LASER PHYSICS, HAZARDS AND SAFETY

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Physical Properties of Light Waves

LIGHT is a transverse electromagnetic radiation of a certain frequency band that produces a visual response when incident on the retina. The electromagnetic spectrum extends from DC through power line frequency (60 Hz or 60 cycles per sec), radio and TV frequencies, microwave, infrared, visible, ultraviolet, X-ray and gamma ray frequencies. These waves have in common that they all travel in vacuum at the same speed, 300,000 km/sec, the "speed of light."

The phrase "transverse electromagnetic radiation" refers to the fact that a light wave carries both time varying electric and magnetic fields which are at right angles to each other and to the direction of travel of the wave. We need concern ourselves only with the electric field or electric "vector."

Any wave is characterized by its wavelength and frequency which are related to the speed of travel by the equation:

$$c = \lambda \upsilon$$

$\lambda = wavelength$

$\upsilon = frequency$

Ordinary light sources produce waves of many different wavelengths, usually radiating in all directions. The light radiation may be thought of as short bursts of waves, called "wave trains," sent out at random times. Each wave train lasts only for a few nanoseconds and the electric vectors are oriented in random directions.

LASER sources differ in that they produce an intense, highly directional monochromatic beam with a very long wave train resulting in high "coherence." The laser can be designed to produce a polarized beam, which is one that has all the electric vectors in a single direction. The laser beam can easily be focused to a very small spot allowing delivery of very high energy density to a localized area of tissue.

The word LASER is an acronym standing for:

Light
Amplification by the
Stimulated

Emission of
Radiation

Physical Principles of the Laser

The physical principles upon which the laser is designed reside in the quantum properties of atomic and molecular radiant emission and the Einstein principles of stimulated emission of radiation from atoms.

The quantum mechanical view of atomic structure states that atoms can take up a series of discrete energy states. The process of changing from one energy state to another involves the absorption or emission of energy, often in the form of electromagnetic waves or light. The energy carried by a light wave is related to its frequency or wavelength by the Planck equation:

$$E = h\upsilon = \frac{hc}{\lambda}$$

In ordinary cases this light is emitted at random but in the specialized circumstances of the laser all the atoms that are capable of giving off light of a certain wavelength are "organized" to emit their waves in step with each other and in the same direction.

In order to give off light (energy) the atom must be in some energy state above the ground state which is the state of zero energy. Ordinary collections of atoms, such as a tube of gas containing hydrogen, will have the vast majority in the ground state. Atoms can be raised to higher energy states (called excited states) by heating or by passing an electric current through the tube. Even then only a small portion of atoms will be in excited states which are extremely short lived. An excited atom will ordinarily give up its energy in a time of the order of a few tens or hundreds of nanoseconds. Further, under ordinary excitation procedures, the higher the energy state the smaller the number of atoms in that state. There is no opportunity for cooperative emission under these circumstances.

Population Inversion and Pumping

In a laser a situation called a population inversion is established where there is a higher state that has a much larger population than the immediately lower state. Thus there are many atoms capable of giving up energy all at the same wavelength. This higher state must have the property of being metastable which means it is much longer lived than the usual. Metastable states may last as long as a

millisecond. That doesn't sound like much but it is ten thousand times longer than the usual state, and is long enough to permit amplification of the light.

In order to produce the population inversion energy must be added to the system by a process called **pumping**. The pump may be a chemical reaction, an electric current passed through the medium, a beam of electrons focused on the material, or an intense light source such as a flash lamp that was used in the first laser, a ruby laser invented in 1960.

The Cavity

In order to have the best cooperative emission of radiation among the excited atoms they are placed in a cavity that reflects the light back and forth many times. This cavity consists of a pair of mirrors aligned carefully to reflect the light back along the same path; i.e. they are exactly parallel to each other. (An alternative cavity has one mirror very slightly concave; this makes alignment somewhat less critical.) The active material is placed in a tube between the mirrors, or the mirrors can constitute the end pieces of the tube. One of the mirrors is made as nearly as possible 100% reflective, the other about 98% reflective. This means 2% of the light escapes at each pass, or the light makes about 50 passes before it all emerges.

The length of the cavity must be an exact multiple of the wavelength of the light being amplified otherwise the waves do not stay in step as they are reflected back and forth. This criterion makes it possible to select the wavelength that will be emitted in the case of a medium, such as argon, that is capable of producing oscillation at several wavelengths. If the laser cavity is wide enough for waves to traverse slightly oblique paths then it can oscillate in more than one mode, reinforcing slightly different wavelengths in the off axis modes. Single mode lasers produce brighter and more coherent light than multiple mode lasers.

The wavelength emitted by the laser is determined by the atoms or molecules used for the active medium, sometimes called the lasant. The first gas laser was the above mentioned helium-neon laser in which the active medium is neon while the helium is used to produce the excited state. The process consists of passing an electric current through the mixture, exciting the helium atoms by electron collision. Helium and neon each has a pair of excited state that lie at very nearly the same energy; this permits efficient transfer of energy from the helium atoms to the neon atoms by collision. In neon these states are also metastable, setting up the conditions for laser action. Oscillations in green

and red are possible; the commonly used one is the familiar red light at 633 nm that is also seen in the scanners commonly used at checkout counters.

Noble Gas Lasers

Argon and krypton lasers are pumped with an electric current, either continuously for low power applications or pulsed for higher power outputs. They are capable of producing a number of different wavelengths which can be either preset by the manufacturer or selected by the operator, depending upon the design of the laser. The wavelengths are all in the visible region:

Argon	Krypton
528.7	647.1
514.5	568
501.7	530
496.5	
488.0	
476.5	
457.9	

Solid State Laser

An example of a laser with a solid state lasant is the Nd:YAG laser that is used in capsulotomy procedures. It emits an intense burst of blue green light at 532 nm. The neodymium ions that exist as impurities in a matrix of yttrium aluminum garnet (YAG) provide the laser action. Pumping takes place either by a flash lamp or by radiant energy from an auxiliary laser whose light is shone on the YAG crystal. The neodymium radiant emission is actually at 1064 nm in the infrared but by the application of another quantum technique called frequency doubling the wavelength is halved to 532 nm.

Excimer Laser

The excimer laser, which stands for excited dimer, uses as an active medium a noble gas and flourine, activated by an electron beam or a very strong current. A chemical reaction takes place between the noble gas (Argon in the most commonly used case) and flourine after the energetic exciting electrons strip off electrons from the noble gas permitting the formation of an unstable molecule of ArF. This molecule is in a metastable excited state. When it dissociates it emits the laser wavelength of 193 nm, an ultraviolet wavelength short enough to disrupt chemical bonds in DNA.

Continuous and Pulsed Lasers

Lasers have two basic modes of operation: continuous or CW and intermittent or pulsed. The familiar helium-neon laser which is in laser pointers that lecturers use represents an example of a CW laser while the ruby laser that is activated by a flash lamp is a pulsed laser. Pulsed lasers have certain advantages in that the beam power and energy are more precisely controlled. Certain special pulsing procedures can yield very high power levels called giant pulses by not permitting amplification to take place until a significant fraction of all the atoms is in the metastable state and then allowing them all to radiate in one short, intense burst.

Power Levels

Laser power levels can be designated by average power or peak power. In the case of the CW laser the average and peak are the same as the power level is constant in time. In the case of a pulsed laser the average power is always less than the peak, sometimes greatly less. When using a pulsed laser it is necessary to know the value of peak power as that determines the maximum rate of energy deposition in tissue.

Pulsing has the effect of amplifying the peak energy compared to the average energy as the following example shows. Suppose a pulsed laser has an average power of 1.0 milliwatt and that it produces 100 pulses per second each of one microsecond duration. The duty cycle of this laser is:

$$\text{duty cycle} = \frac{1 microsecond}{.01 sec} = 0.0001$$

The amplification is equal to the average power divided by the duty cycle or a factor of 10,000. Thus the one milliwatt average power translates into 10 watts of peak power. This kind of power is capable of producing dramatic effects on tissue.

HAZARDS ASSOCIATED WITH LASERS

The intense light emitted by the laser is a hazard to skin and eyes. The unmodified laser beam may be intense enough to cause damage to exposed skin. If the light enters the eye whether directly or by reflection it may be focused to a very small spot on the retina, causing damage by a variety of

means: heating, photodisruption of chemical bonds, or photoacoustical destruction of tissue by concentration of a large amount of energy in a very small volume in a short time (nanoseconds or less).

The intense radiation can cause fire if it falls on dry, flammable material. The carbon dioxide laser is the most intense laser source used in health care; when it is used in a surgical procedure the surrounding area must be covered with gauze pads soaked in sterile saline. Even when the laser is used for an internal procedure there is danger: there have been tragic instances of fires inside a patient's body when laser light impinged upon flammable plastic tubing.

Lasers are electrical devices associated with high voltage power supplies that are capable of delivering a lethal electrical shock. All electrical equipment should be protected in appropriately designed housings and service should be provided by properly trained and equipped personnel.

The plume produced by laser interaction with tissue or with other materials may present a chemical or biological hazard producing what are called "Laser Generated Airborne Contaminants. Precautions are needed to assure that gases or other materials, including blood and blood products, given off by these reactions are disposed of without making contact with workers or staff.

Laser Safety Officer

Each facility at which there are lasers in use that present a hazard to either patients, staff or the general public must have a person responsible for assuring that proper safety measures are in place and observed, and that necessary protective equipment is procured, maintained and used as directed. In a small clinical facility the chief medical person usually acts as the Laser Safety Officer (LSO), adding the knowledge of laser safety to his/her other medical duties.

In large facilities a specially designated individual is given training and responsibility for assuring safe use of lasers in accordance with protocols laid down for that purpose.

Protocols for Laser Safety

There are two basic categories of safety protocol: Engineering or hardware and Administrative or Procedural Controls.

Engineering includes: Warning labels, access controls, protective covers and filters, visual and auditory alarms, and designation of hazard zones.

Administrative protocols include training of personnel, establishment of standard operating procedures (SOP's), designation of authorized personnel, establishment and design of controlled areas.

Risk Categories and Classification of Lasers

Aside from sheer laser power there are certain characteristics that affect the risk of harm from exposure to the radiation:

Temporal characteristics: pulsed vs. continuous
Beam divergence and size
Wavelength
Presence of reflecting surfaces

One of the tasks of the LSO is to establish Maximum Permissible Exposure (MPE) for each situation. ANSI Z136.1 provides a classification scheme for lasers used in health care that may be used as guidance for establishing MPE's.

Class 1: lasers that are considered incapable of producing damaging levels of laser emission.
Class 2: applies to lasers that produce visible radiation that may be viewed for less than 0.25 sec, the aversion time.
Class 3: lasers that may be hazardous for direct or reflected exposure
Class 4: lasers that present significant skin and fire hazards.

Most surgical lasers fall into Class 4, as does any laser emitting more than 0.5 W (500 milliwatts) of power.

Resources for Laser Physics, Hazards and Safety

Understanding Lasers, Gerald Dorros and Darrell L. Seeley, Futura Publishing Co. Mt. Kisco NY, 1991

ANSI 136.3: *Safe Use of Lasers in Health Care Facilities*, American National Standards Institute, 11 West 42 Street, New York NY 10036

Lasers in Ophthalmic Surgery, David B. Karlin, Blackwell, 1995, chapter 1, Fundamentals of Lasers by CKN Patel and OR Wood II

"Laser-Tissue Interactions: Basic Principles" Charles P. Lin, Ophthalmology Clinics of North America, WB Saunders Co., 6,3(1993) 381-391

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