

### 6.2.4 Chemical agent control measurement

There are three major control measures available to control the chemical agents’ hazards: process isolation, exhaust ventilation, and respiratory protection.

The process isolation may be implemented by enclosing the process with physical barriers and using a remote control apparatus. It is recommended when cutting, engraving, welding materials made of metals or plastics. It can be also used for work with biological materials to prevent contamination (disinfection and sterilization must be performed immediately after use).

Exhaust ventilation is easier when the enclosing hoods are used. Building and local exhaust ventilation must be sufficient to keep the concentration of the hazardous chemicals under the applicable limits. Sensors and alarms may be required in some workplaces, gas cabinets, exhaust ducts, etc.

Respiratory protection is only recommended to control brief exposures or as interim measures until engineering controls are put in place.

## 6.3 Biological hazards

Laser generated air contaminants (LGAC) may be present when high power lasers beams interact with tissue (see Table 6-1 for approximate irradiance values). Infectious materials (bacteria e.g.: *Staphylococcus aureus, Escherichia coli*, and viruses e.g.: *HIV DNA, viable bacteriophage, human and bovine papillomavirus*) may survive beam irradiation and contaminate the environment. When handling biological agents, the users must have the appropriate biosafety training and apply the necessary precautions.

## 6.4 Other hazards

### 6.4.1 Ergonomics

Restricted space is a real problem in some laboratories. Users must have enough space to move around the laser system. Consider removing the unnecessary equipment or furniture to allow sufficient space around the laser system set-up. Optical setup alignment may take a long time. Performing alignment may require having the arm or wrist in awkward positions, bending one’s back or do repetitive motions. These positions can produce pain in different parts of the body, creating distractions and increasing the chances of eye injuries.

### 6.4.2 Human factors

Stress, fatigue, hunger, and use of medications, alcohol, or drugs are additional physical or emotional factors, which could influence a user’s behaviour to take unnecessary risks. Consuming or being under the influence of any substances that cause impairment when in a laboratory increases the chances of an accident including a laser accident. When working after hours, weekends, or holidays, arrange for a colleague to be present in the lab. If this is not possible, when the users are tired, they should not engage in complicated alignment, testing or changing of the experimental setting.

# 7 LASER HAZARDS CONTROL

To reduce the risks of a laser accident the following actions are required: recognize and evaluate the hazards, identify the conditions in which the hazards appear, and try to eliminate these conditions.

## 7.1 Hazard assessment

### 7.1.1 Principles of hazard evaluation

Hazard evaluation must take into account the capability of the laser/laser system to cause an injury, the environment in which the laser/laser system is used and the persons who might be affected.

The first principle is the knowledge of laser classification. The laser class is essential when judging the capability of a laser to cause an injury. A class 1 laser or a class 1 working environment (an enclosed laser system with locks and interlocks) is considered safe under normal operations. For class 2, which is always visible, the natural aversion against high brightness light protects the user in case of unintentional eye exposure. Intentionally staring at the class 2 laser beam for more than 0.25 s can cause an injury to the eyes. A class 3R presents a reduced risk of injury under normal conditions of use. Class 3B (average power) and class 4 lasers (high power) can cause harm even when viewing for less than 0.25 s.

The second principle used in the laser hazard evaluation is the experimental setting in which the laser is used. With proper mitigation measures, even a class 4 laser can present a low risk when used under certain conditions; for example, when the laser beam travels inside a multimode optical fibre. In this particular case, the laser will be dangerous just for a short distance compared to the situation when is used directly.

The third principle of hazard evaluation connects the risk with the user's attitude regarding safety. The following considerations must be taken into account:

- The ability of a user to understand the basic physical principles and the different components of lasers
- Competency of a user in understanding and following standard operating procedures
- The maturity of a user to follow instructions and to wear personal protective equipment.

### 7.1.2 The person in charge of hazard assessment

Performing hazard assessments at the workplace is a duty of the supervisor. However, for laser hazards, the Laser Safety Officer (LSO) have the competency and knowledge to oversees the hazard assessment. To perform the hazard assessment, the LSO must be informed of the presence of the lasers in the lab as per the University laser safety program. Whilst there are no regulatory controls for purchasing class 3B and class 4 lasers as for radioactive materials, under the general duty clause 25(2) (h) of the Occupational Health and Safety Act (OHSA) of Ontario, employers are required to take every precaution reasonable in the circumstances for the protection of a worker. This includes the protection of workers from the hazards associated with lasers. When enforcing the general duty clause under OHSA, the Ontario Ministry of Labour's Radiation Protection Service takes into consideration the American National Standards Institute (ANSI) Z136 series of laser safety standards. For the University to ensure compliance with OHSA, laser Permit Holders (PHs) must inform the LSO whenever a new class 3B or class 4 laser is brought into the University.

### 7.1.3 When is the hazard assessment required?

Hazard assessment is required for both existing installations and new equipment. For new equipment, the LSO will analyze the experimental setting and check for the possibility of exposure to the direct and reflected beams (both due to specular or diffuse reflections). The LSO will determine or approved the Nominal Hazard Zone (NHZ) and ensure the access to this area adequately controlled. The possible exposure to every non-beam hazard must be analyzed. All necessary controls must be implemented before any experiments with the laser begin.

For the existing installations, a new hazard assessment is necessary when an experimental setting is changed. All hazards (both beam and non-beam hazards) and the level of the risk must be re-analyzed. The hazard analysis will determine when the controlled area must be changed, the need to re-establish the level of training, when improvements of operating and alignment procedures required, PPE validation, etc.

In a situation where a laser system must be serviced on-site, many control features designed by the manufacturer and required by regulations are likely to be removed or bypassed. In such a special case, the temporary NHZ must be redefined, and new controls must be put in place. Under the general duty, clause 25(2) (h) of OHSA as explain above, the University verifies the credentials, knowledge and experience of the individual performing a service when it is a University staff as well as when it's an external contractor/vendor. The Permit Holder must obtain the contractor's proof of training and previous experience with equipment to be serviced. Under no circumstances, an untrained person or a trainee will be allowed to service unsupervised laser equipment.

The hazard assessment may also be part of an inspection or audit, or when an investigation following an incident or accident.

### 7.1.4 How is the hazard assessment performed?

The individual performing the hazard assessment—usually the LSO—must visit the lab and analyse the system and experimental setting, identify the beam and the non-beam hazards. Results of the hazard assessment are communicated to laser users, the supervisor and the Permit Holder. A record of the hazard assessment must be kept until the experimental setup is changed.

## 7.2 Elements of hazard assessment

### 7.2.1 Beam diameter

A laser beam with an initial diameter and a beam divergence $\phi$ will increase with distance. To calculate the diameter of the laser beam with beam divergence $\phi$ there are two approximations linear and Gaussian. To decide which approximation needs to be used, the beam waist (the smallest diameter) location must be determined. If the beam waist is inside the laser enclosure the linear approximation will be used

$$D = a + r\phi$$

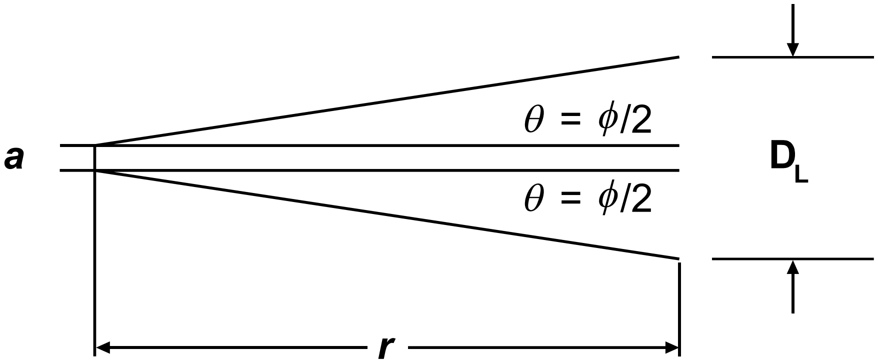


Figure 7-1: Laser beam diameter at distance r.

If the beam waist is located outside the laser enclosure the Gaussian approximation will be used:

$$D = \sqrt{a^2 + (r\phi)^2}$$

The Gaussian approximation gives a larger value for the diameter of the beam. This will result in safer values for further calculations.

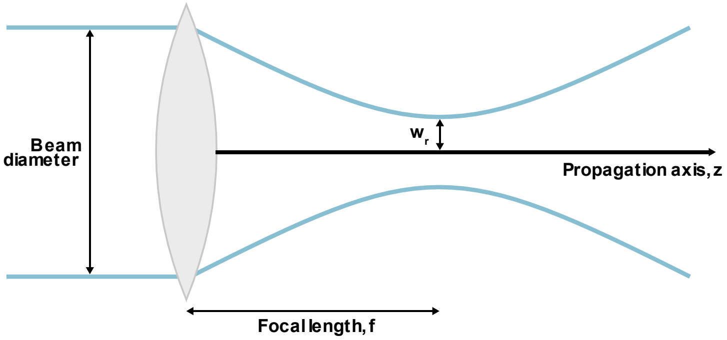


Figure 7-2: Laser beam waist.

### 7.2.2 Maximum permissible exposure

For each laser in the laboratory, the Maximum Permissible Exposure (MPE) will be determined for each wavelength used during experiments. This can be performed by using an approved software using the tables and procedures from the ANSI Z 136.1 standard or a combination of both. One example of an approved software that can be used directly using a web browser can be found at https://lasersafetyu.kentek.com/easy-haz-laser-hazard-software-basic-web-version.

The individual determining the MPE must know the exposure time, the type of laser if the system is a point or an extended source, the wavelength, and in the case of pulsed lasers the pulse duration and the number of pulses per second (PRF).

The exposure can be accidental or non-accidental/intentional i.e. planned for medical purpose. For accidental exposures to the direct or specular reflected laser beam the exposure duration will be 0.25 s for visible (between 400 and 700 nm), 10 s for IR (more than 700 nm) and 100 s for UV (between 180 to 400 nm). For diffuse UV exposure, the duration must be equal to the time spent in the lab (it can be the whole day). If exposure to diffuse UV is possible on consecutive days up to two days must be considered the exposure time. The non-accidental exposure times are applicable only during intentional exposure to laser radiation like in laser surgeries.

### 7.2.3 Nominal Ocular Hazard Distance

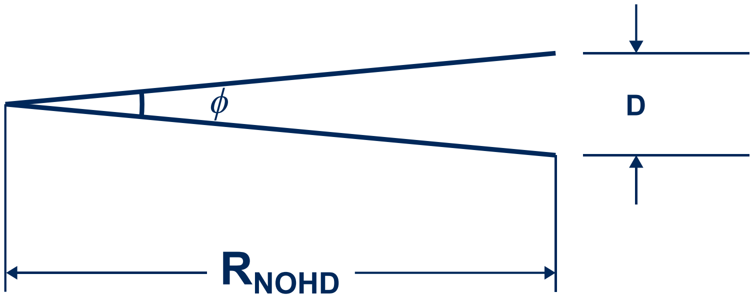


*Figure 7-3: Nominal ocular hazard distance.*

The Nominal Ocular Hazard Distance ($R_{NOHD}$) is the distance along the axis of the unobstructed beam from the laser to the human eye beyond which the irradiance or radiant exposure during operation is not expected to exceed the appropriate MPE.

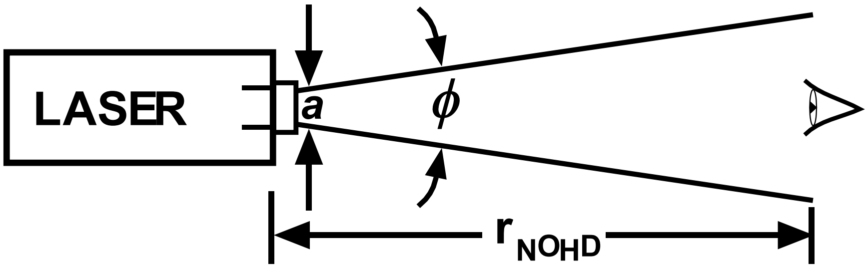


*Figure 7-4: Nominal ocular hazard distance for a beam with an initial diameter a.*

For a CW laser emitting a beam with power P having a negligible initial beam diameter and a beam divergence $\phi$, the beam diameter at distance $R_{NOHD}$ is D = $\phi$ *$R_{NOHD}$, and the beam area A = π*D$^2$/4. Assuming no absorption in the air and unobstructed beam the irradiance will be E = P/A. If we assume no damage to the eye, the power density must be MPE and we have P = MPE*A. Therefore, $R_{NOHD}$ is:

$$\mathrm{R_{NOHD}} = \frac{1}{\phi} \times \sqrt{\frac{4 \times \mathrm{P}}{\pi \times \mathrm{MPE}}}$$

When the initial diameter of the beam is not negligible, the formula to calculate the $R_{NOHD}$ must include the beam diameter *a*:

$$R_{\mathrm{NOHD}} = \frac{1}{\phi} \sqrt{\left(\frac{4P}{\pi \mathrm{MPE}} - a^2\right)}$$

**The lens on the beam**

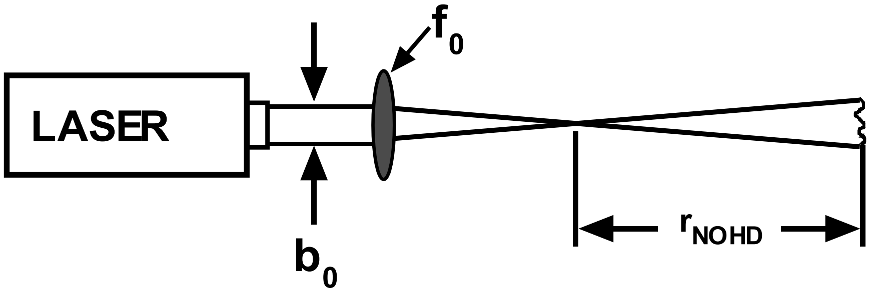


Figure 7-5: Nominal ocular hazard distance when a lens is mounted on the beam.

When a lens with focal distance $f_0$ is mounted in front of a beam with a diameter $b_0$ the $R_{NOHD}$ from the focal point of the lens is calculated with the formula:

$$R_{\mathrm{NOHD}} = \frac{f_0}{b_0} \sqrt{\frac{4P}{\pi \mathrm{MPE}}}$$

**Single-mode fibre optic**

If the laser beam is transmitted through a single-mode fibre the $R_{NOHD}$ calculated from the end of the fibre is given by the formula:

$$R_{\mathrm{NOHD}} = \frac{D_f}{\lambda} \sqrt{\frac{\pi P}{2\mathrm{MPE}}}$$

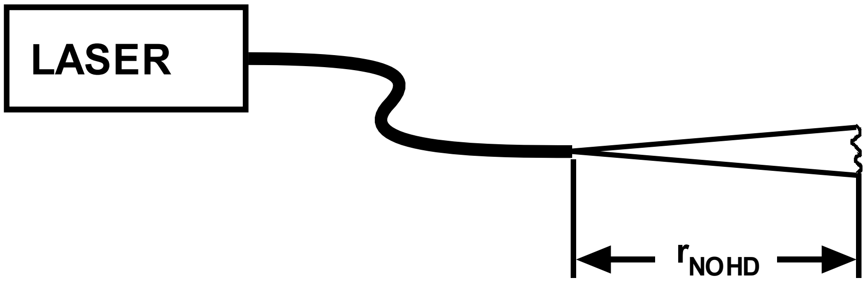


*Figure 7-6: Nominal ocular hazard distance of a beam transmitted through an optical fibre.*

Where $D_f$ is the diameter of the fibre and $\lambda$ is the wavelength.

### Multimode fibre

If the laser beam is transmitted through a multimode optical fibre with a numerical aperture NA the $R_{NOHD}$ is obtained with the formula:

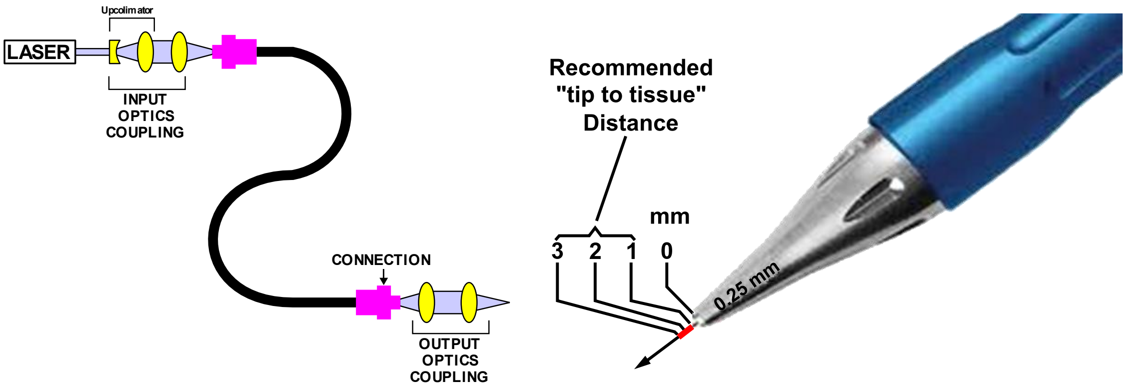


*Figure 7-7: Coupling the laser beam through an optical fibre (left). Laser tip used in surgery (right).*

$$R_{\mathrm{NOHD}} = \frac{1.7}{\mathrm{NA}}\sqrt{\frac{P}{\pi \mathrm{MPE}}}$$

### The lens on fibre optic

In many applications, the beam exiting the fibre is collimated with a lens mounted at the end of the fibre.

The same formula as with the lens on the beam needs to be used. The user needs to know the characteristics of the output coupling optics.

### 7.2.4 Nominal Hazard Zone

The Nominal Hazard Zone (NHZ) is the space within which the level of direct, reflected, or scattered laser radiation during operation exceeds the applicable MPE. The NHZ can be the result of diffuse reflection of the laser beam from an obstacle (e.g. wall, barrier) or of the movement of optics inserted into the laser beam. The horizontal tilt of a lens, mirror,

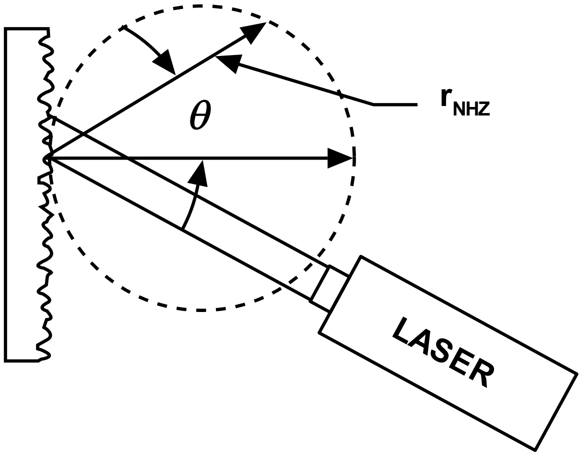


*Figure 7-8: Diffuse reflection Nominal Hazard Zone.*

and prism will transform the $R_{NOHD}$ from a line to a surface. If the beam encounters another optical object that can tilt vertically, the dangerous surface (two dimensions) will be transformed into a dangerous space (three dimensions).

Since in a laser experiment there are many optical objects, the nominal hazard zone in a typical open beam class 3B or class 4 laser laboratory is the whole room or the part of the room separated by curtains, barriers, enclosures, etc.

### 7.2.5 Calculating the laser class

For commercial products in general, classification is made by the manufacturer. It must be written on the labels, together with the wavelength and the maximum power.

For “made in-house” products, or modified laser systems, the classification is determined by the Laser Safety Officer.

The classification is based on the maximum accessible emission level (AEL). To determine the Class 1 AEL, the MPE for total anticipated exposure duration $T_{max}$ is multiplied by the area of the limiting aperture. See Table 7-1.

*Table 7-1: Limiting aperture for AEL determination*

| **Spectral region (mm)** | **Exposure duration t (s)** | **Aperture diameter for the eye (mm)** | **Aperture area for the eye ($cm^2$)** | **Aperture diameter for skin (mm)** | **Aperture area for skin ($cm^2$)** |
|---|---|---|---|---|---|
| 0.180 – 0.400 | $10^{-9}$ to 0.3 | 1.0 | $7.85*10^{-3}$ | 3.5 | $9.6*10^{-2}$ |
| 0.180 – 0.400 | 0.3 to $10^{a}$ | $1.5* t^{0.375}$ | $2.25*10^{-2}* t^{0.375}$ | 3.5 | $9.6*10^{-2}$ |
| 0.180 – 0.400 | 10 to $3*10^{4}$ | 3.5 | $9.6*10^{-2}$ | 3.5 | $9.6*10^{-2}$ |
| 0.180 – 0.400 | 100 | 3.5 | $9.6*10^{-2}$ | 3.5 | $9.6*10^{-2}$ |
| 0.400 – 0.700 | 0.25 | 7 | 0.385 | 3.5 | $9.6*10^{-2}$ |
| 0.700 – 1.400 | 10 | 7 | 0.385 | 3.5 | $9.6*10^{-2}$ |
| 1.400 – 100 | $10^{-9}$ to 0.3 | 1.0 | $7.85*10^{-3}$ | 3.5 | $9.6*10^{-2}$ |
| 1.400 – 100 | 0.3 to $10^{a}$ | $1.5 * t^{0.375}$ | $2.25*10^{-2} *t^{0.375}$ | 3.5 | $9.6*10^{-2}$ |
| 1.400 – 100 | 10 to $3*10^{4}$ | 3.5 | $9.6*10^{-2}$ | 3.5 | $9.6*10^{-2}$ |
| 100 – 1000 | $10^{-9}$ to $3*10^{4}$ | 11 | 0.95 | 11 | 0.95 |

*Under normal conditions, these exposure durations would not be used for hazard evaluation or classification.

**Low classes (1, 1M, 2, 2M and 3R)**

After calculating Class 1 AEL, the following rules are applied to determine the low classes lasers:

- Class 1 laser does not emit above Class 1 AEL measured at 10 cm for an unaided eye with $T_{max}$ = 30,000 s UV and V and 100 s for IR
- Class 1M – cannot emit above Class 1 AEL measured at 10 cm but can emit above Class 1 AEL measured at 2 m (optics transmission) and is under 5 times Class 1 AEL (Class 3B)
- Class 2 and 2M must be visible and the same as for Class 1 and 1M but when determining the MPE use t = 0.25 s instead of $T_{max}$ and the average power must be under 1 mW in 0.25 s. For CW point sources MPE is 2.55 mW/cm$^2$
- Class 3R: between 1 to 5 times Class 1 AEL for UV and IR and 1 to 5 times Class 2 AEL for visible radiation (400 to 700 nm)

**Class 3B:**

- UV (< 400 nm) and FIR (> 1400 nm) more than 5 times Class 1 AEL, but less than 0.5 W for T > 0.25 s or less than 0.125 J total energy emitted in T < 0.25 s
- V (400 to 700 nm) and NIR (700 to 1400 nm) more than class 3R but:
- Less than 0.5 W for exposure time > 0.06$C_A$ ($C_A$ from Table 6a)
- Less 0.03 J*$C_A$ per pulse for exposure time < 0.06 $C_A$ when 0.5 \ W peak power is exceeded, and
- Less than 0.125 J per pulse (pulses separated by less than $t_{min}$ – Table 1, are considered one pulse)

**Class 4:**

- Power or energy emitted more than Class 3B

### 7.2.6 Non-beam hazards

The hazard assessment must include the analysis of all non-beam hazards presented in chapter 6. Some of them may be limited to the power supplies (electrical hazards), or to the areas where chemicals are used (e.g. a fume hood or a glovebox). A list of all non-beam hazards and the areas where they are encountered must be included in the standard operating procedure (SOP).

## 7.3 Hazard controls

To implement the best hazard controls in the lab, the laser user needs first to know the laser and to understand the experimental setup. It is important to read as much as possible about the laser being used and ask questions if something is not clear. The goal of the experiment must be clear to the user. The role of each optical component must be understood. When dealing with complex optics like beam splitters or beam polarizer, is important to understand how they work, where are going the other beams, including all stray beams. An enclosure with locks and interlocks can change an open beam experiment into a class 1 working environment. The laser user may still need to access the beam for alignments and during changes to the experimental setup. If it is possible, the power should be reduced during these procedures. A good idea is to replace the invisible lasers with low power visible laser for alignment purposes.

### 7.3.1 Optical table 101

The following are the basics of working with an open beam. The laser user must follow them at all times.

- The beam should not leave the optical table;
- The beam should not be at eye level (both standing or sitting positions);
- Block the beam when adding or removing optics;
- Avoid oblique and vertical beams;
- The user must always know where the beam and all possible stray beams are;
- Implement all engineering and administrative controls in the lab.

**The good:**

- Use shutters (devices placed in front of the laser exit port with no space in between) to block the beam when inserting a new optical element in the beam;
- Use apertures, irises, and beam tubes;
- Use barriers and enclosures;
- When working with invisible lasers use viewers and cards;
- In the end, the beam must be terminated in beam blocks and dumps;
- Use perimeter guards to prevent all beams and stray beams from leaving the optical table.

**The bad:**

- The use of polarizers (they select a particular polarization and discard the others – know where the discarded beams are). Rotating polarizers have been involved in more laser injuries than any other type of optic;
- Use of beam splitters (partially reflect the incident beam). Accidents occurred with beam splitters inserted in the wrong direction;
- Periscopes are sometimes necessary for your optical setup. The danger comes from unblocked vertical beams;
- The use of vertical optical tables is sometimes required. This violates one of the basic principles of laser safety exposed above (beam should not be at eye level). Additional precautions are required in this situation.

**The ugly:**

- Enemy No. 1: an optical table that is partially used for the experiment and partially for storage;
- Remove spare mirrors and mounts, solvents and other flammables, exposed voltage (most deaths in laser lab come from electrocution), tools and other equipment;
- The most overlooked laser hazard: **other people** – clear all non-essential, unnecessary, and untrained individuals from the work area.

### 7.3.2 Engineering controls

Engineering controls are physical barriers placed between the hazard and the user. They are installed to reduce the risk of exposure to the hazard. An example of an engineering control is a panel that can be removed only by using a tool. If the panel can be removed involuntary; for example, by hitting it with an elbow by mistake, it is not a good engineering control. When building engineering controls in the laser lab the user must consider the beam paths. There are three types of beam paths:

- The total open beam is a beam with an open path larger than 10 cm. In this situation, the user may be hit by the direct beam;
- A limited accessibility beam is the beam path where the open part is smaller than 10 cm. In this case, the user may be exposed to reflected beams from shiny objects;
- The enclosed beam path is the situation when no direct viewing of the beam or the reflected beams (including stray beams) is possible.

Depending on the beam path, different engineering controls may be required. Examples of engineering controls are presented below. When the below-mentioned engineering controls are not practical (due to the laser work complexity), they can be replaced by other controls. The new controls must offer similar or better protection.

#### Protective housing

A commercial laser is usually enclosed in protective housing. The protective housing will cover all electrical contacts and will prevent unexpected exposure to laser radiation. The

*Figure 7-9: A He-Ne laser with and without a protective housing.*

laser beam will be available only through a marked exit port, sometimes controlled by a shutter. When the laser is ON and the shutter is open, the laser beam can be used. Labels indicating the laser power, wavelength and class are required to be visible on the protective housing. Some protective housing has interlocks, preventing the use of lasers when the protective house is removed.

**The use of class 3B and 4 lasers without protective housing must be approved by the Laser Safety Officer.**

Some protective housings have viewing portals and service access panels in case the user needs to see or have access inside of the laser system. These systems must be interlocked to protect the user when inadvertently open.

### Beam enclosures

When enclosed in protective housing, the laser must be mounted in such a way as to avoid the beam hitting directly the protective housing. To terminate the beam, a beam stopper must be used. The role of the protective housing is to avoid exposure to the stray beams and unintentional exposure to the direct or reflected beam.

*Figure 7-10: Plastic beam enclosure that is transparent to many wavelengths but absorbs the laser wavelength (left). Metallic beam enclosure which is completely opaque (right).*

Beam enclosures can be made of plastic transparent to certain wavelengths. In this case, the OD of the plastic at the laser wavelength must be sufficient to decrease the laser beam power density under the applicable MPE. For higher power lasers it is recommended to have metallic protective housing. Black anodized metal is recommended.

### Beam Dump

A beam dump (or a beam block) is necessary to terminate the laser beam at the end of the experiment. For low power laser class 3B, the beam dump can be made of plastic or other materials. For higher power lasers the beam dump must be made of metal or ceramic to withstand the beam for long periods. When high-power lasers are used for long

Figure 7-11: Different types of beam dumps (left). Beam dump design (right).

periods the beam dump must need a cooling system. The cooling can be done with air or water.

The special design of the laser beam dump ensures multiple reflections of the beam on a highly absorbing surface reducing the reflections.

### Locks and Interlocks

Protective housing, enclosures, viewing windows may need to be locked and have an interlock. The interlock may be connected with the laser power supply or to a shutter used to block the laser beam. No laser beam above the MPE should be available when the interlock is activated. The laser must not restart or the beam power above MPE be accessible when the interlock is pressed. To restart the laser the user must have the interlock pressed and have another active device initiated (e.g. press a reset button, give a command on the computer or control panel).

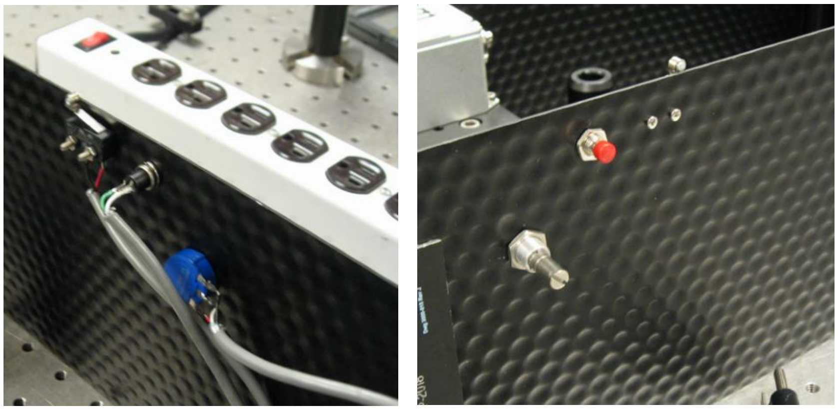


Figure 7-12: Interlock switch (left). Reset button (right).

### Viewing Windows

If the laser system or the experimental setup needs viewing windows, they must be built from a transparent material with OD sufficiently high to protect the laser users. If the

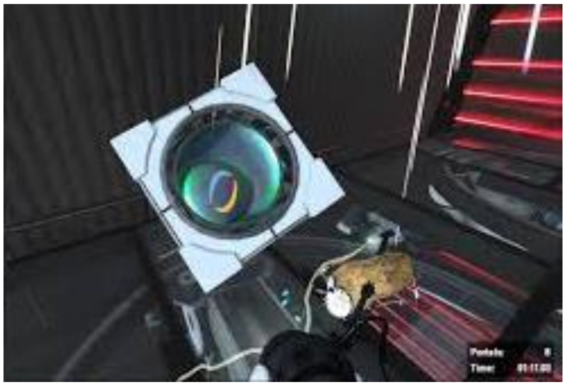


*Figure 7-13: Laser viewing portal.*

viewing windows can be open, they must have an interlock and a reset button or similar device to restart the laser.

### Key Control

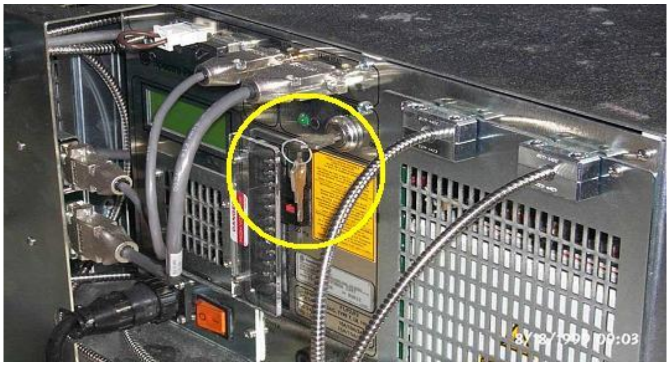


*Figure 7-14: Control key.*

All class 3B and 4 lasers must have a key to start the laser. The key can be replaced by a computer password or similar device. The key or the computer password must be accessible only to authorized laser users. When finishing the laser work the user must remove the key, close the computer/control panel to prevent unauthorized access to the laser.

### Remote Interlock Connector

All class 3B and 4 laser or laser systems must have a remote interlock connector. This is used to install a switch that can disconnect the power supply to the laser in case of an emergency (e.g. a red mushroom emergency stop button). In case of fire, laser accident or another emergency, the red mushroom button (or equivalent) will shut down the laser.

### Class 1 Working Environment

When a class 3B or class 4 laser is enclosed and the user is not exposed to laser power densities above MPE during normal operation, the system can be considered a class 1 working environment. No additional controls are necessary for a system considered a

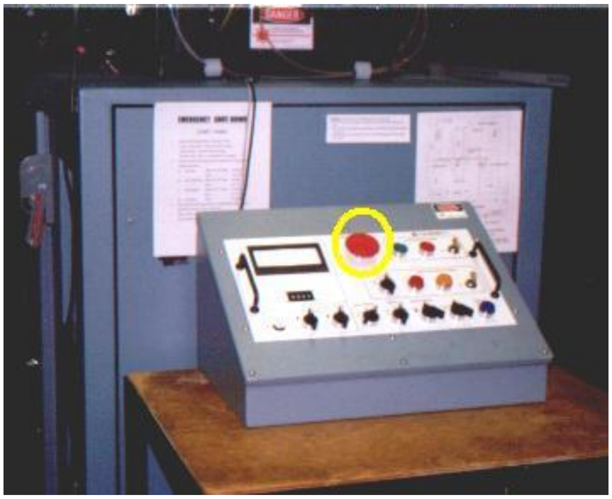


Figure 7-15: Red mushroom emergency stop button.

class 1. The enclosure must have locks and interlocks, and it must be built such that no accidental opening of the enclosure is possible. If the enclosure is opened unintentionally by the user who may be exposed to laser power densities above MPE, the interlock must disable the laser or block the beam. The interlock must disable the laser system fast enough so the exposure time on the eye is minimum. For example, if the total amount of energy entering the eye in one microsecond is above MPE, the time in which the interlock shuts down the system must be less than one microsecond. The LSO must inspect and approved any laser/laser system to qualify as a class 1 working environment.

Figure 7-16: Class 1 enclosure.

### Controlling the stray beams

Stray beams can carry 4% or more of the total incident beam (more if the incident angle is larger – see section 2.3.1).

The best way to control them is by using enclosures. When it is not possible to use enclosures or when they are not practical, anti-reflecting coating (based on destructive interference) can be used. A thin layer of transparent material is deposited on top of optics to prevent reflections. $n_0<n_f<n_s$

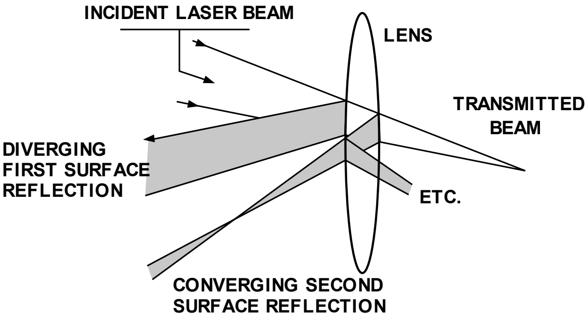


*Figure 7-17: Stray beams from curved surfaces.*

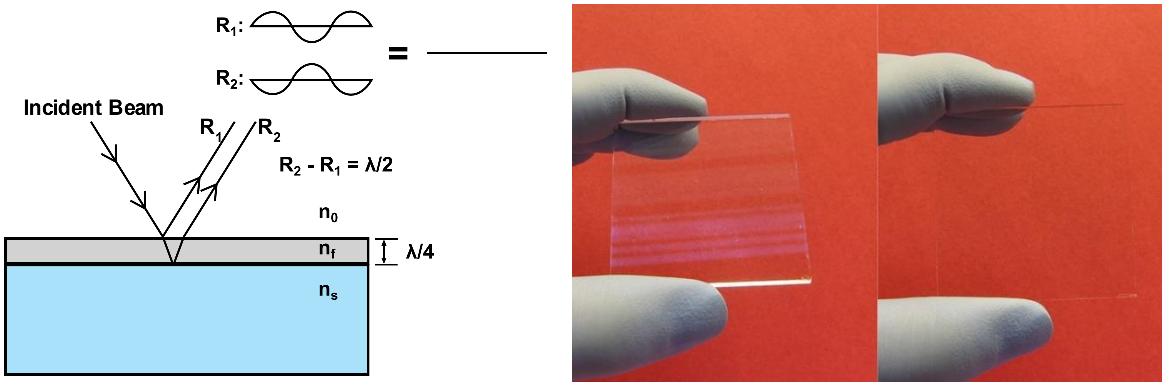


*Figure 7-18: Destructive interference used to control stray beams (left). Glass substrate with antireflex coating at 45° and perpendicular viewing (right).*

### 7.3.3 Administrative and procedural controls

When engineering controls are not possible or practical, they can be replaced by administrative and procedural controls. In a research environment, detailed Standard Operation Procedures (SOPs) may not always be practical. If the experimental setup needs to be changed very often, a more general SOP that includes the areas presented below must be accompanied by the procedure to implement these changes. If changes in the experimental setup are implemented, the procedure must indicate the person who is required to approve these changes (e.g. laser supervisor, permit holder, LSO).

The required elements of an SOP:

- The location, the experimental setup, and list of lasers involved;
- Authorized people involved;
- List of hazards (beam hazards and all applicable non-beam hazards);
- Hazards control implemented to prevent beam and non-beam accidents;
- Alignment procedure;
- Normal operation;
- Emergency procedure.

All open beam class 3B should have and 4 lasers must have an SOP verified by the LSO and approved by the laser Permit Holder.

Other administrative controls required for open beam class 3B and 4 lasers are:

- Output emission limitations – the laser power must be set at the minimum possible value required for the experiment;
- All people working with lasers must be trained – a list of authorized laser users must be maintained up to date by the PH (or laser supervisor);
- All people present in the room when the laser is ON must be informed about the beam and non-beam hazards (e.g. awareness training), must have the approval of the PH, and wear the appropriate Personal Protective Equipment (e.g. laser goggles);
- Laser repairs, maintenance, internal calibrations must be performed only by trained, experienced people;
- Windows protections must be installed to prevent laser beam transmission and reflections;
- Entrance controls, signs and laser warning lights, must be in place (see section 7.3.4)

*Figure 7-19: Window protection, non-transparent cover (left). Window protection with adequate OD for the laser wavelength (right).*

### 7.3.4 Entrance controls, signs, and lights

Entrance in the Nominal Hazard Zone (NHZ) of an open beam class 3B or class 4 laser must be controlled.

Entry controls for an open beam class 3B laser must have:

- Posted by appropriate warning signs;
- Have all windows, doorways, open portals covered;
- All beams above MPE terminated;
- Only diffusive materials in the vicinity of the beam;
- Laser secured to prevent beam at eye level standing or sitting positions;
- Visitors access controlled.

Operated only by trained people such that path is well defined. No direct or specular reflected beams with power above MPE are present outside the optical table. Operators must follow the approved procedures, and remove the key when the laser is not used.

If direct or specular reflected beams are directed towards the entrance, the additional entry controls (required for class 4 lasers) must also be implemented.

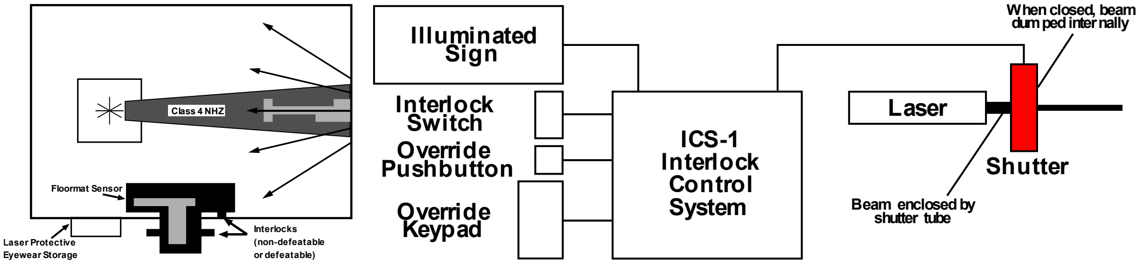


Figure 7-20: Area entry control with interlock (left). Interlock system (right).

For class 4 lasers, all entry controls applicable for class 3B must be followed. Besides, one of the following three controls are mandatory:

- Non-defeatable interlocks are installed at the door or on the floor in front of the entrance. The interlock must shut down the laser or activate a shutter to reduce the beam power density under the applicable MPE. This type of interlock will stop the experiment anytime a person from outside the NHZ enters, even if it is an authorized laser user. A non-defeatable interlock is recommended for very high-power laser applications;
- Defeatable interlocks are also installed at the door entrance. In this type of control, the authorized users can enter using a key, a code, or a magnetic card.

Procedural entry control must be put in place when interlocks are not possible or practical. A barrier, curtain, or similar arrangement must completely cover the entrance inside of the room. This is required to prevent any person from entering the room and be injured by a direct beam or by specular or diffuse reflections.

The entrance in the NHZ of a class 3B laser must be marked with appropriate laser signs. For NHZ of a class 4 laser, in addition to the laser signs, a light indicating when the laser

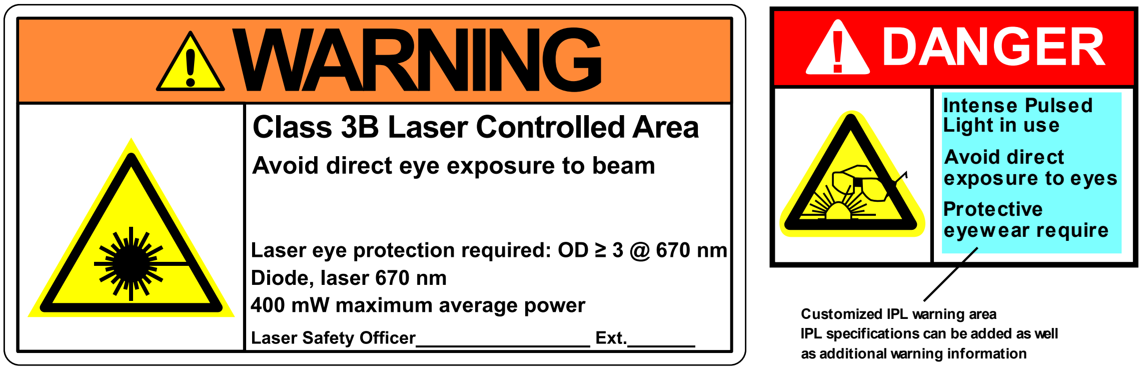


Figure 7-21: Examples of class 3B laser sign (left) and class 4 laser sign (right).

is ON must be installed. The light can be connected to the laser system or controlled manually by the laser user.

A good practice is to communicate with the person using the laser before entering the NHZ.

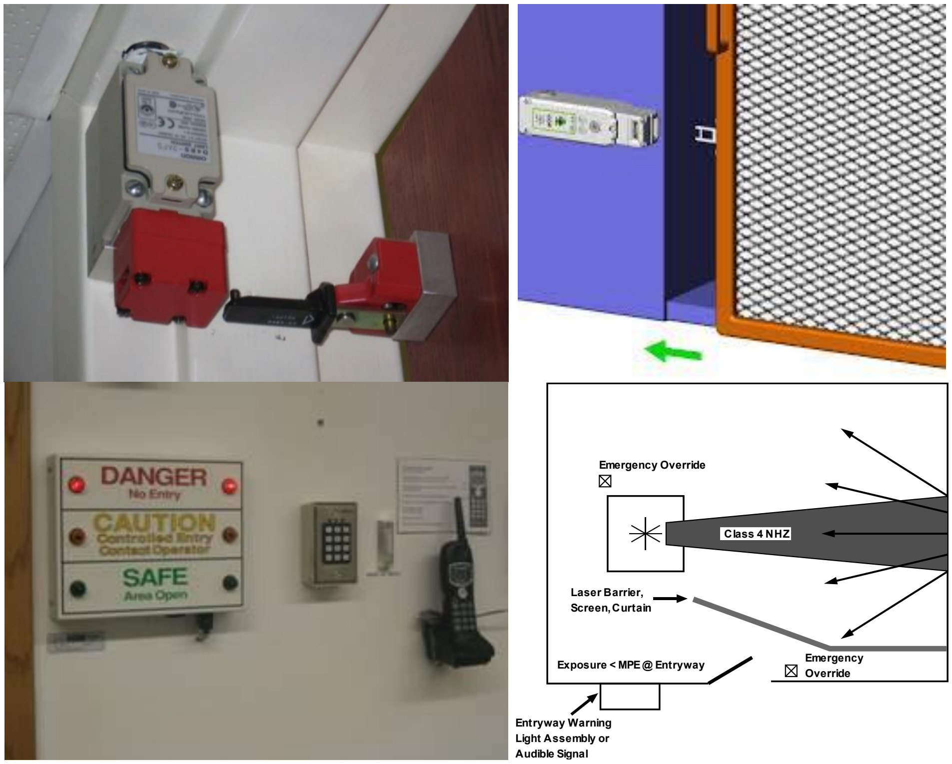


Figure 7-22: Door interlock (top-left). Non-defeatable interlock (top-right) Interlock can be defeated entering the proper passcode on the keypad (bottom-left). Area entry control without an interlock (bottom-right).

The best are light signs with three colours: green indicating when the laser is off, yellow (amber) indicating when the laser is ready to be used, and red when the laser is

Figure 7-23: Laser sign stressing the importance of communication before entering the NHZ.

*Figure 7-24: Three colours laser sign for class 4 lasers (top-left) and its control system (top-right).Other types of common laser lights (bottom row).*

operational. A red flashing light or a light sign indicating when the laser is on is also acceptable.

### 7.3.5 Personal protective equipment

#### Eye protection

Your best defence is knowledge, your last defence is your protective equipment. When all other controls fail, and the beam or the stray beams are directed towards your eye, you

What is the best protection?

**Knowledge.**
**Safety glasses can be hazardous:**
**If you use the wrong type, you may think that you are protected.**
**but instead …**

**Laser accidents - they do happen!**

*Figure 7-25: Knowledge is the best defence.*

need to have the correct laser goggles. Safety eye protection is mandatory inside the NHZ if class 3B and class 4 laser.

Laser goggles work by absorbing or reflecting the laser light. For the laser goggles based on absorption, an absorbing dye is mixed with the laser goggles material, or deposited on top of the glass or plastic. The laser goggles based on reflection use the same principle of dichroic mirrors (also called dielectric or Bragg mirrors – see section 2.3.6).

The transmission of light through the material as defined in section 2.3.3, is the ratio between the intensity of transmitted light to the intensity of the incident light.

$$\mathrm{T} = \frac{\mathrm{I}}{\mathrm{I_0}}$$

As the opposite of the transmission, we have the absorption of light. A measure of the absorption is the optical density (OD) of the material.

$$\mathrm{OD} = \log_{10} T^{-1} = \log_{10} \frac{I_0}{I}$$

The transmission and absorption are wavelength dependent. The absorption and the transmission bands of a certain dye are published by the laser goggles manufacturer.

If the transmitted light can reach the eye of the user it must be at the MPE for the eye or lower level. When MPE is measured in W/cm$^2$ the incident intensity of the light must be measured in the same units. Then OD needed for the eye protection is calculated using the following formula:

$$\mathrm{OD} = \log \frac{P_d}{\mathrm{MPE}}$$

where $P_d$ power density = power /area. The area used in this formula must be the area of the beam if the beam is larger than the aperture area from Table 7-1, or the aperture area if the area of the beam is smaller. OD can also be determined using the free web-based calculator found at [https://lasersafetyu.kentek.com/easy-haz-laser-hazard-software-basic-web-version](https://lasersafetyu.kentek.com/easy-haz-laser-hazard-software-basic-web-version)

The OD of each laser goggles must be specified on the labels.

For ps and fs laser pulses, saturable absorption (see section 2.4.4) can create a hazard.

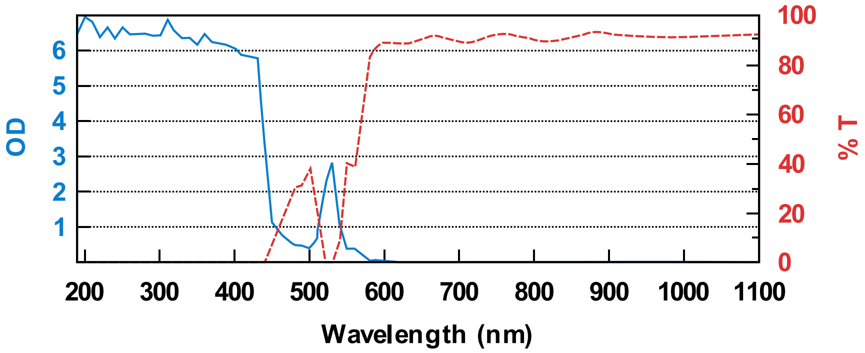


*Figure 7-26: Optical density and transmission curve for certain filter material.*

*Figure 7-27: Laser goggles labels. In the left filter are the labels complying with the ANSI standard. On the right filter are the labels complying with the international standard.*

To solve this problem the manufacturers are asked to test the laser goggles at these exposure times. A copy of the test results must be given to the users, at their request.

The international laser safety standards (followed in Europe) require laser goggles labels for time exposures.

| **D** | **R** | **I** | **M** |
|---|---|---|---|
| CW | > 100ns | 1-100ns | < 1ns |

When the user orders laser goggles they must have the correct OD for the wavelengths involved in the laser experiment. For the visible laser beams, OD should not be much higher than necessary since this can decrease the visible light transmittance of the goggles. If viewing cards are used for UV and IR lasers, the laser goggles must have a good transmittance for the colour of the viewing card.

*Figure 7-28: Labels complying with the international standard (followed in Europe).*

Before putting on the laser goggles, the user must always verify:

- The physical integrity of the goggles (do not use broken or scratched goggles);

- The wavelength and the OD. If multiple wavelengths can be involved (produced by laser or by harmonic generators), the laser goggles must cover all possible wavelengths;
- For ps and fs, verify if the goggles were tested for saturable absorption or if they have the “M” marking;
- The visible light transmission (VLT) must be enough to comfortable perform the alignment and the experiment.

When laser goggles are impossible to use (e.g.: when using a supercontinuum laser with emission in all visible spectrum), the user must consider other options for protection. The laser system must be enclosed, and a closed-circuit TV used to perform the alignment and the operation.

**Skin protection**

When working with class 4, skin must be protected if the power density is above the MPE for the skin. For possible long-term exposure to UV light, the skin must also be protected.

For face protection, a face shield can be used. The OD for the UV radiation must be sufficient to reduce the exposure under the MPE.

If exposure to other parts of the body (arms, hands, legs, etc.) is possible they must be covered. The user must wear long sleeves lab coats, gloves, etc.

If exposure to a beam with a power density above 10 W/cm$^2$ is possible the materials used to cover the skin must be flame retardant.

**Other PPE**

When a high-power laser beam interacts with the sample, laser-generated air contaminants (LGAC) can be produced (see section 6.2.1).

Local exhaust ventilation systems must ensure that the level of toxic chemicals in the breathing air is kept under legal limits. Gas monitoring instruments may be necessary to

*Figure 7-29: When working with class 4 UV laser, protection of the face is also important (left). Face shields provide protection for the skin of the face (right).*

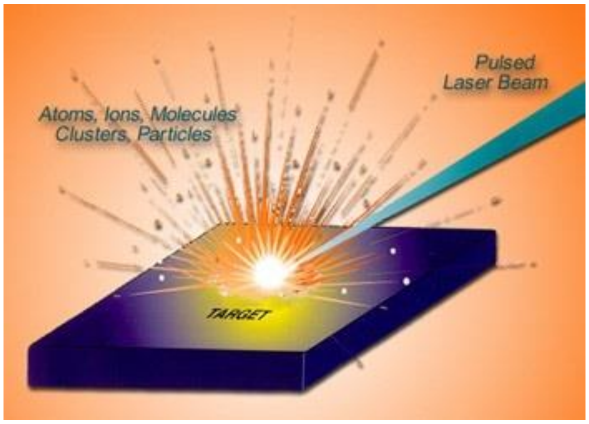


Figure 7-30: Laser-generated air contaminants.

ensure this. The same precautions may be necessary when dangerous gases are used as a lasing medium (e.g.: excimer lasers) or for other purposes in the laser lab.

If the local exhaust ventilation is not adequate, personal respiratory protection may be required. Surgical masks are in general not suitable for LGACs. They offer mainly protection only for nasal or oral droplets. For protection against LGACs and other aerosols or gases, tested mask respirators must be worn.

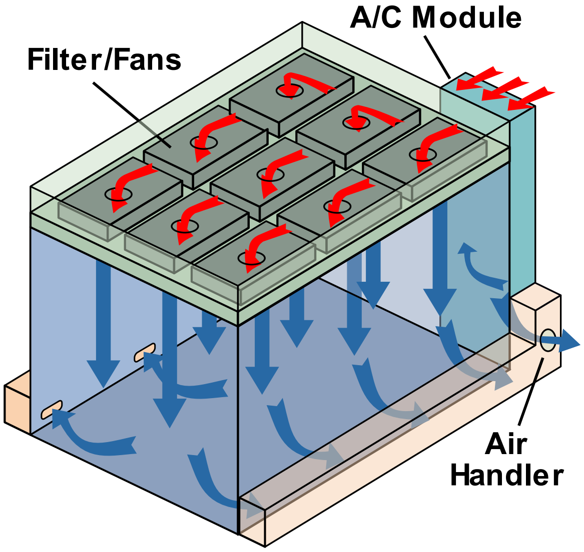


Figure 7-31: Specially designed clear laser room.

# 8 LASER ALIGNMENT AND MEASUREMENT

The laser alignment must be performed only by trained and experienced users. A beginner laser user must not attempt to perform these operations without supervision. Due to the complexity of these operations, most of the laser eye accidents in the laser labs are happening during the alignments.

The alignment of laser components inside the laser protective housing is sometimes called internal alignment. If a misalignment of laser components inside the protective housing happens, it is recommended to contact the manufacturer. The manufacturer should send a qualified technician to perform the alignment.

A laser experiment may require many optical components. The alignment of these components is sometimes called external alignment. External alignment is necessary during the initial setting, reconfiguration of the optical setup, replacement of optical components, or when the optical components are misaligned by accident. Fine adjustments may be necessary to be performed often and depend on the required precision of the laser experiment.

External alignment can be necessary between the optical components required for the laser experiment on the optical table. If the laser beam is delivered through an optical fibre the alignment from the laser to the fibre port, from fibre to fibre, and from fibre to the target.

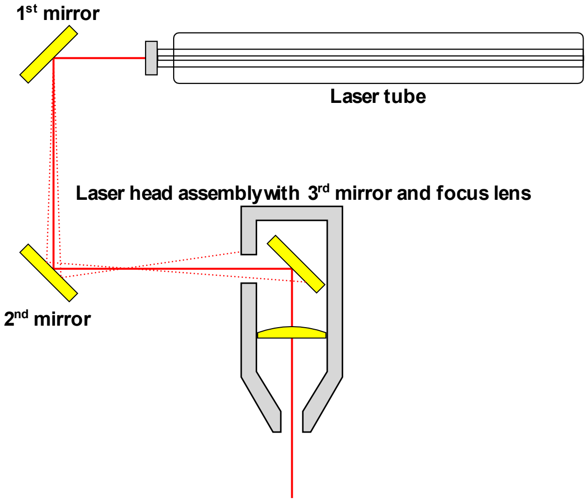


*Figure 8-1: Example of a misaligned system.*

## 8.1 Laser alignment procedure

All laboratories performing laser alignments must have written alignment procedures. It is recommended the procedure be written by an experienced laser user, verified by the Laser Safety Officer, and approved by the laser Permit Holder. Sometimes the laser work may require a small change of the position of an optical component or the addition/removal of an optical component without changing the whole experimental setup. A procedure to perform this change may involve a discussion between the laser worker and a more experienced laser user, like the laser supervisor. This should also be included in the alignment procedure.

The user must include the following in the alignment procedure:

- Perform alignment only after you receive training to do so;
- Only after you received approval from the supervisor;
- Work with a colleague ("buddy system");
- Draw a plan of the setup (a sketch including all optical components and their relative positions) and make a risk assessment;
- Discuss the hazard assessment and the alignment procedure with your supervisor and your "buddy";
- Identify the equipment and materials you need:
  - Indirect viewing of the beam (thermal paper, ceramic discs, IR/UV cards or scopes, business cards can be used for UV)
- Make sure you have eye protection for both low power and high-power beam;
- When necessary, verify if UV skin protection is available (face shield, long sleeves);
- Pay attention to housekeeping by removing all possible specular reflective materials;
- Remove jewellery;
- Isolate and mark the NHZ;
- Reduce the power or replace a high-power laser with a low power visible laser;
- Use the appropriate alignment goggles;
- Remember to switch to the high OD goggles when you increase the laser power;
- Restrict access to the area;
- Turn on the laser warning light at the entrance of the room;

**Before you start:**

- Revise the alignment procedure, the list of hazards, and hazard controls;
- Make sure that all controls are in place;

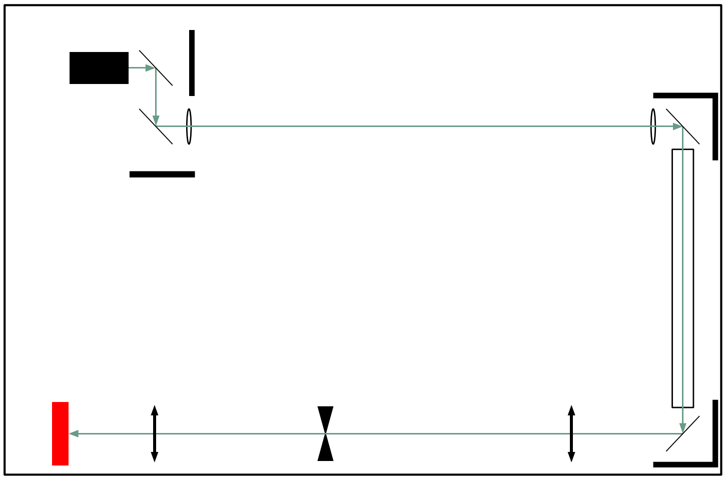


*Figure 8-2: Laser alignment sketch.*

- All unnecessary/untrained persons should leave the room;
- Prepare the lab for the work (clean the lab, put a notice on the door, open the laser light, etc.;
- Prepare the laser table (remove what you do not need and have close-by all tools and optics you need);

**Aligning invisible lasers**

When possible replace the invisible laser with a visible low power laser to perform the laser alignment. When alignment is performed with invisible lasers use viewing cards. The viewing cards will change the invisible radiation into a visible one by fluorescence. When changing UV to visible no charge of the cards is required. When changing from IR to visible the cards must be charged before the alignment. From near IR cards, the charging is done automatically by exposing the cards to visible light. For mid or far IR, the cards may need charging with specially designated UV lamps.

*Figure 8-3: IR viewing card and the UV lamp used for charging it.*

The cards will change the UV or IR radiation to a certain colour. When choosing the cards attention must be paid to the colour which is transmitted by the laser goggles. For example; if the laser goggles will block the red but will transmit green, the viewing card must change the UV or IR radiation into green light.

For aligning far IR may not be possible to use the viewing cards since the yield of transformation may be too low. In these cases, special thermal papers may be necessary.

For high power far IR (like a $CO_2$ laser) regular duct tape may be used to perform the alignment.

*Figure 8-4: Thermal alignment paper.*

## 8.2 Laser measurements

Different types of measurements may be required during research involving lasers. The most usual ones are the beam power or energy per pulse (see section 8.3). Other properties that need to be measured are beam diameter, beam divergence or beam profile. All this information may be presented by the manufacturer in the laser manual or the datasheet. Sometimes the user may need to verify the manufacturer's information. In other situations, like in the case of a home-build or a modified laser, the information may not exist or is modified. For many lasers, the properties may change after many hours of usage and need to be measured again.

### 8.2.1 Beam's profile

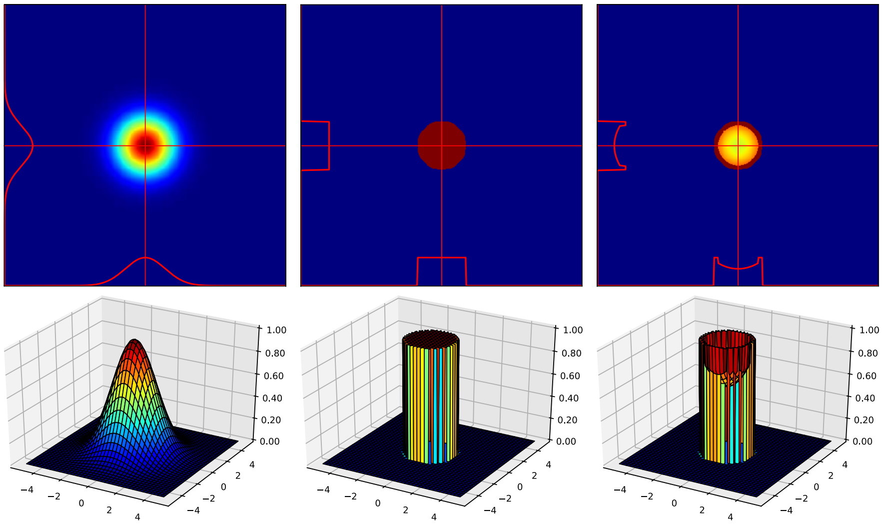


Figure 8-5: Different types of beam profiles.

The ideal laser beam has a Gaussian profile. By determining the intensity of the beam on two perpendicular axes, the user can determine the real beam profile.

A camera connected to a computer can be used to determine the beam's profile. If the power is too high, knife edge or slit scanning techniques are used. The laser beam power is measured using a sharp edge or a scanning slit plotted on a graph to obtain the beam profile.

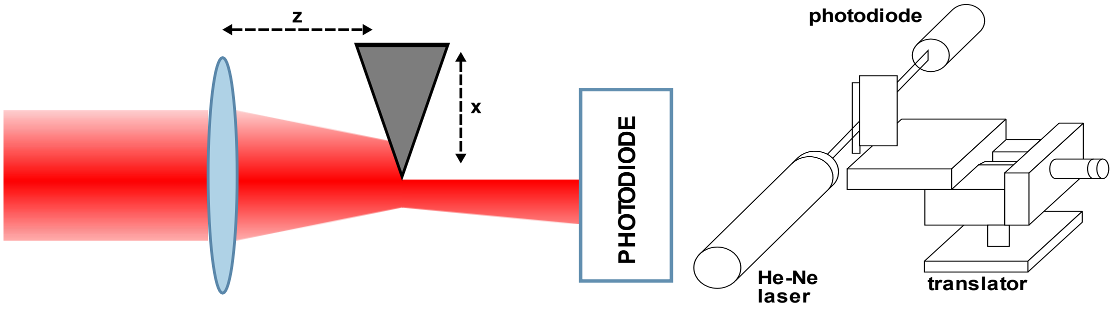


Figure 8-6: Knife-edge technique.

A modified version of the knife-edge technique using a slit can be used to determine irregular beam profiles.

### 8.2.2 Beam's Diameter Measurement

For qualitative measurements of the beam profiles and diameters, photography or heat-sensitive paper can be used.

By using a ruler an approximate beam diameter can be determined.

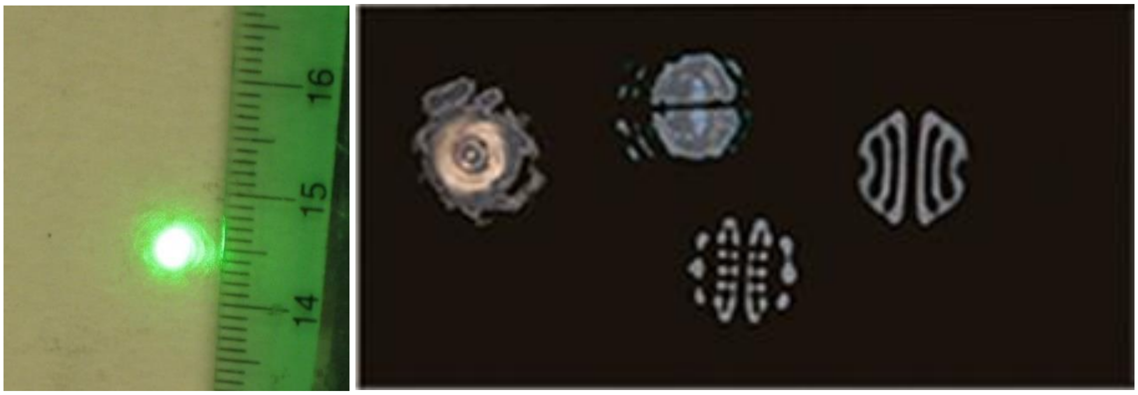


*Figure 8-7: Qualitative measurement of beam diameter with ruler (left). Beam profiles of high-power laser taken with hear sensitive paper.*

A qualitative measurement of the beam diameter can be performed using a simple ruler.

For quantitative measurements, the beam diameter can be determined by using a camera and transmitting the information on a screen. A computer program can be used to fit the profile with a Gaussian.

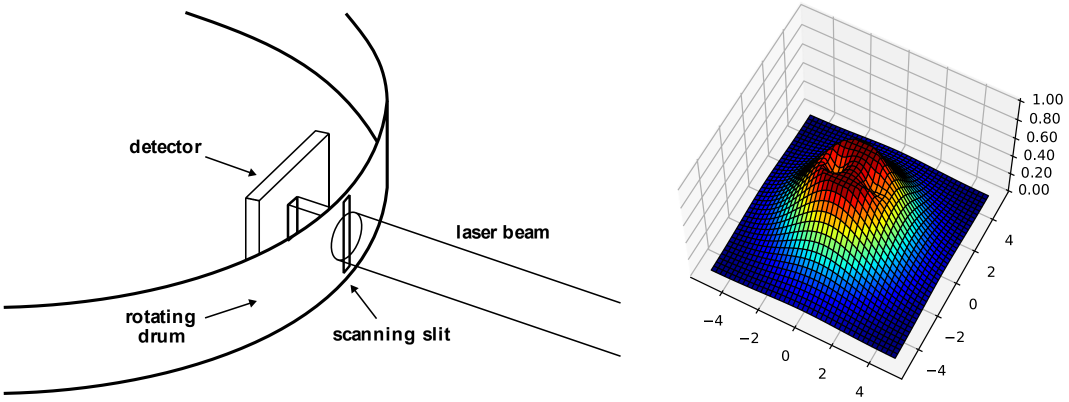


*Figure 8-8: Scanning slit setup (left). Irregular beam profile (right).*

From the laser safety point of view, the beam diameter is defined as being the distance between the points where the beam intensity decreases at 1/e from the maximum (see section 3.5).

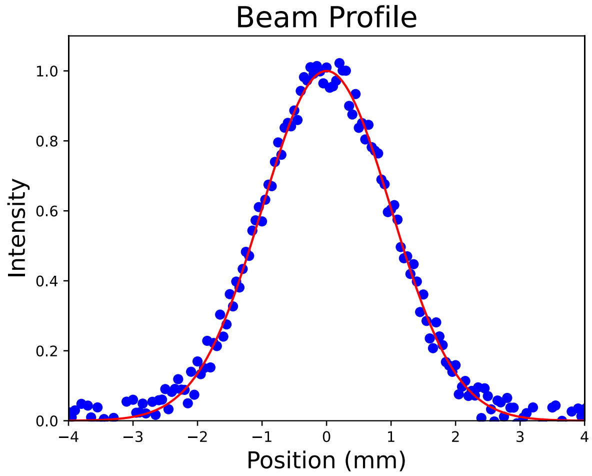


*Figure 8-9: Fitting of a beam profile with a Gaussian function.*

Usually, the beam diameter is measured on both OX and OY axis. For safety purposes, arithmetic means can be used to calculate the beam's diameter.

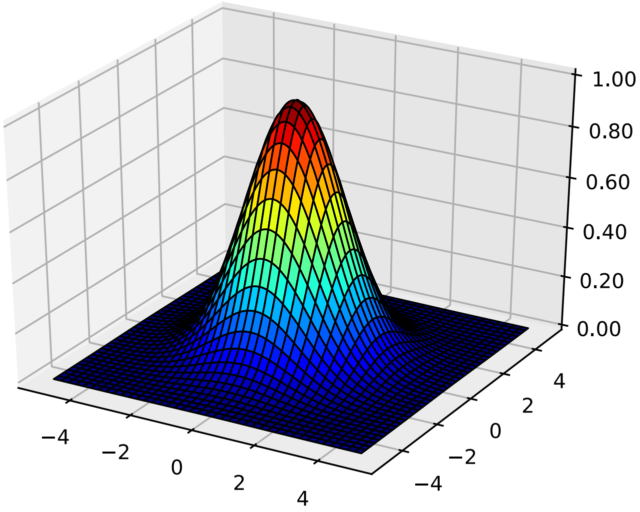


*Figure 8-10: 3D shape of a Gaussian beam profile.*

### 8.2.3 Beam's Divergence

To measure the beam's divergence, the user needs to measure the beam's diameter $D_{L1}$ at distance $r_1$ from the laser head, and the beam's diameter $D_{L2}$ at distance $r_2$.

Calculate the beam's divergence using the formula:

$$\phi = \frac{D_{L_2} - D_{L_1}}{r_2 - r_1}$$

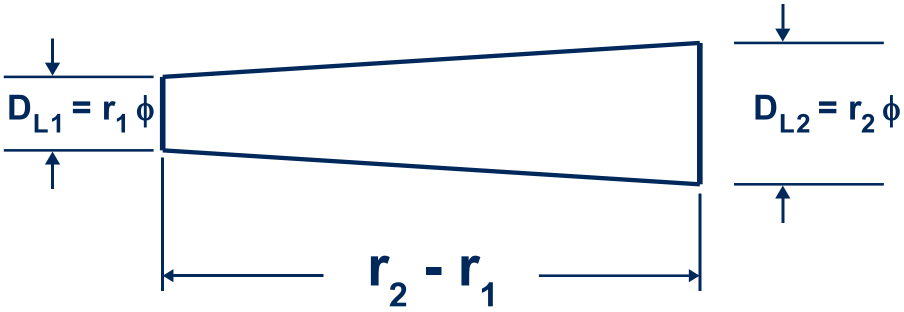


Figure 8-11: Calculation of beam divergence.

## 8.3 Beam's Energy and Power Measurements

There are many methods to measure the beam energy or power. The method used will depend on the power or energy range. For low power or energy lasers, it is common to use a photodiode sensor. The light of the laser will generate a photocurrent in the sensor and, with the proper calibration, this current is related to power. For intermediate to high power or energy lasers, the sensor has a black surface that absorbs the laser light and converts it into heat. This heat can be measured with a thermocouple or a pyroelectric sensor. For very high-power beams, the measurement is done by slowly burning acrylate blocks.

### 8.3.1 Photodiode Sensors

The photoelectric effect is the emission of electrons from a metal when electromagnetic radiation is absorbed. A minimum photon energy is required to create the effect. The kinetic energy of the electrons is the difference between the energy carried by each photon and the electrons' extraction energy (work function) from the metal.

The most used materials for the laser power photodetectors are semiconductors like Si, Ge, GaAs and InGaAs. Photodiode sensors have a strong wavelength dependence.

Depending on the used material, the photodiode sensors can have a good sensitivity in the wavelength range from around 200 nm to 1800 nm.

Instruments using photodiodes sensors, which may have the photodetector made of different materials, have a measuring efficiency that is wavelength dependent. To have

Figure 8-12: Photoelectric effect (left). Photodiode (center). Photodiode sensor (right).

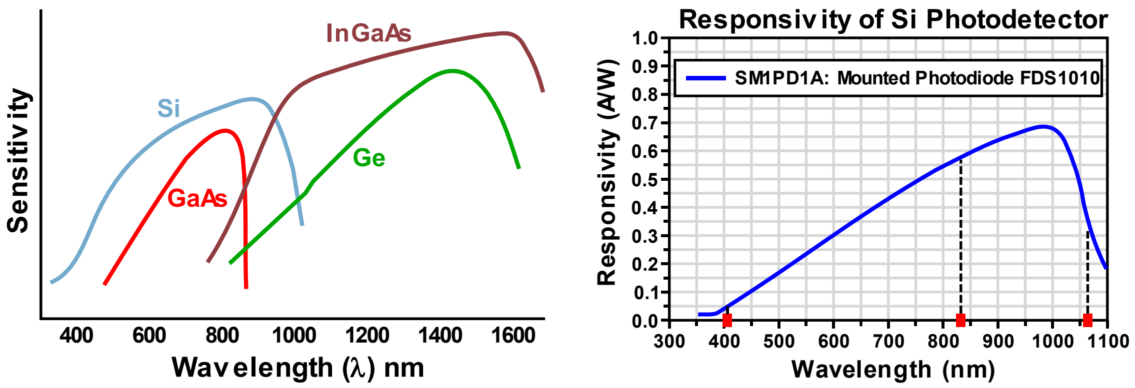


*Figure 8-13: Photodiode dependence on wavelength for different semiconductor materials (left). Example of wavelength dependence of a Si photodiode (right).*

an accurate value of the power or energy, a calibration curve is provided by the meter's manufacturer. The wavelength correction can be included in the meter's software and/or provided by the manufacturer.

Photodiodes can measure laser beam powers in the range of microwatts to tens of milliwatts. They can be used to measure both power and energy per pulse. The typical response time is around 5 milliseconds. Photodiode sensors can measure energy per pulse for a repetitive pulse laser with an upper frequency of around 20 kHz. From the laser safety point of view, a laser with higher frequencies is similar to the CW lasers.

Typical photodiode sensors are between 5 and 10 mm in diameter. Laser power photodetectors are faster and less sensitive to ambient temperature than thermal power detectors.

### 8.3.2 Thermocouple Sensor

The thermoelectric effect is the conversion of a difference in temperature to a voltage and vice-versa. Two wires, each of a different metal, are joined at one end creating a junction. The junction and the free ends of the wires are kept at different temperatures. An electric potential of a few microvolts is created at the free ends of the wires. This voltage is

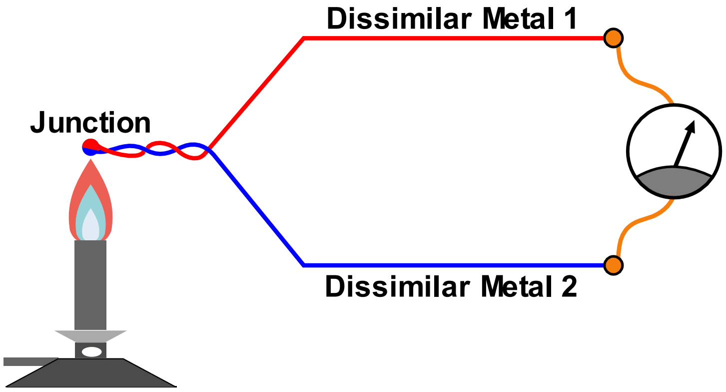


*Figure 8-14: Thermoelectric effect.*

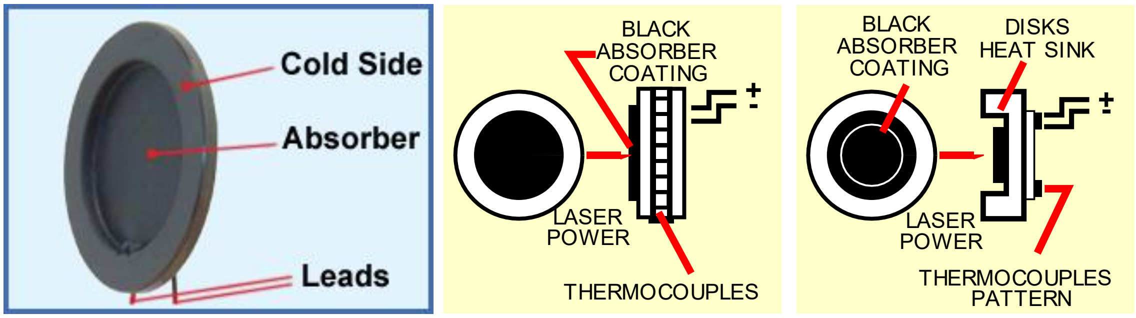


Figure 8-15: Laser thermal sensor (left). Thermocouples used as laser power detectors (center and right).

proportional to the temperature of the junction. By measuring this potential, the temperature of the junction can be determined.

The photons of the laser beam hit one side of the sensing element of the detector and they are absorbed by it. This side of the sensing element has a black coating to maximize absorption. The energy of the photons is converted to heat, increasing the temperature of the sensing element. The thermocouple's junction is in thermal contact with the other side of the sensing element and because of that, at the same temperature. The free end of the thermocouple remains cold, as it is thermally connected to the radiator of the sensor. The temperature difference between the sensing element and the radiator depends on the incident optical power. Therefore, the generated voltage between the two ends of the thermocouple is proportional to the incident power. With precise calibration, the voltage measured by the thermocouple sensor is used to determine the power of the laser beam.

Thermo-couple laser power meters can measure with a good precision laser beam powers from milliwatts to kilowatts. The conversion of optical power into a measurable voltage depends on the capability of the sensor surface to absorb the optical power and convert it into heat. The black coating material on the sensing element should be wavelength-independent and should have a high damage threshold.

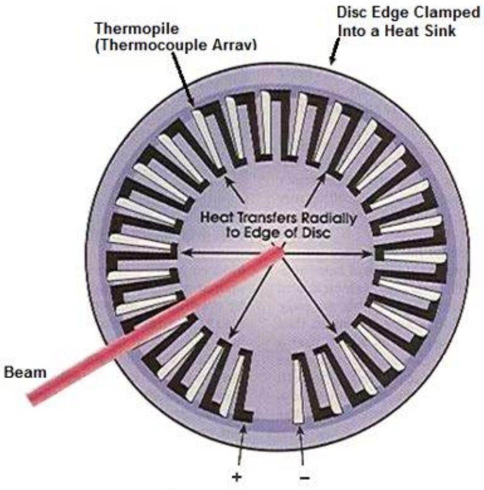


Figure 8-16: Thermopile detector used to measure energy per pulse.

The thermocouple itself is insensitive to the laser wavelength - it only converts the heat into a voltage. However, the absorptive coating shows a wavelength dependence because the coating's surface reflects a small part of the incident light, and the reflectance slightly depends on the wavelength. Since the coating is not transparent, it does not transmit light and, to a very good approximation, the efficiency of the conversion process is solely dependent on the reflection (R) and absorption (A) factors with the equation R + A = 1 or A = 1- R. Consequently, absorbance as a function of wavelength can be calculated by measuring the reflectivity over a certain wavelength range.

When thermocouples are connected in series, this array is called a thermopile. The energy per pulse in a pulsed laser can be measured with a thermopile.

### 8.3.3 Pyroelectric Sensor

The pyroelectric effect is the generation of an electric voltage across the opposite faces of a crystal when the temperature of the crystal changes. If the temperature stays constant at its new value, the pyroelectric voltage gradually disappears due to the leakage current. The leakage can be due to electrons moving through the crystal, ions moving through the air, or current leaking through a voltmeter attached across the crystal.

Pyroelectric sensors are very good indicators of the changes in the temperatures of their environment. Since the voltage dissipates fast in time the pyroelectric sensors are not suitable for measuring the CW laser power but are excellent for measuring the energy per pulse of a pulsed laser. Pyroelectric detectors have a good response from wavelengths between 100 nm to a few mm and response times in the nanosecond range. These sensors can measure energy per pulse for repetitive laser with frequencies up to 25 kHz. From the laser safety point of view, a laser with higher frequencies is similar to the CW lasers.

The energy per pulse range measured with a pyroelectric detector can be from micro joules to tens of joules per pulse.

### 8.3.4 Beam’s Power and Energy Measurement Procedure

Procedure:

- Read the manual first;

Figure 8-17: Pyroelectric effect (left). Pyroelectric detectors (right).

- Powerheads can be used with CW and pulsed lasers;
- Energy heads can be used only with pulsed lasers;
- If external cooling is needed (a fan or water cooling) the air/water flow may influence the measurements. Make sure they are those recommended by the manufacturer;
- Avoid changes in the airflow or drafts around the detector during the measurements;
- Never touch the power detector by hand when measuring, touch only the stand;
- Use only approved connectors between the meter and the detector;
- You should have an approximate idea of what you are measuring. Using the instrument at the wrong wavelength and/or power range might damage it;
- Be aware of other sources of heat;
- Warm up the laser for 25 – 30 minutes. Make sure the laser intensity is stable before starting the measurement;
- Be aware of diffuse back reflections from the surface of the detector (5-15 %);
- Center the beam to the sensor face (more than 98 % of the encircled power centered to the 50 % of the surface of the sensor;
- Warm up the detector for 2 minutes with the laser beam on;
- Block the detector head for 2 minutes;
- With the beam blocked establish the zero level;
- Unblock the beam and wait 1 minute to have the equilibrium;
- Take 5 distinct measurements and use the average of them;
- The instrument may have a self-correction for different wavelengths;
- If it does not, use the calibration chart to make the corrections.

# 9 LASER SAFETY PROGRAM

## 9.1 Principals of Program Development

The best way to protect employees, students and visitors from the hazards associated with the use of lasers, and to satisfy the regulatory requirements, is to develop a good Laser Safety Program. A good Laser Safety Program is a program that, while not interfering with the freedom of research, offers an excellent level of safety.

The extend of the program must be adapted to the number and class of lasers, as well as to the lasers' setup. If an institution has a small number of class 3B or class 4 lasers, which may be enclosed, a shorter laser safety program, implemented by a part-time laser safety officer, may be sufficient. An institution with hundreds of open beam class 3B and class 4 lasers will have a more comprehensive laser safety program. Such an institution will have a Laser Safety Committee, a designated Laser Safety Officer and one or more deputies. The LSO must have sufficient resources to implement and maintain the program, as well as enough authority/support from the institution authorities to enforce the requirements of the program.

The U of T has over 400 hundred open beam class 3B and class 4 lasers, an extensive laser safety program and a Laser Safety Committee (LSC), and two Laser safety Officers. The main role of the U of T LSC is to establish the policies and procedures related to laser safety in the university, to approve the laser safety program and its amendments.

The U of T Laser Safety Program is based on:

- U of T Health and Safety Policy;
- Occupational Health and Safety Act of Ontario;
- ANSI standard Z136.1 Safe Use of Lasers;
- ANSI standard Z136.5 for educational institutions;
- ANSI standard Z136.8 for research facilities.

Due to the continuous technological advances and legislation updates, the program needs to be periodically revised. Easier implementation of the laser safety program can be obtained by issuing a laser safety permit for all Principal Investigators who possess open beam class 3B and 4 lasers.

## 9.2 Content of the Laser Safety Program

The U of T laser safety program, which can be found in the following link, https://ehs.utoronto.ca/our-services/laser-safety/laser-safety-program/, contains:

- Definitions;
- Responsibilities;
- Laser registration;
- Laser safety inspections;
- Training and education;

- Accident/incident reporting and emergency response;
- Medical surveillance;
- Personal protective equipment;
- Engineering controls;
- Administrative and procedural controls;
- Program audit.

In the appendices to the program are presented:

- Laser safety permit;
- Laser inspection check sheet;
- Laser loan form;
- List of authorized laser users;
- Laser registration form;
- Laser room commissioning;
- Decommissioning of class 3B and 4 lasers;
- External contractors form.

## 9.3 Responsibilities

The employer, U of T, has the overall responsibility for laser safety in the institution. This can be achieved by developing and maintaining a good laser safety program. This program is maintained and implemented by the Environmental Health and Safety through the LSOs. Changes to the program are approved by the U of T Laser Safety Committee. The program contains a detailed list of responsibilities for all people involved in laser safety at the university.

The permit holder has the main responsibility for the hazard assessment and the implementation of the laser safety controls in his/her laser laboratories. The Laser Safety Officer verifies the implementation of these controls and gives detailed instructions, if necessary.

The person operating the laser (laser user) has the primary responsibility to operate the laser safely. All responsibilities are correlated with rights. Since the operator of the laser has the right to know the hazards connected with the laser, he/she must be responsible for the safe use of the laser.

## 9.4 Education and Laser Safety Training

As a research and teaching institution, the U of T considers training an essential part of the laser safety program. The level of training must be appropriate for the hazard involved in the laser work.

The work with open beam class 3B or class 4 laser is the most dangerous type of laser work. Therefore, it can be only performed by the users who took the full laser safety training. The full laser safety training has four parts. Laser safety theory can be taken online or in-class, depending on the level of background knowledge in optics and physics of the applicant. The second part is the practical laser safety training. This training is taken in the laser training laboratory where students see and handle lasers and optical components. The third part is on-job training. The on-job training is delivered in the laser laboratory where the work with an open beam is performed. This training is delivered by the Permit Holder or a member of the laboratory with more experience in laser work. The university has a good tradition of mentorship. The students learn from somebody with more experience. The LSO verifies the student's knowledge about laser experimental work during the laser safety follow-up session. Once these three parts of the training are completed, the person using the laser is added to the authorized laser users list in the laboratory. The fourth component of the full laser safety training is the laser safety refresher. The refresher is available online and is mandatory to be taken every 3 years.

Users of laser fibre-coupled lasers or enclosed beams and lower classes can choose to take the full laser safety training or shorter versions of laser safety training dedicated to these specific applications. These laser safety trainings are available online. If the fibre-coupled laser is a class 3B or 4, the online training dedicated to the safe use of fibre-coupled lasers is followed by a follow-up session with the LSO. The users are added to a list of authorized fibre-coupled lasers. For the users of the low class or enclosed beam, online training is recommended. There are no follow-up sessions and no list of authorized users for these types of lasers.

Any person working in the laser laboratory when the open beam class 3B or class 4 laser is ON, but not operating the lasers, must have laser safety awareness training. Examples of these persons are researchers present in the laser laboratory, caretakers, U of T Campus Police, members of the Fire Protection Services, or members of Joint Health and Safety Committees. The laser safety awareness training is available online.

All visits to the laser labs when open beam class 3 B or class 4 laser is on must be approved by the laser Permit Holder. The visitors of the laser labs must be informed about all hazards present in the lab and they have to be provided with the same level of personnel protective equipment as the one used by the laser users.

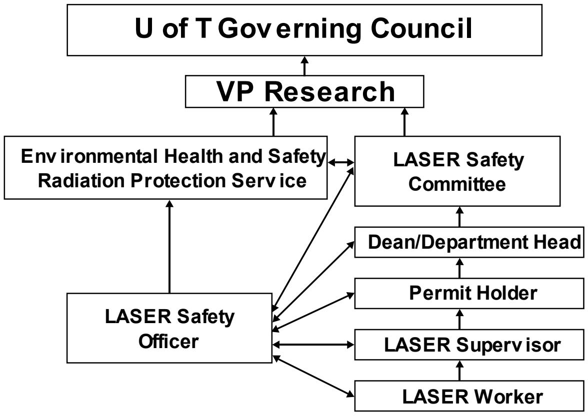


*Figure 9-1: U of T Responsibility chart.*

## 9.5 Laser Safety Database

The Environmental Health and Safety database has a component dedicated to laser safety. The laser safety database is an important part of the laser safety program. The information in the database is kept up to date by the U of T LSO.

All class 3B and class 4 lasers used in open beam experiments must be registered with the Environmental Health and Safety office. People in charge of laser laboratories/facilities must inform the LSO of any new laser being installed. They must provide the following information about the laser:

- Name of supervisor/PH;
- Location (building, room);
- Department;
- Type of laser ($CO_2$, Nd:YAG, He-Ne, etc.);
- Production class (commercial, modified, home-made), manufacturer, model and serial number (SN);
- Laser class, wavelength, maximum power, pulse duration, PRF, energy per pulse, etc.;
- Proposed use (research, teaching, medical, etc.).

This information is registered and kept up-to-date, by the U of T LSO.

Besides the information on the lasers, the database contains information on the laser permits, the list of laser labs, ODs of the laser eyewear, the list of laser users with their history of laser safety training, medical surveillance, etc.

*Figure 9-2: EHS database.*

### 9.6 Medical Surveillance

All users of open beam class 3B and class 4 lasers must enrol and take the pre-assignment medical surveillance. During this assessment, the U of T occupational medical doctor and the occupational nurse will:

- Establish a baseline of ocular conditions before exposure to laser radiation;
- Detect early signs of any ocular damage and initiate prompt treatment;
- Identify persons with photosensitivity of the skin;
- Check visual acuity;
- Check the visual field test – for peripheral vision;
- Perform Amsler Grid test (for macular degeneration);
- Check for colour vision problems.

*Fundoscopic* examination (the visualization of the retina using an ophthalmoscope) is performed to discover evidence of laser accidents, and also, to diagnose high blood pressure, diabetes, endocarditis, and other vascular problems.

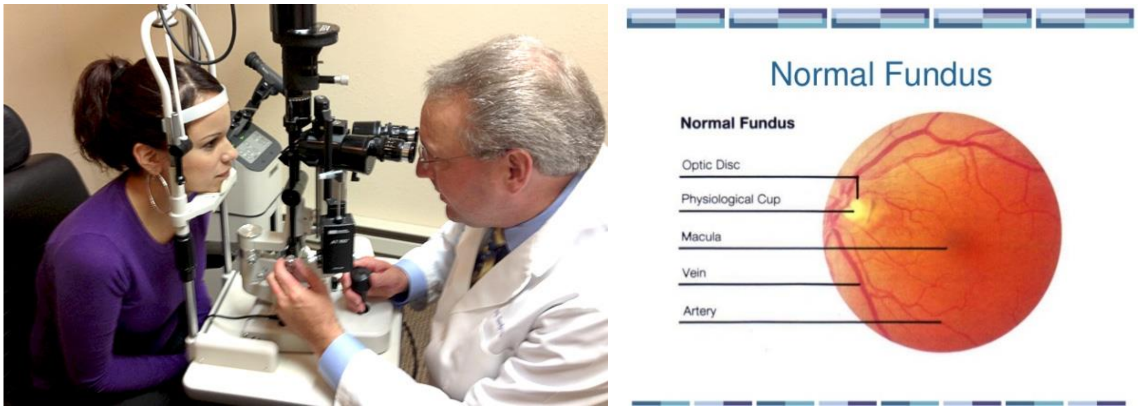


*Figure 9-3: Fundoscopic examination (left). Normal fundus (right).*

The Amsler test for Age Macular Degeneration (AMD), shows the patient a grid pattern. If the grid looks undistorted, the macula is healthy. Distortions in the grid are an indication of a possible AMD.

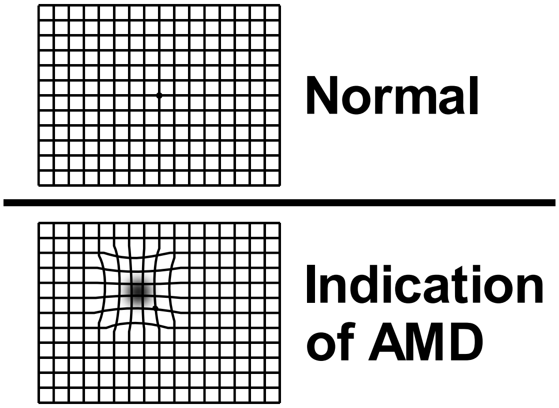


*Figure 9-4: Age macular degeneration.*

The colour test looks for indications for total or partial colour blindness.

Follow-up medical surveillance is not required to be performed periodically. However, it is mandatory immediately after a laser incident/accident to determine the extent of the damage and possible remediations.

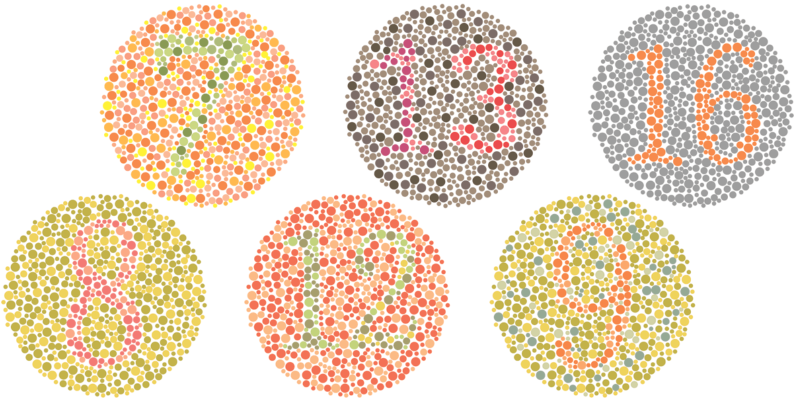


*Figure 9-5: Color vision tests.*

# 10 Laser Accidents

When a laser accident happens the first reaction of the injured person is surprise and shame. The person asks him/herself “how this could happen to me?”. Later, the second reaction is fear of never see with that eye again. Finally, the person feels pain in the eye.

**Famous last words before a laser accident**

- I knew better … I knew better!
- I thought I knew where the beam was
- I only look there for a second
- I thought I could see better without the eyewear on

When people consider themselves infallible is when more likely the accidents happen. People first need to consider that they are human, and humans make mistakes. The approach known as “defence-in-depth” (building multiple barriers) considers all known/possible mistakes and puts controls in place to prevent accidents.

When an accident happens, people need to be prepared to diminish the consequences and to give first aid to the victim of the accident. The laser must be shut down but the laser settings must remain unchanged. The permit holder and the laser safety officer must analyze the accident and prepare a report. In the report, the direct and the root causes of the accident must be identified. To prevent future accidents, corrective measures have to be put into practice at the laser lab and university level. A list of learned lessons may be useful to develop.

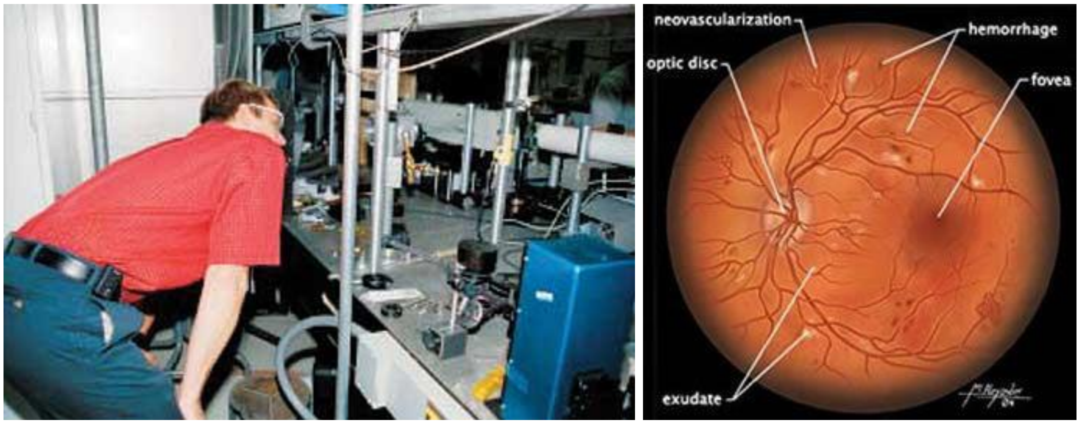


*Figure 10-1: Laser accidents (left). Scotoma (right)*

## 10.1 Direct causes of accidents

Human failure is a more general example of a direct cause of accidents. No wearing the laser goggles or wearing the wrong ones, removing the goggles for a second (to wipe them or to see better) and not blocking the laser beam when inserting new optics are the most common examples of human failure. As mentioned before the laser goggles must be the last line of defence, not the first. Therefore, we should look for a more general approach.

Equipment failure is also possible. The user must verify all optical elements for their physical integrity and functionality.

Engineering controls may be missing or deficient. The user must always understand the principles standing behind any engineering control. For example, the protective layer in the engineer control presented in section 2.3.6 (optics covered with an anti-reflex coating), works only for certain wavelengths and angles of incidence. When used for lasers with other wavelengths, they are ineffective and they can increase the hazard by causing total reflection.

Examples of engineering control deficiencies:

- Beam blockers not used as required
- Beam blockers for stray beams inexistent
- Beam tubes are not used when vertical beams are present.

Not following rules and procedures is another common direct cause of accidents. The standard operating procedures must be read and understood by each user before starting the experiment. In many cases, mistakes happen when new optical elements are added to the experiment without a complete understanding of their functions. Examples of SOPs or alignment procedures deficiencies:

- Laser beams not used for the experiments not being blocked or disabled;
- Not using viewing cards and indirect viewing when possible;
- The beam is not aligned correctly, oblique beams are generated

Criminal intention can be a direct cause of laser accidents. The laser must never be pointed towards a person. Legislation exists and is enforced to prevent using lasers close to the airport areas or pointing the lasers towards the flying planes or helicopters.

Remember that bending or blinking will not help the person towards which the laser is pointed to prevent the accident.

## 10.2 Root causes of accidents

When a laser incident or accident happens, the determination of direct causes is not sufficient. The root causes must be identified. A useful technique to determine the root cause of an accident is by repeatedly asking the question “why?”. For example: why the user was not wearing the laser goggles?

The most common root cause of accidents is the lack of leadership. An accident is always considered a management failure. Safety must be considered a priority by the upper management of any institution. An Integrated Safety Management system must be developed and implemented.

Accidents, in general, happen to two categories of laser users: users with many years of experience and beginners. Experienced users are normally overconfident and this is exacerbated after many years without any incident. They always tell themselves, “If it did not happen in all these years will not happen now”. On the other side of the spectrum are the beginners. They may be afraid of working with high power lasers, they lack experience, knowledge. In university, there is a culture of mentorship. More advanced users are willing to teach newcomers. Depending on the experimental set up the “on-the-job training” may take from a few hours to weeks or months. The beginners must pay attention and ask questions.

Miscommunication is another common root cause of accidents. The users must make sure they understand how the laser works, the experimental setup and operation of each optical component before they attempt to insert it into the laser system.

More concern about “job to be done” than “job to be done right” is a cause of accidents. The users may be in a hurry to finish the work for various reasons. On Friday afternoon people may want to finish the working week and start enjoying the weekend. This can lead to speed up a delicate and dangerous procedure that otherwise should be done at a normal pace. If the experimental setup requires work overnight, the user must perform only simple tasks (e.g.: changing samples). If a more complicated task is necessary (e.g.: laser alignment), this must be performed the next day when the person is on full rest.

A general cause of the accident is inadequate training. In a research setting by following old experiments is unlikely to discover something new. The users must invent new experiments and new procedures. In this case, the importance of understanding, and therefore of the training, is crucial.

### 10.3 Emergency preparedness

To dimmish the consequences of laser accidents, the users must be prepared by having emergency phone numbers readily available. The laser must be shut down immediately, but the experimental settings must be kept undisturbed. This is necessary when the accident analysis is performed.

The next step is to call for help. If the accident happened to the eye, assist the person to visit an ophthalmologist as soon as possible. If major portions of the skin are burned, call 911 and help transport the injured person to the closed hospital.

A class 4 laser can start a fire. To prepare for a fire emergency a fire extinguisher must be available in the laser laboratory. The laser users must know how to use the fire extinguisher. If the fire cannot be stopped with one fire extinguisher, the user must close the door and start the fire alarm. Never go to another room and try to use a second extinguisher. All fires, including the small ones, must be reported.

In case of a fire alarm in the building, the laser user must leave the laser beam enclosed or blocked, if the laser cannot be shut down.

An explosion can cause serious injury. Call 911 for help immediately.

The most common non-beam accident involves electricity. Never try to save a person which is being electrocuted by touching the person directly. Use a tool made of plastic or wood to remove the person from the electrical contact. Cardiopulmonary resuscitation (CPR) must be performed only by a CPR certified person.

## 10.4 Accident analysis

> ***"Errare humanum est.***
> ***Perseverare***
> ***diabolicum"***
>
> **"To err is human.**
> **To repeat error is**
> **of the Devil"**
>
> **Seneca**

*Figure 10-2: Importance of not repeating mistakes.*

The actions taken after any incident or accident are extremely important in the prevention of future accidents.

The best is to learn from somebody's else mistakes. A thorough incident/accident analysis must be performed.

Unfortunately, many accidents are not reported. This practice makes it difficult to learn from previous mistakes. The U of T laser users are encouraged to report any incident, even the ones without consequences, to help prevent future accidents.

The accident analysis must contain a detailed description of the circumstances and the events. The health and safety consequences suffered by the persons involved, and the measures are taken to reduce the consequences of the accident.

The analysis must also contain a list of direct and root causes of the accident (see sections 10.1 and 10.2).

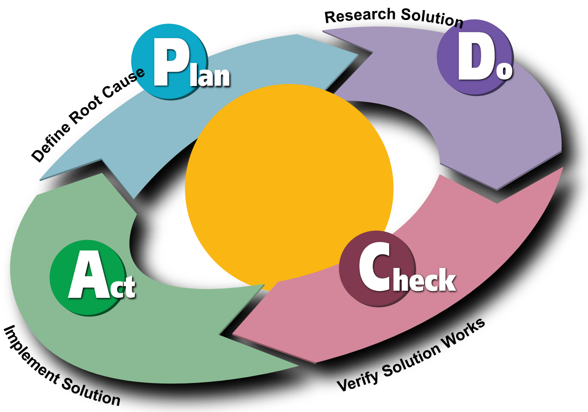


*Figure 10-3: Accident analysis.*

The lessons learned and the suggested changes to the laser safety program must also be part of the accident analysis. Examples of lessons learned, and suggested program changes are:

- Improvements to the laser safety general training insisting on practical alignment training;
- Improvements to the site-specific On Job Training (OJT) performed in the laser laboratory;
- Improving supervision including supervision of settings changes;
- Improving work planning and controls;
- Address specific hazards as:
  - Dimly visible laser beams
  - Optics that can generate out of plane beams
- Authorizing and releasing work (pre-job briefing) required when:
  - New, unfamiliar, or infrequent tasks;
  - Significant configuration change;
  - The facility is returning to operation from extended downtime;
- Improving compliance with safety requirements (supervisors and senior members of the team must be a role model in safety culture);
- Take appropriate corrective and disciplinary actions for safety violations (proportional with gravity: oral warning, written warning, suspension from performing an activity, discharge from employment);
- Develop performance metrics for laser safety.

### 10.5 Accident Reporting

Reportable incidents/accidents are those which result in personal injury or have the potential to result in significant personal injury or property damage. The incident/accident must occur on U of T premises or to U of T employees while performing their work on or off U of T premises.

For a U of T employee, the following form available on the EHS webpage

https://ehs.utoronto.ca/report-an-incident/online-accidentincident-eform-for-employees/

and in case of an injury of a student, visitor, or contractor the following form

https://ehs.utoronto.ca/report-an-incident/online-accidentincident-eform-for-students-contractors-and-visitors/

must be completed by the laser Permit Holder. The form will be transmitted to the Office of Environmental Health and Safety, the Joint Health and Safety Committee, and the Union.

As defined in Ontario Health and Safety Act and regulations a critical injury means an injury of a serious nature that,

a) places life in jeopardy,
b) produces unconsciousness,
c) results in substantial loss of blood,
d) involves the fracture of a leg or arm but not a finger or toe,
e) involves the amputation of a leg, arm, hand or foot but not a finger or toe,
f) consists of burns to a major portion of the body, or
g) causes the loss of sight in an eye. R.R.O. 1990, Reg. 834, s.1.

The laser beam can cause loss of sight in an eye or burns to major portions of the skin. The non-beam hazards can result in loss of life or a critical injury. In all these situations, the Laser Permit Holder must notify the LSO immediately. The site of the accident must remain undisturbed until the Ontario Ministry of Labor inspector arrives. The Laser Permit Holder must assist the U of T LSO to investigate the circumstances of the accident and preparing a written report.

Any injured person must be referred immediately to a physician or ophthalmologist. The U of T Environmental Health and Safety will inform the Ontario Ministry of Labor.