Laser safety manual

University of Victoria, Chemistry Department

Warning symbol for lasers class 2 and higher

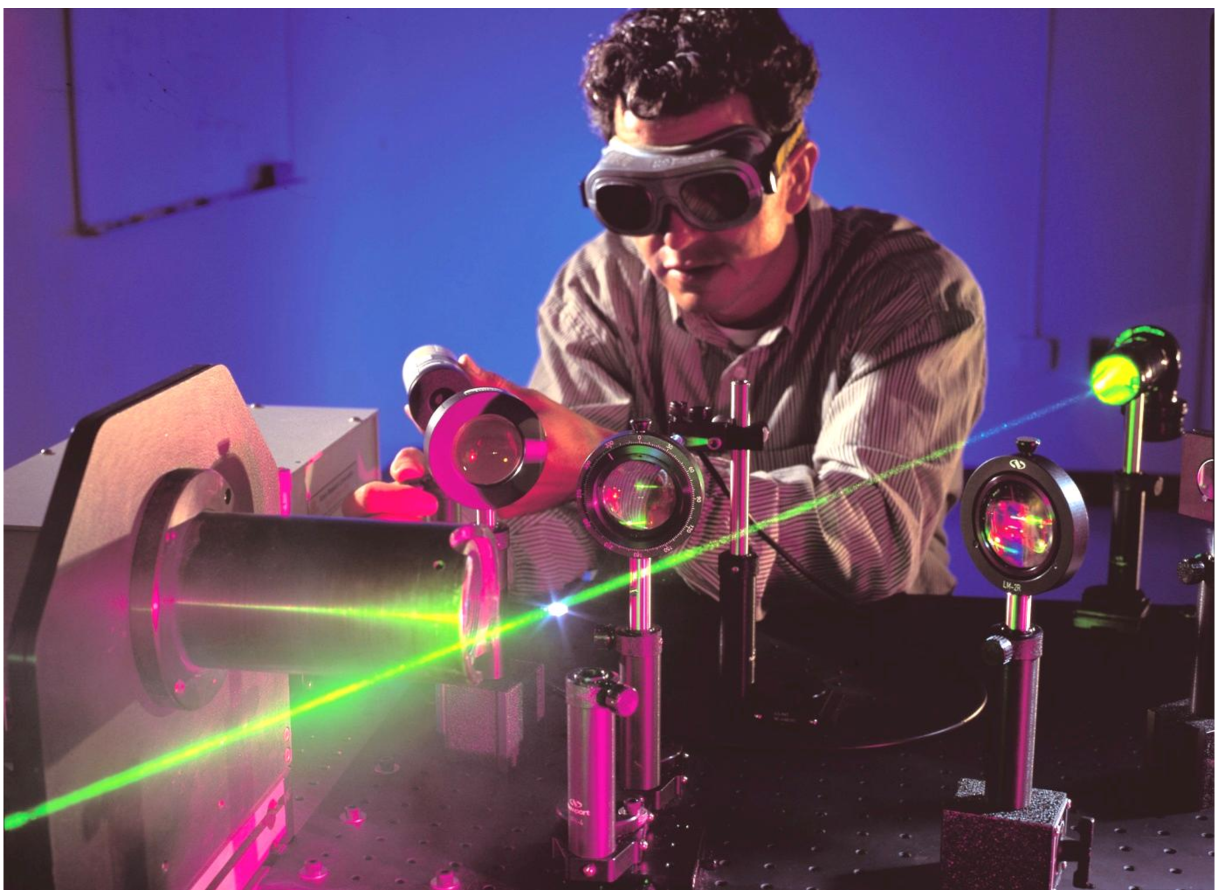


Photo: Prof. D Hahn

Attention

Getting familiarized with the following parts is mandatory

(Reading the whole manual is highly recommended)

Remember the first rule of laser safety:

NEVER UNDER ANY CIRCUMSTANCES LOOK INTO ANY LASER BEAM!

Table of contents

1. Laser Design

The word ***LASER*** is an acronym for "Light Amplification by the Stimulated Emission of Radiation" which describes how laser light is generated at the atomic level.

Ordinary light

Ordinary light, such as that from a light bulb - is produced when tungsten atoms are heated with an electric current causing the tungsten electrons to be "excited" to a higher energy level. The electrons loose their energy of excitation by releasing it in the form of photons of various wavelengths in the visible portion of the electromagnetic spectrum (i.e. white light). Since each excited electron releases its photon independently of the other excited electrons, the individual photons are released at different times and in different directions and the emitted light is released in all directions around the light source (isotropic emission).

1.1 Laser components

Laser light on the other hand is coherent, unidirectional and mono-energetic meaning that the photons are all released at the same time, in the same direction, and are of the same wavelength. Figure 1 shows the typical components of a laser:

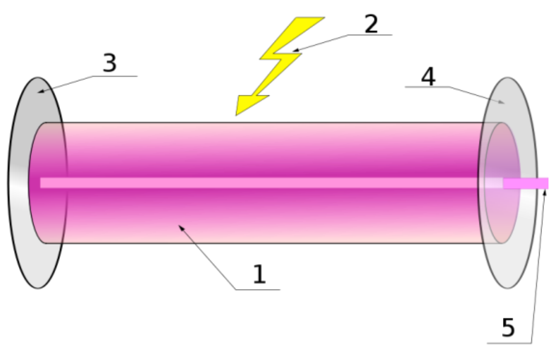


Figure 1.

Principal components:
1. Gain medium
2. Laser pumping energy
3. Fully reflecting mirror
4. Partially reflecting mirror
5. Laser beam

The laser medium may be:

- solid state ex: Nd:YAG
- semi-conductor ex: GaAlAs
- liquid ex: dye solution
- gas ex: XeCl

for more info see Appendix 1

The power supply may be:

- flash or arc lamp - for solid state lasers
- electrical current - for semi-conductor and gas lasers
- another laser - for liquid laser

1.2 Laser light production

Radiative Transitions:

Electrons normally occupy the lowest available energy level (the atom is said to be in its ground state). Electrons can, however, occupy higher energy levels, leaving some of the lower energy states vacant or sparsely populated. One way that electrons can change from one energy state to another is by the absorption or emission of light energy, via a process called radiative transition.

Absorption:

An electron can absorb energy from a variety of external sources. From the point of view of laser action, two methods of supplying energy to the electrons are of prime importance. The first of these is the transfer of all energy of a photon directly to its orbital electron. The increase in the energy of the electron causes it to "jump" to a higher energy level; the atom is then said to be in an "excited" state. It is important to note that an electron can accept only the precise amount of energy that is needed to move it from one allowable energy level to another. Only photons of the exact energy acceptable to the electron can be absorbed. Photons of slightly more or less energy will not be absorbed.

Another means often used to excite electrons is an electrical discharge. The energy is supplied by collisions with electrons which have been accelerated by an electric field. The result of either type of excitation is that, through the absorption of energy, an electron has been placed in a higher energy level than the one in which it originally resided.

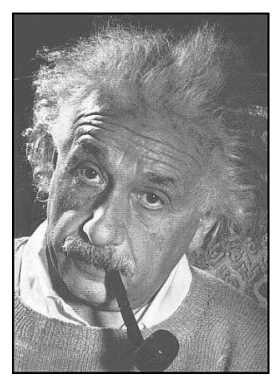
Spontaneous Emission:

The nature of all matter is such that atomic and molecular structures tend to exist in the lowest energy state possible. Thus, an excited electron in a higher energy level will soon attempt to ***de-excite*** itself by any of several means. Some of the energy may be converted to heat.

Another means of de-excitation is the spontaneous emission of a photon. The photon released by an atom as it is de-excited will have a total energy equal to the difference in energy between the excited and lower energy levels. This release of a photon is called spontaneous emission. One example of spontaneous emission is the neon sign. Atoms of neon are excited by an electrical discharge through the tube. They de-excite themselves by spontaneously emitting photons of visible light.

Stimulated Emission:

In 1917, Einstein postulated that a photon released from an excited atom could, upon interacting with a second similarly excited atom, trigger the second atom into de-exciting itself with the release of another photon. The photon released by the second atom would be identical in frequency, energy, direction, and phase with the triggering photon. The triggering photon would con tinue on its way unchanged. Where there was one photon, now there are two. These two photons could proceed to trigger more photon releases through the process of stimulated emission.



If an appropriate medium contains a great many excited atoms and de-excitation occurs only by spontaneous emission, the light output will be random and approximately equal in all directions. The process of stimulated emission, however, can cause an amplification of the number of photons traveling in a particular direction.

A preferential direction is established by placing mirrors at the end of an optical cavity. Thus, the number of photons traveling along the axis of the mirrors increases greatly and ***"Light Amplification by the Stimulated Emission",*** may occur. If enough amplification occurs, ***LASER*** beam is created.

The process of stimulated emission will not produce a very efficient or even noticeable amplification unless a condition called ***"population inversion"*** occurs. If only a few atoms in several million are in an excited state, the chances of stimulated emission occurring are very small. The greater percentage of atoms in an excited state, the greater the probability of stimulated emission. In the normal state of matter most of the electrons reside in the ground level, leaving the upper excited levels largely unpopulated. When electrons are excited and fill these upper levels to the extent that there is of atoms in the excited state, the population is said to be inverted.

The spectral output of a laser generally consist of a number of discrete wavelengths which can be spatially separated from one another by passing the light through a prism.

In summary:
An energy source such as an intense light source or electrical current can be used to excite electrons in a solid, liquid or gas. If the material contains atoms which have a meta-stable excited state, the excited electrons will accumulate in this excited state and can be stimulated to de-excite and emit a photon of the same wavelength, phase and direction as the stimulating photon - i.e. laser light.

2. Laser Operation
- Continuous Wave (CW)
- Pulsed

A pulsed laser emits a pulse of energy lasting less than 0.25 seconds. Some lasers emit a train of pulses with a pulse repetition frequency up to hundreds of thousands of pulses per second. In a **Q-switched laser**, the population inversion (usually produced in the same way as CW operation) is allowed to build up by making the cavity conditions (the 'Q'uality) unfavorable for lasing. Then, when the pump energy stored in the laser medium is at the desired level, the 'Q' is adjusted (electro- or acousto-optically) to favourable conditions, releasing the pulse. This results in high peak powers as the average power of the laser (were it running in CW mode) is packed into a shorter time frame.

2.1 Radiant energy and power
The radiant energy or power output of the laser determines its classification with respect to ANSI Z136.1 - 2000, American National Standard for Safe Use of Lasers and this standard has been adopted for regulatory purposes in B.C. and other provinces. The radiant energy of the laser is determined by the manufacturer and is expressed as joules (J) of output per pulse. For CW lasers the radiant energy is expressed as joules of output per unit time or watts (1W = 1 J/s).

2.2 Radiant exposure and irradiance
Although the radiant energy and power are useful units for classifying the laser, it is the concentration of radiant energy or power in the beam that determines if the laser is a hazard for most exposure conditions. The concentration of radiant energy and power is expressed as joules per cm^2 (radiant exposure)and watts/cm^2 (irradiance) respectively. Biological damage is a function of the rate of energy absorption in a specific amount of tissue and not simply the total energy absorbed. For example, if the energy was absorbed slowly in a given mass of tissue the temperature rise in the exposed tissue would not be as great as it would be if the energy was absorbed quickly in the same mass of tissue. This is because the heat which is produced in the tissue is conducted into the surrounding tissue. If the rate of heat conduction is equal to the rate of energy absorption, the temperature of the tissue will remain constant and the tissue will not suffer any thermal damage.

The exception to this is exposure to UV radiation in which both photochemical and thermal damage can occur. While heat conduction away from the tissue may prevent thermal damage from occurring it will not prevent photochemical damage from occurring. Photochemical damage is a function of the total energy absorbed per mass of tissue and not the rate of energy absorption. Photochemical damage is caused by the induction of chemical reactions in a cell due to absorption of ultraviolet light photons.

2.3 Beam divergence
Although a laser beam is directional, some divergence (beam spread) does occur. This results in an increase in the beam diameter as the distance from the exit port of the laser increases. Beam divergence is measured in

milliradians (17.5 mrad = 1°) and lasers typically have a beam divergence of about 1 mrad. Therefore, at indoor distances there will not be a significant decrease in beam irradiance over the distance of travel.

2.4 Beam reflection

The portion of the beam that is not absorbed or transmitted is reflected off an object. Two types of reflections are important:

- Specular reflection
- Diffuse reflection

Specular reflections are mirror-like reflections in which the cross-sectional shape and intensity of the beam remain unchanged. Optical components such as mirrors and other shiny objects produce specular reflections at most wavelengths. In general, a specular reflection will occur when the wavelength of the laser is larger than the size of the irregularities in the surface of the reflecting object.

A diffuse reflection occurs when the irregularities on the surface of the object are randomly oriented and are larger than the wavelength of the laser light impinging upon it. The light is reflected in all directions from diffuse surfaces resulting in a significant decrease in the irradiance when viewed from any angle. Specular reflections are much more hazardous than diffuse reflections. Eye or skin contact with a specular reflection is equivalent to contact with the direct beam therefore efforts must be made to eliminate unnecessary specular reflections of the laser beam.

It should be noted that objects which appear rough and diffusely reflecting for visible light might produce specular reflections for longer wavelength infrared light.

2.5 Maximum permissible exposure

The maximum permissible exposure (MPE) is the level of laser radiation to which a person may be exposed without hazardous effect or adverse biological changes in the eye or skin. ANSI Z136.1 - 2000 has several tables that list MPE values for the eye and skin based on wavelength and estimated exposure time. For example, the ocular (corneal) MPE for a frequency doubled, continuous wave, Nd:YAG laser which emits 532nm light is 2.5 mW/cm^2 assuming a blink reflex time of 0.25 seconds. The skin MPE for this laser is 200 mW/cm^2. The ocular MPE for visible light is lower than the skin MPE in order to protect the retina from the increase in irradiance that occurs when light passes through the lens of the eye and is focused on the retina.

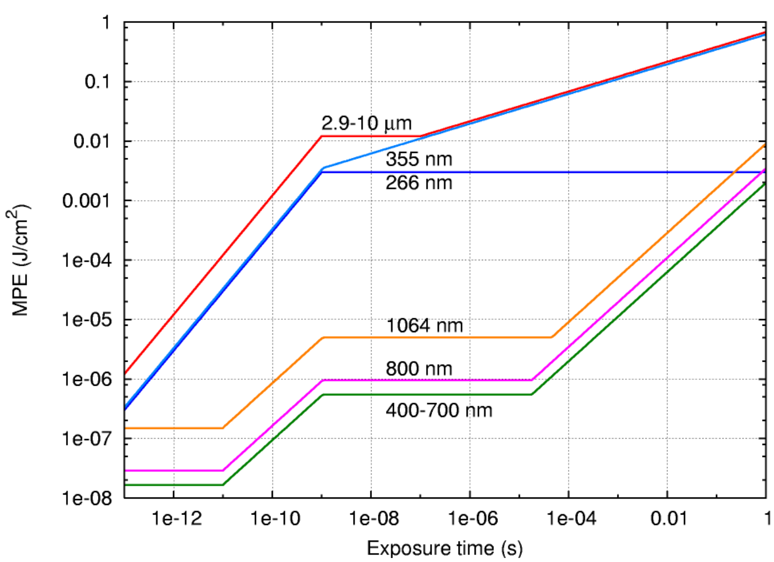


Fig. 2. Maximum permissible exposure (MPE) at the cornea for a collimated laser beam as energy density versus exposure time for various λ.

2.6 Nominal hazard zone

The nominal hazard zone (NHZ) is the space within which the level of direct, reflected or scattered laser light exceeds the MPE level for the laser. The NHZ is determined by first identifying all possible beam paths, both direct and reflected. The radiant exposure or irradiance is then calculated for each beam path and these values are compared to the eye and skin MPE values for the laser. Wherever the MPE is exceeded, that becomes part of the NHZ. Within the NHZ, personal protective equipment (e.g. laser goggles) must be worn.

3. Laser Classification

The classifications categorize lasers according to their ability to produce damage in exposed people. There are two classification systems, the **"old system"** used before 2002, and the **"revised system"**. The latter reflects the greater knowledge of lasers that has been accumulated since the original classification system was devised. From 2007, the revised system is also incorporated into ANSI Z136.1. The old and revised systems can be distinguished by the 1M, 2M and 3R classes used only in the revised system and the IIIA and IIIB classes used only in the old system.

The classification of a laser is based on the concept of *accessible emission limits* (AEL) that are defined for each laser class. This is usually a maximum power (in W) or energy (in J) that can be emitted in a specified wavelength range and exposure time. For infrared wavelengths above 4 µm, it is specified as a maximum power density (in W/m^2). It is the responsibility of the manufacturer to provide the correct classification of a laser, and to equip the laser with appropriate warning labels and safety measures as prescribed by the regulations.

Safety measures used with the more powerful lasers include:

- key-controlled operation
- warning lights to indicate laser light emission
- beam stop or attenuator
- electrical contact that the user can connect to an emergency stop or interlock.

The old classification system: (examples of caution and danger signs are shown on the right)

Class I

A class 1 laser is safe under all conditions of normal use. This means the maximum permissible exposure (MPE) cannot be exceeded. This class includes high-power lasers within an enclosure that prevents exposure to the radiation and that cannot be opened without shutting down the laser. Exempt from control measures

Class II

- All Class II lasers operate within the visible region of the spectrum (400-700 nm)
- Output is not intended to be viewed (for example, a grocery scanner)
- Eye protection is normally afforded by the aversion response to bright light (blink).
- Upper power limit for Class II continuous wave (CW) lasers is 1 mW
- Class II lasers shall have a "Caution" sign posted on the outside door

Class IIIa

- Power output is up to 5 times greater than Class II - 5mW.
- Laser or laser systems that would not normally produce a hazard if viewed for only a moment with the unaided eye (for example a laser pointing device) .
- Beams may present a hazard if viewed through collecting optics.
- Class IIIa lasers shall have a "Caution" sign posted on the outside of the door.6

Class III b

- Maximum power output is less than 500 mW.
- CW lasers operate between the upper Class IIIa limits (5mW) and the maximum power for Class IIIb lasers (500 mW).
- Diffuse reflections are usually not hazardous. However, lasers or laser systems may produce a hazard if viewed directly through intrabeam viewing or specular reflections.
- Class IIIb lasers shall have a "Danger" sign posted on the outside of the door.

Class IV

- Power exceeds Class IIIb limits of 500mW.
- High-powered lasers and laser systems capable of causing severe eye damage with short duration exposures (0.25 seconds) to the direct, specularly, or diffusely reflected beam.
- Capable of causing severe skin damage.
- Can ignite flammable and combustible materials.
- May produce laser generated air contaminants or hazardous plasma radiation.
- Class IV lasers shall have a "Danger" sign posted on the outside of the door.

The larger part of the lasers in the chemistry department is marked according to this system.

Every laser user in the department must be aware which class is the laser they are working with.

The revised classification system

Class 1

A class 1 laser is safe under all conditions of normal use. This means the maximum permissible exposure (MPE) cannot be exceeded. This class includes high-power lasers within an enclosure that prevents exposure to the radiation and that cannot be opened without shutting down the laser. For example, a continuous laser at 600 nm can emit up to 0.39 mW, but for shorter wavelengths, the maximum emission is lower because of the potential of those wavelengths to generate photochemical damage. The maximum emission is also related to the pulse duration in the case of pulsed lasers and the degree of spatial coherence.

Class 1M

A Class 1M laser is safe for all conditions of use except when passed through magnifying optics such as microscopes and telescopes. Class 1M lasers produce large-diameter beams, or beams that are divergent. The MPE for a Class 1M laser cannot normally be exceeded unless focusing or imaging optics are used to narrow the beam. If the beam is refocused, the hazard of Class 1M lasers may be increased and the product class may be changed. A laser can be classified as Class 1M if the total output power is below class 3B but the power that can pass through the pupil of the eye is within Class 1.

Class 2

A Class 2 laser is safe because the blink reflex will limit the exposure to no more than 0.25 seconds. It only applies to visible-light lasers (400–700 nm). Class-2 lasers are limited to 1 mW continuous wave, or more if the emission time is less than 0.25 seconds or if the light is not spatially coherent. Intentional suppression of the blink reflex could lead to eye injury. Many laser pointers are class 2.

Class 2M

A Class 2M laser is safe because of the blink reflex if not viewed through optical instruments. As with class 1M, this applies to laser beams with a large diameter or large divergence, for which the amount of light passing through the pupil cannot exceed the limits for class 2.

Class 3R

A Class 3R laser is considered safe if handled carefully, with restricted beam viewing. With a class 3R laser, the MPE can be exceeded, but with a low risk of injury. Visible continuous lasers in Class 3R are limited to 5 mW. For other wavelengths and for pulsed lasers, other limits apply.

Class 3B

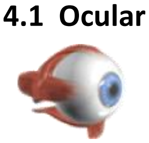
A Class 3B laser is hazardous if the eye is exposed directly, but diffuse reflections such as from paper or other matte surfaces are not harmful. Continuous lasers in the wavelength range from 315 nm to far infrared are limited to 0.5 W. For pulsed lasers between 400 and 700 nm, the limit is 30 mJ. Other limits apply to other wavelengths and to ultrashort pulsed lasers. Protective eyewear is typically required where direct viewing of a class 3B laser beam may occur. Class-3B lasers must be equipped with a key switch and a safety interlock.

Class 4

Class 4 lasers include all lasers with beam power greater than class 3B. By definition, a class-4 laser can burn the skin, in addition to potentially devastating and permanent eye damage as a result of direct or diffuse beam viewing. These lasers may ignite combustible materials, and thus may represent a fire risk. Class 4 lasers must be equipped with a key switch and a safety interlock. Many industrial, scientific, and medical lasers are in this category.

4. Biological Effects

4.1 Ocular effects



The biological effects of laser light on the eye depend on the wavelength of the laser light since light of different wavelengths differ in their ability to penetrate through the ocular components of the eye (Figure 3, also Appendix 2).

The first rule of laser safety is: NEVER UNDER ANY CIRCUMSTANCES LOOK INTO ANY LASER BEAM! If you can prevent the laser beam and beam reflections from entering the eye, you can prevent a painful and possibly blinding injury.

4.1.1 Ultraviolet light

Ultraviolet light (100 - 400 nm) is weakly penetrating. UV-C (100 -280 nm) and UV-B (280 - 315 nm) are absorbed on the cornea and in the aqueous humor and cannot penetrate to the iris or lens of the eye. The principal hazard is photokeratitis (welder's flash) and erythema (reddening) which are reversible conditions if the damage is not too severe. UV-A (315 - 400 nm) can penetrate past the aqueous humor and absorb on the lens of the eye. The principle hazard is the formation of cataracts in the lens of the eye. UV-A cannot penetrate to the retina.

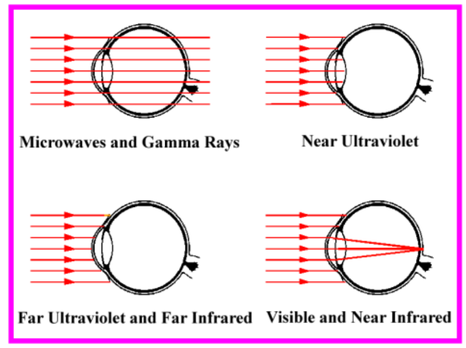
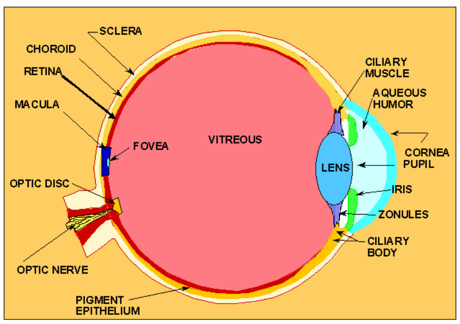


Fig. 3. Eye penetration of different wavelengths



4.1.2 Visible light

Visible light (400 - 780 nm) is deeply penetrating and absorbs principally on the retina of the eye. In addition to this, the lens of the eye focuses images on the retina with an optical gain of approximately 100,000. This means that an external light source that produced an irradiance of 1 W/cm^2 on the cornea of the eye, would result in an irradiance of 100,000 W/cm^2 on the retina. Generally, an irradiance exceeding 10 W/cm^2 is enough to cause tissue damage. The type of damage to the retina depends on the location on the retina where the light source is focused. The most severe effects occur when laser light is focused on the optic nerve since damage to this area can lead to total blindness.

4.1.3 Infrared light

Infrared light (780 nm - 1 mm) also has different penetrating ability depending on the wavelength. IR-A (780 - 1400) is a retinal hazard, similar to visible light. The difference is that IR-A can't be seen and could result in longer exposures since there would not be the aversion response (i.e. blink reflex) that there is to bright visible light. IR-B (1400 - 3,000 nm) does not penetrate past the lens but can cause cataracts. IR-C (3,000 nm - 1mm) absorbs principally on the cornea and can cause burns in this location if the irradiance is great enough.

4.2 Skin effects

The biological effects of laser light on skin include:

- thermal effects
- photochemical effects
- delayed effects

Thermal effects in skin occur when the rate of energy absorption exceeds the rate at which the tissue safely conducts heat away from the volume of tissue exposed. Experimental studies involving several cm^2 of skin exposed for 0.5 seconds with penetrating white-light (400-750 nm) have shown that a first degree burn to the skin (superficial reddening) can occur when the irradiance exceeds 12 W/cm^2 on the skin surface. A second degree burn (blistering) can occur when the irradiance exceeds 24 W/cm^2 and a third degree burn, involving complete destruction of the outer layer of skin (epidermis), can occur when the irradiance exceeds 34 W/cm^2. However, the irradiance level that will result in damage depends on the total area of skin that is exposed since

the rate of heat conduction at the centre of the exposed area will decrease as the total area of exposed skin increases.
Photochemical effects such as sunburn are due to induced chemical reactions in tissue from the absorption of ultraviolet radiation. The degree of damage is related to the amount of energy absorbed in a given volume of tissue and is independent of the rate of heat absorption and conduction in the exposed area.
Delayed effects include skin cancer and accelerated skin aging. Skin cancer is due to the absorption of ultraviolet radiation which can cause mutations in the DNA of living cells. The probability of cancer is related to the total dose of radiation received whether the exposure is acute (short period) or chronic (long period).
The depth of penetration of radiation into the skin depends on its wavelength.
UV-B and IR-B penetrate somewhat deeper into the layer of living skin tissue and can cause damage above certain thresholds. UV-B, because of its ability to penetrate to deeper tissue and induce photochemical reactions in the cells of this tissue, poses a risk of skin cancer that is not associated with other wavelengths. UV-A and IR-A penetrate even deeper into the skin and can cause damage by thermal effects. UV-A causes skin tanning and is also associated with accelerated aging of skin by modifying fibres that maintain skin resiliency. Visible light penetrates to the deepest layer of skin and its effects are entirely thermal in nature.

5. Laser Hazard factors
There are three factors which influence the degree of hazard of a laser:
- The laser's potential for causing injury
- Environmental factors
- Human factors

A laser's potential for causing injury depends on the emergent beam irradiance (W/cm^2) and radiant exposure (J/cm^2). If the maximum possible irradiance or radiant exposure for a particular laser exceeds the MPE then the laser is considered hazardous and control measures are required. In determining the maximum possible irradiance or radiant exposure for a particular laser it is assumed that all of the power or energy emitted by the laser is collected within an area defined by the limiting aperture of the eye. For example, the area of a fully dilated pupil is 0.385 cm^2. Therefore, a laser is considered to be hazardous if the following relationship exists:
1. For continuous-wave and repetitively pulsed lasers:

$$\frac{Laser\ power\ output\ (W)}{Limiting\ aperture\ (cm^2)} > MPE\ (W/cm^2)$$

2. For single pulse lasers:

$$\frac{Laser\ energy\ output\ (J)}{Limiting\ aperture\ (cm^2)} > MPE\ (J/cm^2)$$

The larger the margin by which the irradiance or radiant exposure of the laser exceeds the MPE, the greater the hazard of the laser and the greater the number of control measures required.

Also, the specific application of the laser will be a factor in determining the overall hazard. For example, in some applications it may be possible to fully enclose the laser beam, which greatly reduces the risk of exposure. Conversely, applications which require open beam conditions during normal operations or during beam alignment procedures increase the risk of ocular and skin exposures.
The potential for accidents also depends on the level training and maturity of persons operating or working in the vicinity of a laser. A laser which falls into the hands of untrained or irresponsible individuals is a serious

risk. Therefore, in evaluating the overall risk of the facility, the supervision and security over laser operations must be considered.

6. Non-Beam Hazards and Controls

Hazards which are related to the use of a laser other than exposure to the laser radiation itself are called non-beam hazards. These include electrical, chemical and physical hazards associated with the laser, laser system or target material. Safety control measures must be implemented for these hazards, many of which can be life threatening.

Electrical hazards

Lethal electrical hazards may be present in most lasers, particularly in high power laser systems.

Exposure to electrical components of the laser system involving greater than 50 volts is an electrical shock hazard. Risks of electric shock can occur during installation, maintenance, modification or repair to the laser and may involve the power supply or the internal components of the laser itself. The consequences vary depending on the magnitude of the exposure but in a worse-case situation can result in death by electrocution. Since the powerful lasers use water for cooling and the water is electro-conductive a maximum precaution is suggested in that case. The control measures that should be implemented include:

- Don't work alone - in the event of an emergency another person's presence may be essential.
- Always keep one hand in your pocket when anywhere around a powered line-connected or high voltage system.
- Properly ground all laser equipment.
- Cover and insulate electrical terminals.
- Prevent contact with energized conductors through use of a barrier system.
- Ensure electrical warning signs and labels are posted and visible.
- Ensure "power-up" warning lights are clearly visible.
- Ensure that capacitors are properly discharged and grounded before service or maintenance.
- Avoid excessive wires or cables on the floor.

Fire hazards

Irradiance levels in excess of 10 W/cm^2 can ignite combustible material. Most Class 4 lasers have irradiance levels exceeding 10 W/cm^2 and are therefore fire hazards. Flammable substances can be ignited at even lower irradiance levels making Class 3b lasers possible fire hazards in the presence of flammable substances.

Barriers and enclosures around a laser must be capable of withstanding the intensity of the beam for a specific period of time without producing smoke or fire. It is important to obtain information from the manufacturer on the properties of the barrier or enclosure to ensure it will provide adequate protection under worse-case conditions of exposure. Other items such as unprotected wire insulation and plastic tubing can catch on fire if exposed to sufficiently high reflected or scattered beam irradiance. When working with invisible wavelength lasers this should be kept in mind since it may not be obvious that these surfaces are exposed.

The two types of lasers most commonly associated with fires are CO2 and Nd:YAG lasers. One study showed that 16 percent of all non-personnel related laser accidents were due to fires. Therefore, provisions must be made to prevent and respond to laser related fires should they occur. The control measures include using non-combustible material in the laser controlled area especially in the beam path and having adequate fire protection of the facility including sprinkler systems, fire extinguishers, etc..

Explosion hazards

High pressure arc lamps, filament lamps, capacitor banks, target material or items in the path of the laser have the potential for disintegrating, shattering or exploding. Gases used as part of the laser itself or as part of the target material can become heated and explode. Where an explosion hazard exists, adequate enclosures must be installed to protect persons and equipment from the potential effects of the explosion.

Collateral radiation

Collateral radiation includes any radiation produced by the laser or laser system other than the laser beam itself. Collateral radiation includes; x-ray, ultraviolet, visible, infrared, microwave or radiofrequency radiation which is generated by the laser power supply, discharge lamp or plasma tube. It can also be emitted from plasma produced by metal targets after the absorption of pulsed laser radiation in excess of 10^{12} W/cm^2.

- **X-radiation**

  X-rays can be produced by high voltage vacuum tubes and laser-metal induced plasma. Lead shielding may be required to keep exposure below the maximum permissible exposure level specified in the Radiation Protection Regulation.

- **Ultraviolet and visible radiation**

  UV and visible radiation can be produced by discharge lamps used to pump the laser. Protection is normally afforded by the protective housing over the laser, however additional UV shielding may be required when the housing is removed for maintenance or servicing of the laser while the beam is on.

Compressed gases

There are a variety of gases used in laser systems with varying toxic and hazardous properties. All compressed gases are physical hazards by virtue of the high pressure under which the gas is contained. If the gas is released in a rapid and uncontrolled fashion due to a rupture of the cylinder head, the cylinder can become a dangerous projectile causing damage and injury. If the gas is toxic (carbon monoxide) or corrosive (hydrogen chloride) it can burn tissue and cause pulmonary edema if allowed to leak into the work space. Even an inert gas such as argon or helium can cause asphyxiation if it leaks into an enclosed space and displaces oxygen. The safety control measures used with compressed gases include:

- Isolation of the gas cylinder from personnel
- Proper storage of the gas cylinder when not in use (capped, supported, ventilated enclosure, segregated)
- A system for isolating and purging the gas line after use
- Proper cylinder identification
- Area gas detection

Dyes and solvents

Some lasers use dyes dissolved in a solvent as the laser medium. The dye is a fluorescent organic compound that may be toxic, mutagenic or carcinogenic. The solvent may be flammable and easily absorbed through the skin carrying the dye compound with it. Therefore, care must be exercised in preparing the dye solutions, transferring the dye solutions into the laser cavity and in cleaning or maintaining the laser system. The safety control measures used with laser dye solutions include:

- Material Safety Data Sheet available and referenced
- Use of less hazardous solvents (e.g. ethanol instead of methanol)

- Personal protective equipment (gloves, lab coat, respirator)
- Use of fume hoods or glove boxes to prepare dye solutions
- Containment of dye solution transfer pumps and reservoirs

Laser-generated air contaminates (LGAC)

Air contaminates may be generated by the interaction of the laser radiation with the target material or other components in the optical path of the laser beam. They can arise from a variety of target material including metals, combustibles and living tissue of patients treated with laser radiation. LGAC exposure accounted for 9 percent of all non-beam accidents in a recent study of laser related accidents. The types of contaminates that are generated vary from toxic (methyl methacrylate) and carcinogenic (benzene) chemical compounds to hazardous biological agents (microorganisms). LGACs are usually generated when the beam irradiance exceeds 10^7 W/cm^2 due to the vaporizing effect of the laser radiation on the absorbing material at its surface. If LGAC production is suspected, control measures must be employed to ensure that the concentration of the LGAC is less than the occupational exposure limit specified in the Chemical Hazards Regulation.

7. Protection

The types of personal protective equipment used include:

- Protective eyewear
- Skin protection

Although enclosure of the laser beam is the preferred method of protecting persons from exposure to laser radiation it is often necessary to perform work around open laser beams. In this case, eye and skin protection must be utilized to protect persons who might be exposed to stray beams of laser light.

Protective eyewear

Protective eyewear in the form of spectacles or goggles with appropriately filtering optics can protect the eyes from the reflected or scattered laser light with a hazardous beam power, as well as from direct exposure to a laser beam. Eyewear must be selected for the specific type of laser, to block or attenuate in the appropriate wavelength range. For example, eyewear absorbing 532 nm typically has an orange appearance, transmitting wavelengths larger than 550 nm. Such eyewear would be useless as protection against a laser emitting at 800 nm. Eyewear is rated for optical density (OD), which is the base-10 logarithm of the attenuation factor by which the optical filter reduces beam power. For example, eyewear with OD 3 will reduce the beam power in the specified wavelength range by a factor of 1,000. In addition to an optical density sufficient to reduce beam power to below the maximum permissible exposure, laser eyewear used where direct beam exposure is possible should be able to withstand a direct hit from the laser beam without breaking for at least 10 seconds. The protective specifications (wavelengths and optical densities) are usually printed on the goggles, generally near the top of the unit.

Therefore, in selecting protective eyewear two characteristics must be considered:

- Optical density
- Damage threshold

Example:
Determine the required optical density of eyewear for working with a 0.5 W laser that emits 532nm light.
Solution:
The limiting aperture for visible light is 0.7 cm corresponding to an area of 0.385 cm^2
Therefore, the irradiance (E) on the eye as defined by the limiting aperture is:
$E = 0.5\ W / 0.385\ cm^2$
$E = 1.30\ W/cm^2$

The transmitted irradiance must be no greater than the MPE for this wavelength, i.e. $2.5 \times 10^{-3}\ W/cm^2$.
Therefore, the required optical density of the protective eyewear is:
$D_\lambda = \log (1.30 / 2.5 \times 10^{-3})$
$D_\lambda = 2.7$
The optical density of protective eyewear depends on the wavelength of the incident light. While most protective eyewear offers protection over a range of wavelengths, not all of the wavelengths will be attenuated to the same extent. **Therefore, in selecting protective eyewear it is important to ensure that the optical density of the eyewear is adequate for the wavelength of interest.**

Studies have shown that protective filters can exhibit non-linear effects such as saturable absorption when the filter is exposed to pulses of ultra-short duration (i.e. $< 10^{-12}$ s). Therefore, the optical density of the filter may be considerably less than expected for very short pulses and it is strongly recommended that the manufacturer be consulted when choosing eyewear for these types of lasers.

The other factor that is important in selecting protective eyewear is the damage threshold specified by the manufacturer. The damage threshold is the level of irradiance above which damage to the filter will occur from thermal effects after a specified period of time - usually 10 seconds. Once the damage threshold is exceeded, the filter ceases to offer any protection from the laser radiation and serious injury can result. The damage threshold varies with the type of material used in the filter and some typical ranges are given below:

Type of Material	Damage Threshold (W/cm^2)
Plastic	1 - 100
Glass	100 - 500
Coated Glass	500 - 1,000

Intense, Q-switched, laser pulses can cause filters to crack and shatter up to 30 minutes following the exposure and some filters have exhibited photobleaching after exposure to Q-switched laser pulses.
Other factors that should be considered when selecting protective eyewear include:
- The need for side-shield protection and peripheral vision
- Prescription eyewear
- Comfort and fit
- Strength and resistance to mechanical trauma and shock
- Potential for producing specular reflections off of the eyewear
- Need for anti-fogging design or coatings
- The requirement for adequate visible light transmission

Protective eyewear must be clearly labelled with the optical density and wavelength for which protection is provided. In a multi-laser environment color coding of the protective eyewear is recommended.

Protective eyewear must be regularly cleaned and inspected for pitting, crazing, cracking, discoloration, mechanical integrity, the presence of light leaks or coating damage. When damage is suspected the protective eyewear should be either retested for acceptability or discarded.

When purchasing protective eyewear the wavelength, optical density, damage threshold, shelf life, storage conditions and limitations for use should be requested from the manufacturer before the purchase is made. This will ensure that the eyewear is adequate for the anticipated conditions of use.

Skin protection

It is especially important to protect the skin from ultraviolet radiation which is known to cause skin cancer. This can be easily accomplished through the use of face shields, laboratory coats, coveralls and cotton gloves. For other wavelengths, these items may not provide adequate protection and the use of special curtains and screens may be needed to protect the skin.

Panic button

Some lasers have a large, red, mushroom shaped button that is connected to the laser power supply. Its purpose is to facilitate the immediate shutdown of a laser in the event of an emergency such as a fire or a sudden and unexpected change in beam direction that creates a hazard to personnel. It must be clearly marked with the words "Panic Button". In case the laser has no panic button the users must be trained to use a quick shut-off in emergency situations.

Entryway controls

Entryway controls are measures taken to control access into the laser controlled area during laser operations. Entryway controls prevent persons from being exposed to hazardous levels of laser light that might exist inside the laser controlled area and also provide security over the laser. There are two types of entryway controls:

- Doors and barriers that are interlocked to the laser power supply
- Doors and barriers that are not interlocked to the laser power supply

Interlocked doors and barriers provide the best level of protection and assurance that persons will not be injured upon entry into a laser controlled area. Provisions can be made for defeating the interlocks to allow selective entry of personnel or for those occasions when restrictions on access can be relaxed.

Beam path control

Beam path control is any measure taken to reduce the nominal hazard zone around the laser. This can include the following:

- Use of a mechanically stable, optical table
- Careful placement of optical components to ensure the beam path is well defined
- Keeping the beam path above or below eye level
- Use of screens, curtains, window covers, etc

A mechanically stable, optical table and careful placement of the optical components will ensure that the beam path stays within the nominal hazard zone determined in the initial hazard analysis. The optical platform should be designed to withstand vibration, bumping or other forces which might disturb it during laser operations. Environmental forces should also be considered such as earthquakes and storms.

Careful placement of the optical components is necessary to prevent beams from straying from their intended path. This is particularly important during the initial alignment of the beam when there is a greater potential for beams to exit windows and doors or strike persons in the area. The beam should be aligned in a manner which keeps it above or below eye level once laser operations commence.

The use of screens, curtains and window covers provide protection from direct and scattered radiation should the beam suddenly stray from its normal path due to unforeseen events. Screens, curtains and window covers must be designed to attenuate the beam to levels below the MPE for the skin and eyes for a specified period of time, typically 60 seconds. Also, the barrier must not support combustion or release toxic material if exposed to laser radiation and if the barrier or curtain does not extend completely to the floor or ceiling, the possibility that the nominal hazard zone extends beyond the barrier must be considered. Commercially available laser barriers exhibit threshold limits ranging from 10 - 350 W/cm^2 for different wavelengths.

Administrative control measures

- **Security and access**
  - Control over keys to entryway doors
  - Control over keys and passwords for energizing the laser
  - Area monitoring by security personnel, cameras, etc.
- **Training**
  - Fundamentals of laser operation
  - Bioeffects of laser radiation
  - Types of hazards and control measures
  - Site specific procedures
  - Duties and responsibilities of personnel

Standard operating procedures

Standard operating procedures are the step-by-step instructions for operating the laser in a safe and controlled manner. The instructions include general precautions and specific directions for the type of laser in use. The following general precautions should be included in the standard operating procedure:

- Avoid looking at the output beam or its reflections !!!
- Avoid wearing jewelry or other reflecting objects while using the laser.
- Use protective eyewear at all times.
- Operate the laser at the lowest beam intensity possible for the required application.
- Maintain adequate supervision over the laser at all times during operation.
- Keep the protective cover on the laser head at all times.
- Identify all beam paths using warning signs, non-reflective barrier tape, etc.
- Close the beam exit shutter when the laser is not in use.
- Avoid directing the laser or its reflections toward windows or area openings.
- Expand the beam wherever possible to reduce beam intensity.
- Use the "long pulse" mode whenever possible especially during beam alignment.
- Avoid blocking the output beam or its reflections with any part of the body.
- If applicable, use an IR detector to verify that the laser is off before working in front of it or to find stray reflections.
- Avoid exposure to skin or clothing which can be burned or ignited by the laser beam.
- Establish a laser controlled area and limit access to persons trained in laser safety.
- Maintain a high ambient light level in the laser controlled area.
- Post readily visible warning signs in the laser controlled area.
- Operate the laser so that the beam is above or below eye level if possible.
- Provide enclosures for beams whenever possible.

- Set up shields to prevent unnecessary reflections.
- Use a beam dump to capture the beam and its reflections to prevent accidental exposure.
- Do not use the laser in the presence of flammables, explosives, or volatile substances.
- Follow the instructions provided in the operating manual.

In addition to the general precautions given above, the standard operating procedures should have written instructions for start-up, use and shutdown of the laser or laser system. This would include the following:

- Obtain the interlock key to the power supply of the laser from its secure location.
- Ensure that all unauthorized personnel leave the laser controlled area.
- Secure the entryway doors and activate the access control measures (e.g. entryway interlocks).
- Have emergency telephone numbers readily available.
- Ensure all persons have removed wristwatches or other reflective jewelry.
- Set up the optical components necessary to conduct the work.
- Check that all beam stops are in place and that there are no unnecessary reflective surfaces in the beam path. One block should be placed behind the first optical component. A second block should be placed behind the second optical component etc..
- Turn on the cooling water to the laser (if applicable).
- Set the laser power control to the lowest power possible.
- Ensure that appropriate laser safety eyewear is worn by everyone in the area.
- Insert the interlock key into the laser switch and unlock the laser.
- Announce loudly, with a short countdown that the laser is being turned on.
- Turn the laser on.
- Align the optical components starting with the component nearest the laser. When it is aligned, move the first beam block behind the third optical component. Repeat this procedure until the entire optical system is aligned. It is important that the laser beam be limited to one new component at a time until the system is aligned. This will minimize uncontrolled reflection during the alignment procedure.
- Do not remove protective eyewear during the alignment phase. The eyewear should have an optical density which allows a faint image of the beam to be seen. Use non-reflecting fluorescent paper to assist in locating the beam.
- Increase the beam power if necessary and complete the assigned task. Always use the lowest beam power necessary for the application.
- Turn the laser off.
- Remove protective eyewear and place it in the proper storage location.
- Allow the laser to cool down and then turn off the cooling water.
- Remove the key from the laser interlock system.
- Deactivate area control measures.
- Return the interlock key to its secure location.

Maintenance and service procedures

During maintenance or servicing, most of the beam precautions provided in the standard operating procedures are followed except that beam enclosures are frequently removed to perform the work. A temporary controlled area with appropriate warning signs must be established around the area of the laser if an open beam condition exists.

Only trained and qualified persons are permitted to perform maintenance or servicing of the laser system.

Persons often remove protective eyewear during the course of a beam alignment because they cannot see the beam with the eyewear on. This problem is due to improper selection of eyewear for beam alignments. Lower optical density alignment goggles need to be purchased to allow visualization of a faint trace of the beam while performing the alignment. Some other steps which can be taken to reduce the risk of hazardous exposure during beam alignments include:

- Perform the alignment at the lowest possible power and longest pulse duration
- Use IR/UV viewing cards
- View diffuse reflections only
- Use a beam finder for IR wavelengths
- Perform the alignment of non-visible light laser using a coaxial, low power, visible laser
- Isolate the process and minimize the possibility of stray beams or reflections through the use of beam blocks

8. Emergency procedures

Emergencies include the sudden occurrence of a fire, explosion, release of toxic gas, or serious injury to personnel. The actions taken must be immediate so as to reduce the effects of the accident and should include the following measures:

- Shut the laser off using the panic button or remove the interlock key. Instruct persons to evacuate the area.
- If there is a fire, get everyone out of the area immediately while at the same time shouting "FIRE" loudly and frequently. Activate the fire alarm pull-station. Do not try and fight the fire from inside the area but from the entrance to provide an escape route.
- Contact the Campus Security at 721-7599 and describe the emergency.

9. Security and Area Control

9.1 Signage

Laser area warning signs must be posted on the entrance door(s) to the laser controlled area.

9.2 Visitors

Visitors that are granted permission to enter an area where a Class 3b or 4 laser is operated must be accompanied by an approved staff member and must be provided with the following:

- Information on potential eye and skin hazards
- Information on safety precautions (e.g. no bending, sitting down or entering laser hazard zone)
- Laser protective eyewear

9.3 Staff

Admission of staff members is subject to the following restrictions:

- Only authorized staff members are permitted entry into the laser controlled area during laser operations. All other staff are considered to be a visitor to the laser controlled area.
- Persons requiring access to the laser controlled area must be provided with laser hazard awareness training and personal protective equipment before hand.

9.4 Training

All workers who are likely to be exposed to Class 3b or 4 lasers must be well informed of the potential hazards of the laser and the precautions to be taken to protect themselves and other persons from those hazards. To comply with this requirement the following must be brought to the attention of each worker:

- The type of laser sources with which the worker will be working
- Laser protection principles and maximum exposure limits for lasers
- Known or suspected health hazards associated with the lasers

Appendix 1 Gas lasers

Laser type, gain medium	Operation wavelength(s)	Pump source	Applications and notes
Helium-neon laser	632.8 nm (543.5 nm, 593.9 nm, 611.8 nm, 1.1523 µm, 1.52 µm, 3.3913 µm)	Electrical discharge	Interferometry, holography, spectroscopy, barcode scanning, alignment, optical demonstrations.
Argon laser	454.6 nm, 488.0 nm, 514.5 nm (351 nm, 363.8, 457.9 nm, 465.8 nm, 476.5 nm, 472.7 nm, 528.7 nm, also frequency doubled to provide 244 nm, 257 nm)	Electrical discharge	Retinal phototherapy (for diabetes), lithography, confocal microscopy, spectroscopy pumping other lasers.
Krypton laser	416 nm, 530.9 nm, 568.2 nm, 647.1 nm, 676.4 nm, 752.5 nm, 799.3 nm	Electrical discharge	Scientific research, mixed with argon to create "white-light" lasers, light shows.
Xenon ion laser	Many lines throughout visible spectrum extending into the UV and IR.	Electrical discharge	Scientific research.
Nitrogen laser	337.1 nm	Electrical discharge	Pumping of dye lasers, measuring air pollution, scientific research. Nitrogen lasers can operate superradiantly (without a resonator cavity).
Carbon dioxide laser	10.6 µm, (9.4 µm)	Transverse (high power) or longitudinal (low power) electrical discharge	Material processing (cutting, welding, etc.), surgery.
Carbon monoxide laser	2.6 to 4 µm, 4.8 to 8.3 µm	Electrical discharge	Material processing (engraving, welding, etc.), photoacoustic spectroscopy.
Excimer laser	193 nm (ArF), 248 nm (KrF), 308 nm (XeCl), 353 nm (XeF)	Excimer recombination via electrical discharge	Ultraviolet lithography for semiconductor manufacturing, laser surgery.

Chemical lasers

Laser type, gain medium	Operation wavelength(s)	Pump source	Applications and notes
Hydrogen fluoride laser	2.7 to 2.9 µm for Hydrogen fluoride	Chemical reaction in a burning jet of ethylene and nitrogen trifluoride (NF_3)	Used in research for laser weaponry by the U.S. DOD, operated in continuous wave mode, can have power in the megawatt range.
Deuterium fluoride laser	~3800 nm (3.6 to 4.2 µm)	chemical reaction	MIRACL, Pulsed Energy Projectile & Tactical High Energy Laser

COIL (Chemical oxygen-iodine laser)	1.315 µm	Chemical reaction in a jet of singlet delta oxygen and iodine	Laser weaponry, scientific and materials research, laser used in the U.S. military's Airborne laser, operated in continuous wave mode, can have power in the megawatt range.

Dye lasers

Laser type, gain medium	Operation wavelength(s)	Pump source	Applications and notes
Dye lasers	390-435 nm (stilbene), 460-515 nm (coumarin 102), 570-640 nm (rhodamine 6G), many others	Other laser, flashlamp	Research, spectroscopy, birthmark removal, isotope separation. The tuning range of the laser depends on which dye is used.

Metal-vapor lasers

Laser type, gain medium	Operation wavelength(s)	Pump source	Applications and notes
HeCd metal-vapor laser	441.563 nm, 325 nm	Electrical discharge in metal vapor mixed with helium buffer gas.	Printing and typesetting applications, fluorescence excitation examination, scientific research.
HeHg metal-vapor laser	567 nm, 615 nm		Rare, scientific research, amateur laser construction.
HeSe metal-vapor laser	up to 24 wavelengths between red and UV		Rare, scientific research, amateur laser construction.
HeAg metal-vapor laser	224.3nm		Scientific research
NeCu metal-vapor laser	248.6nm	Electrical discharge in metal vapor mixed with neon buffer gas.	Scientific research
Copper vapor laser	510.6 nm, 578.2 nm	Electrical discharge	Dermatological uses, high speed photography, pump for dye lasers.
Gold vapor laser	627 nm		Rare, dermatological and photodynamic therapy uses.

Solid-state lasers

Laser type, gain medium	Operation wavelength(s)	Pump source	Applications and notes
Ruby laser	694.3 nm	Flashlamp	Holography, tattoo removal. The first type of visible light laser invented; May 1960.

Nd:YAG laser	1.064 µm, (1.32 µm)	Flashlamp, laser diode	Material processing, rangefinding, laser target designation, surgery, research, pumping other lasers (combined with frequency doubling to produce a green 532 nm beam). One of the most common high power lasers. Usually pulsed (down to fractions of a nanosecond)
Er:YAG laser	2.94 µm	Flashlamp, laser diode	Periodontal scaling, Dentistry
Neodymium YLF (Nd:YLF) solid-state laser	1.047 and 1.053 µm	Flashlamp, laser diode	Mostly used for pulsed pumping of certain types of pulsed Ti:sapphire lasers, combined with frequency doubling.
Neodymium doped Yttrium orthovanadate (Nd:YVO_4) laser	1.064 µm	laser diode	Mostly used for continuous pumping of mode-locked Ti:sapphire or dye lasers, in combination with frequency doubling. Also used pulsed for marking and micromachining. A frequency doubled nd:YVO_4 laser is also the normal way of making a green laser pointer.
Neodymium doped yttrium calcium oxoborate Nd:$YCa_4O(BO_3)_3$ or simply Nd:YCOB	~1.060 µm (~530 nm at second harmonic)	laser diode	Nd:YCOB is a so called "self-frequency doubling" or SFD laser material which is both capable of lasing and which has nonlinear characteristics suitable for second harmonic generation. Such materials have the potential to simplify the design of high brightness green lasers.
Neodymium glass (Nd:Glass) laser	~1.062 µm (Silicate glasses), ~1.054 µm (Phosphate glasses)	Flashlamp, laser diode	Used in extremely high power (terawatt scale), high energy (megajoules) multiple beam systems for inertial confinement fusion. Nd:Glass lasers are usually frequency tripled to the third harmonic at 351 nm in laser fusion devices.
Titanium sapphire (Ti:sapphire) laser	650-1100 nm	Other laser	Spectroscopy, LIDAR, research. This material is often used in highly-tunable mode-locked infrared lasers to produce ultrashort pulses and in amplifier lasers to produce ultrashort and ultra-intense pulses.
Thulium YAG (Tm:YAG) laser	2.0 µm	Laser diode	LIDAR.
Ytterbium YAG (Yb:YAG) laser	1.03 µm	Laser diode, flashlamp	Optical refrigeration, materials processing, ultrashort pulse research, multiphoton microscopy, LIDAR.
Ytterbium:$_2O_3$ (glass or ceramics) laser	1.03 µm	Laser diode	ultrashort pulse research, [2]
Ytterbium doped glass laser (rod, plate/chip, and fiber)	1. µm	Laser diode.	Fiber version is capable of producing several-kilowatt continuous power, having ~70-80% optical-to-optical and ~25% electrical-to-optical efficiency. Material processing: cutting, welding, marking; nonlinear fiber optics: broadband fiber-nonlinearity based sources, pump for fiber Raman lasers; distributed Raman amplification pump for telecommunications.
Holmium YAG (Ho:YAG) laser	2.1 µm	Laser diode	Tissue ablation, kidney stone removal, dentistry.

Cerium doped lithium strontium(or calcium) aluminum fluoride (Ce:LiSAF, Ce:LiCAF)	~280 to 316 nm	Frequency quadrupled Nd:YAG laser pumped, excimer laser pumped, copper vapor laser pumped.	Remote atmospheric sensing, LIDAR, optics research.
Promethium 147 doped phosphate glass ($^{147}Pm^{+3}$:Glass) solid-state laser	933 nm, 1098 nm	??	Laser material is radioactive. Once demonstrated in use at LLNL in 1987, room temperature 4 level lasing in ^{147}Pm doped into a lead-indium-phosphate glass étalon.
Chromium doped chrysoberyl (alexandrite) laser	Typically tuned in the range of 700 to 820 nm	Flashlamp, laser diode, mercury arc	Dermatological uses, LIDAR, laser machining.
Erbium doped and erbium-ytterbium codoped glass lasers	1.53-1.56 µm	Laser diode	These are made in rod, plate/chip, and optical fiber form. Erbium doped fibers are commonly used as optical amplifiers for telecommunications.
Trivalent uranium doped calcium fluoride ($U:CaF_2$) solid-state laser	2.5 µm	Flashlamp	First 4-level solid state laser (November 1960) developed by Peter Sorokin and Mirek Stevenson at IBM research labs, second laser invented overall (after Maiman's ruby laser), liquid helium cooled, unused today. [1]
Divalent samarium doped calcium fluoride ($Sm:CaF_2$) laser	708.5 nm	Flashlamp	Also invented by Peter Sorokin and Mirek Stevenson at IBM research labs, early 1961. Liquid helium cooled, unused today. [2]
F-center laser.	2.3-3.3 µm	Ion laser	Spectroscopy

Semiconductor lasers

Laser type, gain medium	Operation wavelength(s)	Pump source	Applications and notes
Semiconductor laser diode (general information)	0.4-20 µm, depending on active region material.	Electrical current	Telecommunications, holography, printing, weapons, machining, welding, pump sources for other lasers.
GaN	0.4 µm		Optical discs.
AlGaAs	0.63-0.9 µm		Optical discs, laser pointers, data communications. 780 nm Compact Disc player laser is the most common laser type in the

			world. Solid-state laser pumping, machining, medical.
InGaAsP	1.0-2.1 µm		Telecommunications, solid-state laser pumping, machining, medical..
lead salt	3-20 µm		
Vertical cavity surface emitting laser (VCSEL)	850 - 1500 nm, depending on material		Telecommunications
Quantum cascade laser	Mid-infrared to far-infrared.		Research,Future applications may include collision-avoidance radar, industrial-process control and medical diagnostics such as breath analyzers.
Hybrid silicon laser	Mid-infrared		Research

Other types of lasers

Laser type, gain medium	Operation wavelength(s)	Pump source	Applications and notes
Free electron laser	A broad wavelength range (about 100 nm - several mm); one free electron laser may be tunable over a wavelength range	relativistic electron beam	atmospheric research, material science, medical applications.
Gas dynamic laser	Several lines around 10.5 um; other frequencies may be possible with different gas mixtures	Spin state population inversion in carbon dioxide molecules caused by supersonic adiabatic expansion of mixture of nitrogen and carbon dioxide	Military applications; can operate in CW mode at several megawatts optical power.
"Nickel-like" Samarium laser	X-rays at 7.3 nm wavelength	Lasing in ultra-hot samarium plasma formed by double pulse terawatt scale irradiation fluences created by Rutherford Appleton Laboratory's Nd:glass Vulcan laser. [3]	First demonstration of efficient "saturated" operation of a sub–10 nm X-ray laser, possible applications in high resolution microscopy and holography, operation is close to the "water window" at 2.2 to 4.4 nm where observation of DNA structure and the action of viruses and drugs on cells can be examined.
Raman laser, uses inelastic stimulated Raman scattering	1-2 µm for fiber version	Other laser, mostly Yb-glass fiber lasers	Complete 1-2 µm wavelength coverage; distributed optical signal amplification for telecommunications; optical solitons generation and amplification

in a nonlinear media, mostly fiber, for amplification			
Nuclear pumped laser	See gas lasers	Nuclear fission	Research

Appendix 2 Laser Output Wavelengths And Organs Affected

Electromagnetic Spectrum Region	Wavelength Range	Affected Organ
Ultraviolet	200 - 400 nm	Cornea, lens, skin
UV -C	200 - 280 nm	Cornea & Conjunctiva
UV - B	280 - 315 nm	Cornea & Conjunctiva (cataract formation)
UV - A	315 - 400 nm	Lens (cataract formation)
Visible light	400 -780 nm	Retina
Near Infrared	780 nm - 1.4 µm	Retina, lens, skin
IR - B	1.4 - 3.0 µm	Cornea & skin
IR - C	3.0 µm - 1 mm	Cornea & skin

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The document officially ends here