Laser Applications

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1. Laser Industrial Applications

Lasers are used in science, medicine, industry, agriculture, entertainment and in many other applications. Laser properties required are related to each application; high coherence of laser is an essential in holography, whereas laser peak power is what we really need in range finding.

Lasers are utilized for welding, drilling, cutting, heat treatment (hardening, annealing, glazing, cladding etc) as well as laser ablation, oil and gas exploration, automotive industry etc. Laser material processing (LMP) is recommended in the processing of difficult to machine hardened metals, composites and ceramics; as compared to normal mechanical material processing techniques.

Pulsed, as well as CW lasers, are employed for industrial applications. Nd: YAG (~10KW) and CO_2 (~25KW) are the most commonly employed high power lasers. High monochromaticity and directionality of the laser gives the laser beam a small wavelength spread and low divergence. Therefore, laser can be focused to a very small spot size, resulting in very high intensity.

Basic laser material processing (LMP) system consists of a high power laser, beam delivery unit with focusing optics and beam parameter-monitoring unit coupled to a CNC machine. Delivery and manipulation of laser beams to extremely complex work shapes and inaccessible places is a critical aspect of an LMP system. Wavelength, energy, power, beam diameter, divergence etc decide the transmission method. Near IR lasers like, Nd: YAG (1064 nm) and COIL (1315 nm) can be transmitted to the work area using optical fiber cables, where one can bend and twist the laser beam as desired. CO_2 laser at 10.6μm wavelength has to use a rather unwieldy mechanical arm, consisting of lenses, prisms, mirrors etc to reach the work area due to the non-availability of a suitable fiber cable for high power laser transmission.

Material properties like, reflectivity, absorption, specific heat, thermal conductivity, heat capacity, diffusivity, melting, latent heat of fusion, vaporization etc play a major role in LMP. Knowledge of interaction of laser with the target material is of great importance in deciding the type of the laser to be used for the particular material-processing environment, since the material should absorb the laser energy. Type of work, speed of operation and the nature of material decide the type of laser to be used. In LMP, the material absorbs the laser energy and then the material is melted or removed by evaporation or by melt ejection. During LMP, debris, particulate matter, fumes etc can damage the optical components of the focusing system. These can adversely affect the laser beam itself. A gas shield, mostly employing helium gas, is provided as a protection from these. Plasma cutting and oxy-acetylene systems have their own gas jets. As LMP does not have this, an auxiliary jet is provided from a pressurized gas source. Plasma generated during the laser machining, lessens the penetration capability of laser. It is essential to blow away the plasma for the successful performance of the system. High-pressure gas impinging on the work piece from above produces local pressure, which is more than the atmospheric pressure existing below the work piece. Consequently this difference in pressure helps the melt to be blown away from the bottom. Latest LMP systems employ a coaxial nozzle in which the laser and the gas both exit through the same orifice.

The amount of laser energy absorbed by the material decides the rise in temperature leading to melting or boiling. The high laser intensity facilitates rapid heating; and this does not allow the heat to be spread to the bulk of the material; localized phenomenon. Major laser parameters for LMP system are energy, pulse width and wavelength. Laser can be manipulated to process extremely complex shapes or to reach areas where other tools could not have access. An important aspect in the industrial scenario is the safety of the personnel, since many of them are unaware of the biological and physical hazards that can be caused by laser. Some of advantages and disadvantages of lasers are listed below.

Advantages

- High maneuverability.
- Highly focused spot, where the heating is very much localized.
- Minimum distortion to target material.
- No force is exerted on the work piece.
- Non-contact process and as such there is no wear and tear of tool.
- Not affected by magnetic field.
- Angular operation is possible.
- High speed of processing (improved productivity).
- Adaptability with existing machines.
- Ability to operate in inaccessible areas.

Disadvantages

- Cost of machine and operator is high.
- High cost of operational maintenance.
- Laser safety.

Laser light is absorbed within the first few atomic layers for opaque materials such as metals thus making it possible to put the applied energy precisely on the area of surface of interest. Common advantages of laser surface treatment include chemical cleanliness, controlled thermal penetration, remote non-contact processing, and localized heating. There are three distinct regions – surface heating, melting and vaporization. Processes, which come under these categories, include:

Important Features of interest

Physical mechanism of LMP is characterized and controlled by the interaction of laser radiation with matter. LMP is a thermal process and the material removal is by either melting or vaporizing the volume of interest. Optical and thermal properties of material play a major role in LMP and mechanical properties have only a minor role. The material with low thermal conductivity and thermal diffusivity is the best candidate for LMP. Being a non-contact process, the energy transfer occurs through irradiation and as such, mechanically introduced vibration damages are avoided and that also without any tool wear. The same laser machine can be used for welding, drilling, cutting and heat treatment processes with a multi-axis work piece positioning station. This flexible environment gives LMP its unique nature, hitherto unavailable in mechanical systems. The most interesting feature of LMP is the multi-dimensional process. Drilling can be considered as a single dimensional process, since laser beam is stationary relative to work piece. If we take the cutting process, laser and the work piece are in relative motion perpendicular to each other. This situation can be considered as a two dimensional process. If more than one laser beam is employed, each laser will have a two dimensional nature with one edge being common. This situation makes the LMP as a three dimensional process.

Identify the specific high power laser for a particular industrial application requires knowledge of the interaction of laser beam with the work piece and the concept of heat transfer. The absorption of laser energy by the material decides the temperature rise in the material. Type of operation like drilling, cutting, welding etc along with the speed of operation is also of importance in deciding the types of laser to be used. In addition, wavelength pulsed or continuous, spot size, divergence etc are also very significant. Further, monitoring of the laser beam parameters like power, intensity distribution and beam diameter is also very important.

Though laser beams can be manipulated to process extremely complex shapes, its delivery to work area is critical. Wavelength, power, energy, beam diameter, divergence etc of the laser beam decide the transmission method. Flexible optical fiber can be used to transmit near infra-red lasers like Nd: YAG (1.06 micron) and COIL (1.13 micron), but the same cannot be used to transmit CO_2 laser (10.6 micron), where mirrors and prisms have to be employed. High power lasers can heat the optics thus altering the shape of the

surface quality of the optics adversely affecting the beam quality. It is likely that the space between the optics may get heated up due to the high intensity of the laser beam, which reduces the beam quality due to thermal blooming.
Safety of personnel is of paramount importance as the potential laser hazards include biological, fire, electrical shock, fumes, debris etc. Safety aspect of laser beams will be discussed in detail in another section. It is also to be remembered that the training of the personnel is costly, time consuming and laborious.

To have an idea of radiance, let us look at the radiance of sun and 1 mw laser. The radiance of a 1 milli-watt He-Ne laser with an output diameter of 1mm and of divergence of 1 milli-radian is 160 x 10^6 Watts/m^2 – steradian where as the radiance of the sun with emission power of 10^{26} Watts is only about 10^6 Watts/m^2 steradian.

Material processing applications require very high laser intensity at the working region. As can be seen, laser beam can be focused to a very small spot size, thus generating the highest intensity possible. We know that diffraction limits the minimum spot size that can be achieved. When a laser beam with divergence Θ is focused with a lens of focal length f, then the estimated focal spot focus radius r is,

$$\mathbf{r = f.\,\Theta}$$

Since the divergence of the beam is determined by the diffraction at the aperture of the laser, the divergence angle Θ can be approximated to,

$$\mathbf{\Theta = \lambda/d}$$

Where λ is the wavelength of the laser and d is the diameter of the aperture, then,

$$\mathbf{r = f.\,\lambda/d = \lambda f/d}$$

When focusing the laser with an F-number lens, then r = λ, i.e. a laser beam can at best be focused to a spot size equal to the order of its wavelength, due to diffraction.

The above discussion is truly applicable to beams with Gaussian profile only, where the laser beam oscillates in the lowest mode. The lowest Gaussian mode is TEM_{00} and the divergence is lowest. But practical laser systems operate with much higher divergence and F-numbers. The minimum spot size that can be achieved is about 6 microns for Nd: YAG (λ = 1.06micron) and 60 microns for CO_2 (λ = 10.6 micron) lasers. Another important parameter is depth of focus and the beam waist. When a laser beam is focused with a lens, the minimum size of the beam at the focal plane is referred to as beam waist. The intensity of the beam does not reduce much on either side of the beam waist as it propagates. The depth of focus is the distance over which the intensity on either side of the beam falls to 50% of its peak value. The diameter of the focal spot and the depth of focus are related to the focal length of the lens. A short focal length lens can produce a smaller focal diameter compared to a longer focal length lens. But depth of focus in the shorter focal length lens will be shorter than the one that can be obtained with the longer focal length lens. Therefore, one has to be very judicious in designing the focal length of the focusing system, which will be decided by the application, say as in welding operations. Further, one also has to remember that a short focal length lens will have large spherical aberration. To reduce this defect one has to employ aspherical or multi-element lens system.

- 1-D heat flow model is very convenient to explain most of the experimental results. As per this model, if the heat flows in one direction and there is no convection or heat generation, it is assumed that there is a constant extended surface heat input and constant thermal properties, with no radiant heat loss or melting then

$$T_{zt} = \frac{2F_0}{k}\left\{(\alpha t)^{\frac{1}{2}}\, ierfc\left[\frac{z}{2\sqrt{\alpha t}}\right]\right\}$$

At z = 0, the surface power density is

$$F_0 = \left\{\frac{P_{tot}\left(1 - r_f\right)}{A}\right\}$$

Where T = temperature, z = depth, t is time, k is thermal conductivity, α is thermal diffusivity, F_0 is the absorbed power density, r_f is the reflectivity of the surface. The surface temperature T_{0t} can thus be written as:

$$T_{0t} = \frac{2F_0}{k}\sqrt{\alpha t}$$

- For a continuous Gaussian source, the temperature of a surface central point under stationary condition is given by

$$T_{cont}(0,0,t) = \frac{2P\left(1-r_f\right)D}{\pi D^2 k\sqrt{T}}\tan^{-1}\left[\frac{2\left(\sqrt{\alpha t}\right)}{D}\right]$$

Maximum possible temperature is

$$T_{max} = \frac{1.77P\left(1-r_f\right)}{\pi k D}$$

Where; D is the diameter of the laser spot.

- The amount of power effective on any other point on the surface within the beam depends on the power distribution. For example, for a Gaussian mode structure, TEM_{00}, the power at any point is given as

$$P_{xy} = \frac{P_{tot}}{r_b^2\pi}\exp\left(\frac{-2r^2}{r_b^2}\right)$$

Where

$$r^2 = x^2 + y^2$$

and r_b is the beam radius at the work piece.

Some of the important features related to some important industrial applications of Lasers are given below:

Laser Heat Treatment:

The main goal of laser heat treatment is selective hardening for wear reduction. However it is also being used to change metallurgical and mechanical properties. Practical uses of laser heat treatment include hardness increase, strength increase, friction reduction, wear reduction, increase in fatigue life, surface carbide creation and for changing metallurgical and mechanical properties. Laser heat treatment is usually carried out on titanium, some aluminum alloys, steel; with sufficient carbon contents and cast iron with pearlite structure. An absorbing coating is usually applied to the metal surface to avoid laser power loss. As the laser beam impinges on the metal surface, the temperature starts rising and the thermal energy is conducted into the metal component. The laser energy should be sufficient to result in temperature rise corresponding to transformation temperatures, which are required for a particular process. However, it should not lead to melting. Laser power densities required for these applications are in the range of $10^3 - 10^4$ W/mm^2 and the workpiece speed lies in between 5 – 50 mm/sec. The affected depth in laser heat treatment effects depend on the laser power P and the heating time i.e. D/V, where D is the laser spot diameter and V is the traverse speed. Mathematically, the depth of penetration'd' can be given as

$$d = A + B \frac{P}{\sqrt{DV}}$$

Where (A) and (B) are constants.

Surface heating works for most metals, but for steel it requires heating to a temperature above the (α-γ) transition point; between (750-900 ^{o}C); depending on the carbon content. At this temperature, the soft pearlite phase transforms into austenite upon subsequent cooling. The latter transforms into the metastable martensite (hard) phase. It is a localized heating without melting and nearly distortion free process. It allows easy control of hardened depth and profile of treated area. For iron, it redistributes the carbon content by fast heating ($2x10^4$) ^{o}C/s and fast cooling ($\approx 10^5$) ^{o}C/s. The surface temperature at d = 0 is:

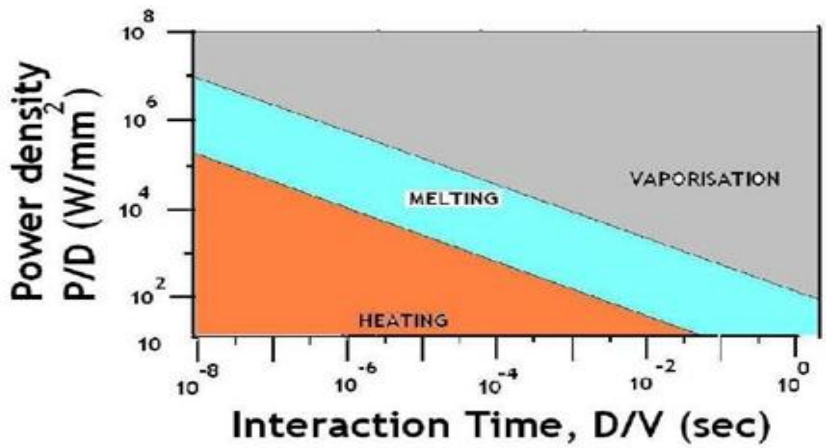
$$T(0,t) = (2\ \varepsilon\ I_o/k).(Nt/\pi)$$

Where; ε is the emissivity ≈ 1, N: thermal diffusivity, k: thermal conductivity, t: time and I_o: laser intensity. The hardened depth (d) is:

$$d = E_o(1\text{-}R)/[a^2 \pi C_p\rho.(T_{aust} - To)]$$

Where; E_o: incident laser energy, R: surface reflectivity, ρ: material density, Cp: specific heat, a: laser beam radius. For constant uniform irradiation on surface, the thermal penetration depth (d_{th}) is:

$$d_{th} = (4Nt)^{1/2}$$



- Hardness increase
- Strength increase
- Reduced friction
- Wear reduction
- Increase in fatigue life
- Surface carbide creation
- Magnetic domain control
- Stereo-lithography
- The depth of hardness is proportional to $\mathbf{P/(DV)^{1/2}}$

Laser Surface Melting:

The main characteristics of laser surface melting process are:

- Rapid solidification rates leading to almost homogeneous structures
- Very little thermal penetration little distortion (god for sensitive material)
- Good surface finish
- Process flexibility, because of automation and software control

Focused or near-focused laser beam heating is used to obtain moderate to rapid solidification of molten; i.e. producing fine – near homogeneous structure at little thermal penetration (little distortion) with surface finish ≈ 25 μ. The control keys are: reflectivity, beam shape, and shrouding the melt pool. The reflectivity is controlled by angle of incidence, anti-reflection coating, polarization, addition of small amount of O_2 to inert shroud gas, and using reflection dome. Non-homogeneous structure (cast iron, tool sheet, etc …) can be made homogeneous by this method.

Powers of the order of $10^3 – 10^6$ W/cm^2 are usually employed for these processes. The surface to be melted is shrouded by an inert gas. There are mainly three metallurgical areas of interest: cast irons, tool steels and certain deep eutectics that can form metallic glasses at high quench rates. All these are essentially non-homogeneous materials, which can be homogenized by laser surface melting. Surface alloying with a laser is similar to laser surface melting except that another material is injected into the melt pool. The alloyed region shows a fine microstructure with nearly homogeneous mixing throughout the melt region. Further most materials can be alloyed into most of the substrates. The high quench rates ensure that the segregation is minimal. The thickness of the treated zone can vary from few microns to a couple of millimeters. Very thin and fast quenched alloy regions can be fabricated using Q-switched Nd: YAG lasers. The metal to be alloyed can be placed on the base material by electroplating or vacuum evaporation or powder coating or ion implantation or diffusion such as boron or reactive gas shroud. Surface alloying of copper, silicon or carbon in mild steel can result in cheap superficially exotic materials. Similarly laser surface hardening of aluminum by alloying with silicon, carbon, nitrogen and nickel has shown excellent properties in car and aircraft industries.

Rapid solidification rates thus produce almost homogeneous structures

- Little thermal distortion, therefore it can be used for thermally sensitive materials
- Good surface finish (20 – 25 µm) thus no post laser processing of the work piece
- Cleaning
- Glazing
- Marking
- Welding
- Cladding
- Laser surface alloying
- Ion implantation
- Diffusion
- Reactive gas shrouding to form nitride, hydride etc.

Vaporization

- Shock Hardening
- Drilling
- Cutting

Laser surface alloying: It is a similar process to laser surface melting except that another material is added to the melt pol. The alloyed region shows fine microstructure and nearly homogeneous mixing. Some in-homogeneity can develop at very fast melting tracks; 0.5 m/s. Most materials can be alloyed to most substrates. The high growth rate ensures minimum segregation. The possible alloyed depths can be between (1-2000 μ).

Laser cladding: Laser cladding is slightly different than laser alloying. In cladding, the purpose is to overlay one metal over another metal to form a sound interfacial bond or weld but without mixing with one another. Claddings are usually thick greater than 200 microns. For laser cladding one can have powder pre-placed on top of the other metal, or can have layers grown by laser physical vapor deposition of layers grown by laser chemical vapor deposition. Cladding with pre-placed powder is one of the simplest method in which area is covered with powder with some binder and the workpiece is shrouded with inert gas. The powder is scanned with a defocused laser beam; resulting the powder to melt and weld with the underlying substrate. Usually laser power of the range of 2 kW can be used to have a clad thickness of few millimeters. It is an overlaying one metal with another to form interfacial bond or weld without diluting the cladding metal with substrate material. In this application, dilution is considered contamination of cladding which degrades its mechanical or corrosion resistance properties. In the pre-placed or blown powder configuration the key parameters are particle size, particle type, feed rate, and flow direction. Reflectivity dome is used; but not always.

Laser surface texturing: Chopped laser beam is used to make regular pattern of small pits or dimples in the surface of the texturing role in a temper mill. Sheets passed through the mill will be surface dulled to aid paint adhesion and to improve press formability.

Laser Drilling

Drilling operation requires focusing of the laser beam at the point of interest. When laser is focused on the work piece, say metals, the surface gets heated up first and then conduction heats the subsurface. Drilling of metals by laser is based on surface heating. Laser material interaction depends on material properties like reflectivity, absorption, thermal conductivity and diffusivity, specific heat, melting and vaporization, latent heat of fusion, heat capacity etc.

Metals are basically very good reflectors. Since reflectivity varies with wavelength, this aspect has to be kept in mind while selecting a laser. The reflectivity of polished silver is about 15% at 300 nm and it increases steeply to about 95% in the visible region, reaching 98% for far infrared region. In the case of copper, reflectivity is 30% at 200 to 400 nm and it increases to 90% at 700 nm, reaching to 98% at 3 mm wavelength. Reflectivity of aluminum is 80% at 400 nm, reducing to 75% at 1μm and then increasing to 90% at 2.5

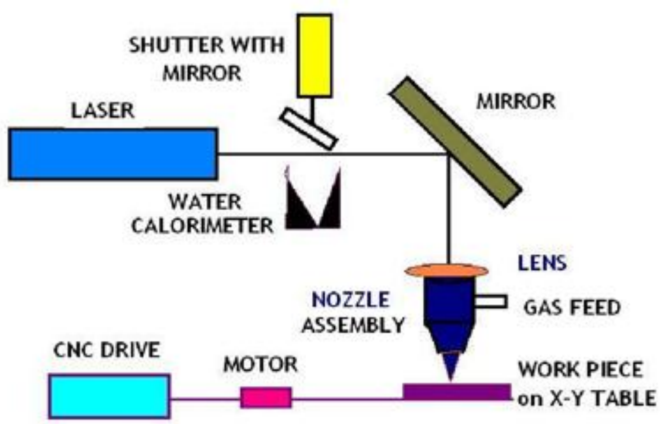
μm, remaining same for longer wavelengths. In case of carbon steel, reflectivity increases from 40% at 400 nm to 85% at 4μm. CO_2 lasers and free running as well as Q-switched Nd: YAG / Nd: Glass lasers are normally employed for drilling of holes in various materials with thickness varying from millimeter to few centimeters. From the above discussion regarding reflectivity aspects, it can be seen that Nd: YAG (1064 nm) is better suited for drilling operation than CO_2 laser (10.6 μm). The average power levels of the lasers employed vary from tens of watts to few KWs. The power levels and the pulse duration of lasers are decided by the nature and the thickness of the work piece. Absorption of laser energy by the target material is another important aspect. Oxidized surfaces absorb laser energy much better than un-oxidized surfaces since the reflectivity of the former is much less than the latter.

As the penetration depth of the laser increases, the absorbed energy heats up the work piece and at high irradiance level of 10^6 W/cm^2 onwards, the laser focal spot starts melting. The melted material is removed by flushing. As the vaporized material is removed, a new surface is formed for further drilling.

Laser intensity plays a very important part in drilling. The ratio of vapor and liquid material removal is proportional to laser intensity. Consider nickel as example. It takes 1.84 millisecond to reach vaporization for laser intensity of 10^5 W/cm^2, where as it is only 1.84 nano second when the laser power is increased to 10^7 W/cm^2. Another aspect is the dependence of process velocity on laser intensity, especially when drilling holes with single pulse. The process velocity is defined as the constant velocity with which the vapor pressure drives the interface melt into the material. It is found that above certain threshold intensity, the processing velocity increases from zero to a higher value, which is material specific and then remains constant as the laser intensity increases. Let us take two materials, aluminum and copper as examples to illustrate the above statement. For aluminum, the processing velocity increases from zero to 25 m/s, as the laser intensity is increased from 300 watts/cm^2 to 500W/cm^2 and it remains same as the laser intensity increase to 2Kw/cm^2. For copper, processing velocity increases from zero to 20 m/sec when the laser intensity is raised from 700 W/cm^2 to 1 kW/cm^2 and then remaining almost constant for higher laser intensities.

Vaporization and material removal depend on the materials. While drilling, these two reach saturation level due to absorption and refraction of laser by the expanding plasma, which shields the work piece from further drilling. Drilling efficiency depends on power density, pulse duration and number of pulses. Higher machining rate can be achieved, when drilling with high repetition rate pulses and lower laser energies rather than vice versa. Laser with longer pulses with lower energies produce deeper holes compared to shorter pulses with higher energies and the former require less number of pulses as well. Nd: YAG laser in the free running mode as well as in the Q-switched mode with power levels varying from hundreds of watts to few kilowatts and pulse width varying from (0.1 to 3) milliseconds are normally employed for drilling holes with diameter in the millimeter range through metals up to several centimeters thick. CO_2 lasers in the CW mode as well as in the pulsed mode with 0.5-millisecond pulse length are used for drilling holes in polymers and ceramics. Nd: YAG lasers are used for drilling hundreds holes, at a rate of 60 holes per second with diameters of 50 micrometers to 100 micrometers in the production of filters for fuel injection purposes. Radio frequency excited sealed CO_2 lasers as well as TEA CO_2lasers producing high pulse repetition rate of tens of thousands with peak power of few hundred to 1000 watts and average power of few hundreds of watts, with pulse duration ranging from tens of microseconds to milli-second duration are also used for drilling. Basically, Nd:YAG lasers are better suited for drilling operations compared to CO_2 lasers as wavelength of former (1.06 µm) is ten times shorter than the latter (10.6 µm) and consequently the focal spot size is ten times shorter for the same focusing system. Further, absorption of energy at 1.06 µm is much more than at 10.6 µm in metals.

Laser Cutting



Typical Arrangement for Laser Cutting

- Laser cutting is today the most common industrial application of lasers. In Japan, around 80 % of the industrial lasers are used for this application only. The advantages of using lasers are that these can cut faster and with a higher quality as compared to other competing processes like abrasive fluid jet, sawing, oxy flame, wire EDM, ultrasonic, plasma and NC milling.

- The cut can have a very narrow kerf width (width of the cut opening) resulting in substantial saving of material.

- The cutting edges can be square and not rounded as with most hot jet processes or other thermal cutting techniques.

- The cut edges can be smooth and clean thus do not need any further treatment.
- There is no edge burr as with mechanical cutting techniques
- There is very narrow Heat Affected Zone as a result of re-solidification. This results in minimum distortions.
- Cut depth is limited and depends on laser power. 10 – 20 mm is the current range for high quality cuts.
- Fastest cutting process.
- Tool wear is zero since the process is non-contact one.
- The noise level is low.
- The process can be made easily automatic.
- All materials (brittle, electric conductors or non-conductors, hard or soft) can be cut. Only high reflective materials such as aluminum or copper can pose a problem but proper beam control these can also be cut. The major components of the laser cutting process include laser with some shutter control, beam guidance, focusing optics, CNC drive for precisely moving the workpiece. When not in use, the laser beam is directed towards beam dump, which may be a water calorimeter. Gas jet not only assists the cutting process but also works as an air knife that blows sideways across the exit from the optic train thus deflecting any smoke and splatter.

Laser cutting process is a function of a multiple parameters like laser beam properties, work piece transport properties, gas properties and material properties. Beam parameters include spot size and mode, power, pulsed or CW, polarization and wavelength. Transport properties speed of the stage carrying work piece and focal position of the laser. Gas properties comprise of jet velocity, nozzle position, nozzle shape and alignment and gas composition. Material properties of relevance are mainly, optical and there are various processes, which can be utilized for cutting depending on the power available and the material.

Laser fusion cutting

The process is also called Melt and Blow. Once a penetration hole is made or cut is started from the edge, then it is possible with sufficiently strong gas jet to blow the molten material out of the cut kerf thus avoiding the temperature increase of workpiece. The melt is removed before any significant conduction occurs. In this manner one requires almost one tenth of the power otherwise required for vaporization. The laser beam after arriving at the surface, most of it passes through the hole or kerf; while some part is reflected off the un-melted surface. At slow speeds the melt starts at the leading edge of the beam and much of the beam passes clean through the kerf without touching the material particularly when the workpiece is thin. The absorption takes place on the steeply sloped cut via Fresenel absorption – that is direct interaction of the beam with the material and secondly by plasma absorption. The plasma build up is not very significant as it is blown away by the gas. At high speeds, the beam is coupled to the workpiece more efficiently by less being lost in the kerf. The beam tends to ride ahead onto the un-melted surface. When this happens, the power density increases since the surface is not sloped and so the melt proceeds faster and is swept down into the kerf. If the gas used in cutting is capable of reacting exothermally with the workpiece then another heat source is added to the process thus overall reducing the laser energies.

Mild steel, stainless steel and titanium can be cut with speed up to 80 mm/sec using oxygen jet with energies of 5.7J/mm^2, 5J/mm^2 and 3J/mm^2 respectively. Energy required cutting with nitrogen or argon is higher than what required for oxygen. Mild steel requires energy of 10J/mm^2 with nitrogen as compared to 5.7J/mm^2 with oxygen. Stainless cutting requires energies of the order of 13J/mm^2, 8J/mm^2 and 5J/mm^2 with argon, nitrogen and oxygen respectively. If all absorbed laser energy is used for melting or evaporating the work-piece, the laser power at inert gas fusion cutting is:

$$P_l = \alpha_1\alpha_2\ S.t.V.\rho.[C_p\Delta T + L_f + m.L_v]$$

P_l: Incident laser power
α_1: Absorptivity
α_2: Correction factor for ( ) due to gas flow
S: Kerf width
t: Thickness
V: Cutting speed
ρ: Density
C_p: Specific heat
T: Temperature rise to melting point
L_f: Latent heat of fusion
m: Mass of evaporated material
$L_{v:}$ Latent heat of evaporation

Laser cutting is governed by the following power balance:

$$AP_l + P_{ox} = P_c + P_{proc}$$

AP_l: Laser power coupled to work-piece
P_{ox}: Power contribution of exothermic reaction
P_c: Power loss due to conduction
$P_{proc:}$ Processing power

$$P_{proc} = S.t.V.\rho. [C_{sol}T_m + h_m + C_{liq}\ \delta T]$$
$$= S.t.V.\rho. [h_f + CT_m]$$

$C_{sol,}$ C_{liq}: Specific heat capacity of solid and liquid material
T_m: Specific heat enthalpy
δT: Average temperature rise of molten beyond Tm
h_f: Specific enthalpy to heat up the kerf material from room temperature to Tm + δT

[Enthalpy = energy content = internal energy + (pressure X volume) of the system]

$$hf = U + PV$$

Laser vaporization cutting:
In this cutting mode, the process relies on vaporization. The laser beam first heats up the surface to boiling point and thus generates the keyhole. The keyhole causes a sudden increase in the absorptivity due to multiple reflections and the hole deepens quickly. As a result, the vapors are generated which escape blowing the material out of hole thereby stabilizing the walls temperature of the hole. This is a common method of cutting the materials, which do not melt like wood, carbon, and plastics mainly employing pulsed lasers. When the metals are cut using this technique, the heat-affected zone is at its minimum. This case is usually of the order of few microns. Typically, if we use a laser of 2 kW focused to a 0.2mm beam, the power density is 6.3 x 10^{10} W/m^2. With this power density, the vaporization temperature of most of the metals like tungsten, titanium, steel etc can be achieved within a microsecond and the speeds of cutting can be high as one meter per second. For vaporization cutting, the penetration velocity (v) is:

$$V = (I_o/\ \rho). [L_f + C_p. (T_v\text{-}T_o)$$

I_o: Laser intensity

For (1-D) heat flow with constant energy input, the surface temperature at any time (t) after laser irradiation is:

$$T(0, t) = (2I_o/k). (Nt/\pi)^{1/2}$$

N: Thermal diffusivity
k: Thermal conductivity

Time needed to reach vaporization (t_v) is:

$$T_v = (\pi/N). [C.T_B.k/2I_o]^2$$

Scribing and Thermal Stress Cracking:

These processes require the minimum power. Scribing is a process for making a groove or line of holes in order to make the make the structure weak so that it can be mechanically broken. Particularly silicon chips and alumina substrates use this technique. Low energy, high density pulses are used to remove the material mainly as vapor. In case of brittle material, thermal stress cracking is usually preferred. These materials are neatly severed, by guiding a crack with a fine spot heated by a laser. The laser heats a small volume of surface causing it to expand and hence to cause tensile stresses all around it. If there is a crack in this region, it will act as a stress enhancer and the cracking continues in the direction of hot spot. The speeds of the order of meter / sec can be achieved with this. Material like glass, quartz, alumina, sapphire can be cut with powers as low as 10 W with speed up to half a meter per second.

Burning Stabilized Laser Gas cutting:

In this mode, laser is used more of a matchstick to ignite the metal in an oxygen stream. Very thick sections can be cut with relatively less power. The process is essentially oxygen cutting with wide kerf widths of the order of 3 – 4 mm, however the quality of edge and squareness is far better as compared to oxy/plasma cutting. Typical rates for cutting 80 mm thick mild steel are 0.2 mm/min with 1.2 kW and 1 mm/sec with 2 kW of laser power.

Cold Cutting:

UV lasers like Excimer have been used for this mode of application. The energy of the ultraviolet photon is 4.9eV, which is similar to the bond energy for many organic materials. Thus if a bond is radiated with such a photon, the bond is broken. When this radiation is impinged onto plastic with sufficient flux of photons such that at least there is one photon for each bond, then the material just disappears without heating leaving a hole without leaving any debris. The process is being widely used for laser ablation of materials for thin film applications. There are potential medical applications also including microsurgery and conventional ablation of tumor cells. There are numerous applications of laser cutting. These include:

- Profile cutting in metals
- Cutting of quartz tubes
- Cutting alumina and dielectric boards
- Cutting radioactive materials
- Cutting of materials in prototype car production and shipbuilding
- Hole drilling in electronic industry
- Laser machining

Laser Welding

The intensity of focused laser beam is comparable to electron beam and is one of the highest power densities available in industry today, At energy densities in the range of $10^{10} - 10^{12} W/m^2$, almost all materials are likely to evaporate provided the energy is completely absorbed. In laser welding, a hole is usually formed by evaporation, which traverses through the material with molten walls sealing up behind it. This is keyhole weld; characterized by its parallel-sided fusion zone and narrow width.

The concept of welding efficiency is known as joining efficiency and is defined as mm^2 joined per kJ of energy supplied. In terms of power and thickness and traverse speed, welding efficiency is equal to

$$\acute{\eta} = Vt/P \ mm^2/KJ$$

Where V, t and P are traverse speed in mm/sec, thickness welded in mm and laser power in kW respectively. The higher is the value of joining efficiency, lower is the laser power used and thus lower are the distortions and heat affected zone. High frequency Resistance welding is the best in this respect having joining efficiency of the order of 65 – 100 mm^2/kJ as compared to 15 – 30 mm^2/kJ achievable in Laser and electron beam welding. Nevertheless it is far more efficient than oxy acetylene flame and tungsten inert gas welding. As Lasers offer high quality, high speed welding, the process is capturing fast and is likely to take 25 – 30% of world market share for neat and reliable. The melting time needed to achieve good welding is:

$$T_m = (\pi k^2/4N.I_o).\ [(T_m-T_o)/\ (1-R)]$$

Where: R is the surface reflectivity. Compared to continuous laser cutting, pulsed laser welding offers more variables; pulse repetition rate and %overlap.

For pulse laser welding, the welding speed is:

$$V_{welding} = \text{spot size X P.R.R. X (1- \%overlap)}$$

The speed is independent on power, while the penetration is a function of power. Too much power initiates vaporization and material ejection. This will therefore require longer laser pulses than used for drilling.

Interaction time, τ is (focal spot diameter/welding speed), i.e.

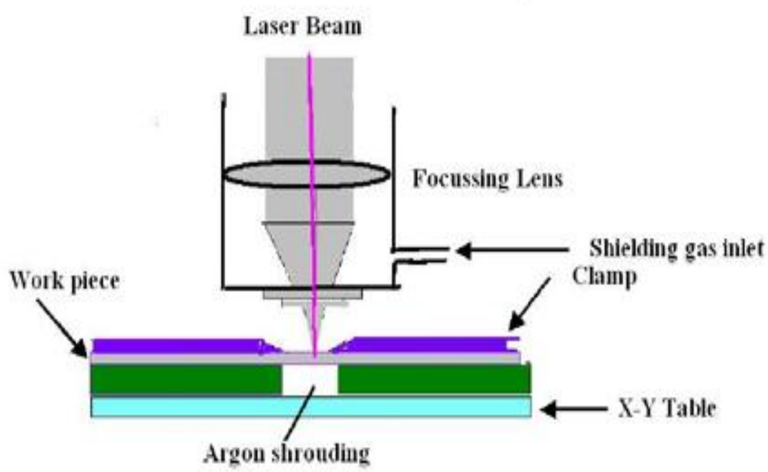
$$\tau = (2\omega_o/V)$$

Thermal input, E is:

E = (Power/Speed) = P/V in J/mm

The advantages of use of lasers in welding can be summarized as follows:

- High energy density "keyhole" type weld leading to less distortion
- High processing speed
- Rapid start
- Weld at ambient pressure unlike electron beam welding
- No X-ray generated unlike electron welding
- Narrow weld
- Little heat affected zone
- No contamination
- Easy to automate
- Accurate and reliable welding



General set up for laser welding

The welding relies mainly on a tightly focused laser beam and the general set up is shown in the adjoining figure. Shrouding is a feature that is almost used in all the welding techniques. It protects the optics as well from spatter. There are two modes of welding. Conduction limited welding occurs when the laser power density is insufficient to cause boiling particularly in the case of broad beams required for welding variable gaps. In this case, it generates the keyhole at a given traverse speed. The weld pool in this case has a strong stirring forces resulting from the variation in surface tension with temperature. The other mode is keyhole welding in which there is sufficient laser energy to cause evaporation and hence the hole is in the melt pool. The pressure from the vapor being generated stabilizes this hole. The keyhole behaves as an optical black body in that the radiations enter the hole and are subjected to multiple reflections and are unable to escape. There are two principle areas of interest in the mechanism of keyhole welding. The first is the flow structure since this directly affects the wave formation on the weld pool and hence the final frozen weld bead geometry, which is a measure of weld quality. The second is the mechanism for absorption within the keyhole, which may affect both the flow and the entrapped porosity and hence decides about the quality of the weld.

Laser welding process is a function of laser beam properties, work piece transport properties, shroud gas properties and material properties. Beam parameters include spot size and mode, power, pulsed or CW, polarization and wavelength. Transport properties speed of the stage carrying work piece, joint geometries, gap tolerance and focal position of the laser. Shroud Gas properties comprise of composition, shroud design, pressure and velocity. Material properties of relevance are mainly composition, surface condition, optical and thermal.

Good quality weld can be obtained with the right choice of power and weld speed. The welding speed for a given thickness increases with the increase in laser power. Typically for welding a 2 mm titanium alloy, the weld speed can be increased from 5 mm/sec to more than 50 mm/sec if the laser power is increased between 1-2 kW.

Penetration is inversely proportional to the weld speed for a given lode, focal spot size and laser power. Typically, for welding stainless steel (304), the penetration depth increases from 3mm to more than 20 mm for a 5 kW laser power when welding speed is reduced from 150 mm/sec to about 10 mm/sec.

For pulsed lasers such as Nd: YAG, pulse width is an important consideration. For example, pulse width less than a millisecond with energies up to 10 J are best suited for cutting and drilling, whereas larger pulse width in the range of 2–5 milliseconds with almost similar energies are suitable for welding. Higher energies (> 10 J) and larger pulse widths (> 4 millisecond) are being employed for deep welding.

In welding of butt joints, the gap must be small enough that the beam cannot pass straight through the joint. In other words, the gap should be smaller than half the beam diameter. In case where is a larger gap, either the beam is defocused a bit or a filler material like wire or powder is added in the joint. The gap 'g' that can be tolerated in butt joints is given by:

$$g = A\beta\Delta Tw$$

Where β is the coefficient of thermal expansion, ΔT is the temperature change usually the melting point, w is the weld width and A is a constant.

However, the gap between the plates 'g' which can be tolerated in case of lap welding is given by

$$g = B\beta\Delta T2t_p$$

Where t_p is the sheet thickness and B is a constant.

The shroud gas can affect the formation of plasma, which may block or distort the beam and thus may affect the absorption of the laser energy. The formation of the plasma is a result of reaction of the hot metal vapors from the keyhole with the shroud gas. The plasma blocking effect is usually less for those gases having a high value of ionization potential. This is the reason why helium is preferred over other gases. However, if the shroud gas is reactive with the weld material, it may form a thin layer such as oxide that results in enhancing the optical coupling.

In order to have an idea about the power requirements for welding, one can assume Laser welding based on keyhole model: model using the moving line source that assumes that the energy is absorbed uniformly along a line in the depth direction. Analytical equations can be used to estimate power or speed of the job

$$Y = \frac{vw}{\alpha}$$

$$X = \frac{Q}{gkT}$$

And

$$Y = 0.483X$$

Where v is the welding speed, w is the weld width, α is the thermal diffusivity, Q is input power per unit time and is given as Q = P (1-rf), g is the job thickness to be welded, k is thermal conductivity and T is the temperature of the plate. For example, to weld a 10mm thick stainless steel at a 10mm/s speed, assuming a weld width of 1.5 mm, the laser power required can be estimated using above relations. For (304) stainless steel, the value of α, k and melting point Tm are 0.49 x 10-5 m2/s, 100 W/m/K, and 1527 oC respectively. The values of Y and X are

$$Y = \frac{0.01 \times 0.0015}{o.49 \times 10^{-5}} = 3.0$$

$$Y = 0.483X$$

$$X = \frac{3.06}{0.483} = 7 = \frac{Q}{gkT} = \frac{Q}{0.01 \times 100 \times 1527}$$

$$Q = 10.6kW$$

If one assumes transfer efficiency of 90%, total power required is 11.8 kW. Some of the important applications of laser welding in industrial applications include:

- Welding of transmission systems and other subsystems for car industry.
- Hermetically sealing of electronic capsules
- Welding of thick pipes
- Repair of nuclear boiler tubes
- Welding of sheet metal products such as washing machines and heat exchangers
- It is used for 3D welding process because of its well- controlled manipulation.
- Welding of polymers & plastics using 20-40 W diode 800 – 900 nm diode lasers.

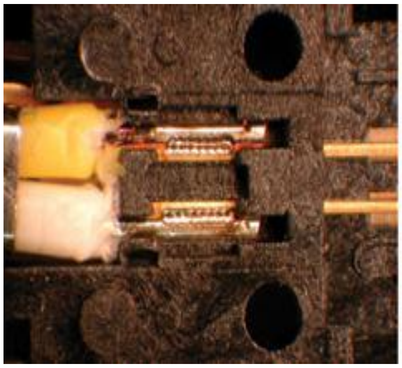
Microwelding

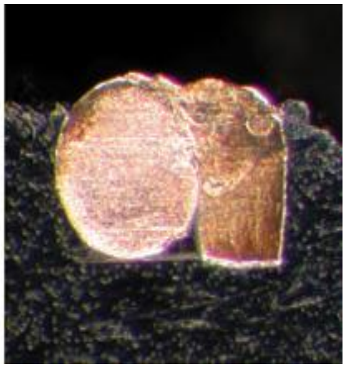
Welding small conductive parts is a unique challenge for welding technologies. Laser welding offers a great fit for this scale of joining; however, 1064 nm pulsed Nd: YAG technology is inadequate for joining conductive materials such as copper, silver, and gold. Frequency-doubled green Nd: YAG sources are legitimizing the use of lasers in conductive microwelding applications.

The growing medical device industry, a rapid increase in automotive sensor sales, and the rebound of the telecommunications industry have driven a need for joining conductive materials such as copper, silver, and gold. Welding these materials is problematic for any technology and has even proved extremely difficult or impossible with traditional 1064 nm pulsed neodymium: yttrium aluminum garnet (Nd: YAG) laser-welding technology. But a recent innovation—a frequency-doubled 532 nm green Nd:YAG pulsed laser capable of 4 J pulse energies—offers nearly an order-of-magnitude increase in material absorption over the 1064 nm wavelength, expanding and legitimizing the use of lasers in conductive microwelding applications.

Microwelding examples

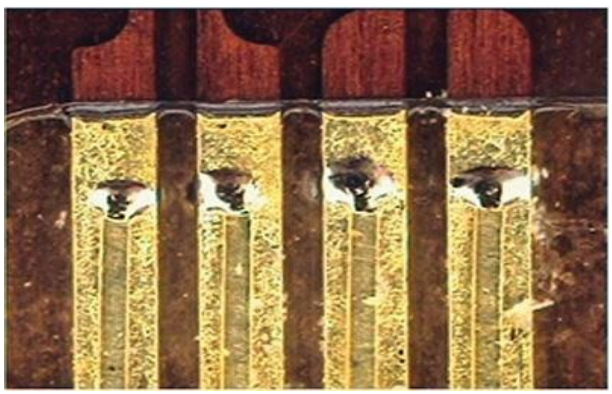
Electrical connections come in many different sizes, shapes, and materials. The requirement for high-quality, reliable terminal connections occurs in many industries, and the welding of electrical contacts needs to create a conduction path that is seamless to the operation of the part such that the joint performs as a single, solid, continuous component. Laser welding offers this potential. For example, the automotive industry has seen a significant increase in sensor technology to monitor car performance, functionality, and environment. Each sensor has many terminal connections that must survive for the lifetime of the car. In this arena, laser microwelding provides a viable option. Connection requirements are also important in the medical industry in implantable devices and sensing/monitoring instruments, where each connection is essential to maintaining part functionality and performance. In the communications, signal strength and integrity are crucial to maximize part performance and ensuring that the joint is not a limiting factor in the part's design.





A small seam weld between a gold-plated copper connector of rectangular cross-section and a 0.016-in.-diameter cylindrical silver-plated copper wire (left). A cross-sectional view of the laser microweld shows a uniform weld seam.

Bonding 0.0015-in-thick gold-coated copper flat wire to metalized pads is challenge. Ideally the pad thickness is at least 1.5 times the thickness of the ribbon, creating a good thermal balance between the wire and the pad and prevents overheating the pad. The flexibility of the laser is extremely valuable in welding different joint geometries and terminal shapes. A laser microweld between a gold-plated copper connector of rectangular cross-section and a cylindrical silver-plated copper wire requires the weld to be made in a butt configuration, with the position of the wire in relation to the terminal showing some variation (see Fig. 2). The controlled and consistent absorption of the 532 nm laser power to both parts enables a reliable weld.



Laser welding of 0.2mm thick Cu flat wire to 0.2mm thick Cu lead frame

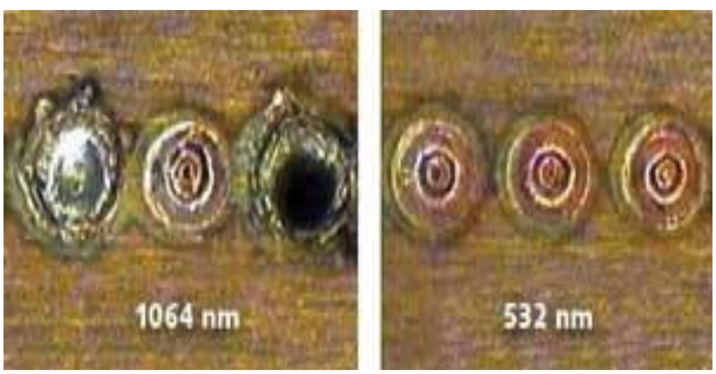
For high-volume production, welding multiple joints on lead frames is all about quality and speed. Laser welding lends itself to volume manufacturing by executing many welds per second depending on the effectiveness of motion integration with the weld tool. By removing the barrier of high reflectivity for 1064 nm laser microwelding of conductive metals, the 532 nm green Nd: YAG laser welder offers a viable method for microwelding copper and other conductive materials.

Laser welding is a fast, accurate, non-contact process and needs only a single-sided access, but suffers from material reflection. The technology is useful for working on extremely small joint areas, and can be used to weld different shaped parts, different joint geometries, and dissimilar materials. It uses no consumables that need to be maintained or replaced and the weld cycle is milliseconds. On the face of it, laser welding appears to be an excellent solution for copper micro welding - but there is a problem. The pulsed Nd: YAG (neodymium-doped yttrium aluminum garnet) used for the majority of micro welding applications has a wavelength of 1064 nm, which is more than 90 percent reflected by copper. Extremely high power is required to overcome the reflectivity and to ensure that sufficient light energy is delivered to the copper to initiate. However, once some laser power is delivered to the copper and raises its temperature, the reflectivity decreases. As the absorption of laser power occurs in times less than a billionth of a second, there is a rapid change in how much power is absorbed. The high power that was initially required now far exceeds what is required to form the weld. As a result, the material rapidly overheats and vaporizes, leaving a large porosity or a hole.

Comparison of reflectivity for 1064 and 532 laser wavelengths

Material	**Wavelength**	
	1064 nm	532 nm
Copper	90%	45%
Gold	98%	42%

A number of techniques have been used to overcome this reflectivity, including pulse shaping, oxygen assist, and the use of less reflective plating. Pulse shaping is not reliable, because the reflectivity of copper and other conductive parts varies, and so the precise moment at which the laser power should be reduced also varies. There have been some attempts to better anticipate this 'precise moment' by implementing feedback techniques, but none have so far proven viable. Oxygen has been shown to dramatically increase penetration in seam welding copper by building an oxide layer on the part to be welded, but this has not been effective for spot welding applications because the positive effect of oxygen is seen only after several pulses in succession and so does not offer a reliable technique for single spot welding or short seams. Using less reflective coatings such as nickel or tin helps to reduce initial reflection, but does not fully solve the problem as large energies are still required to continue the coupling into the copper; thus the process window for micro welding becomes very small.

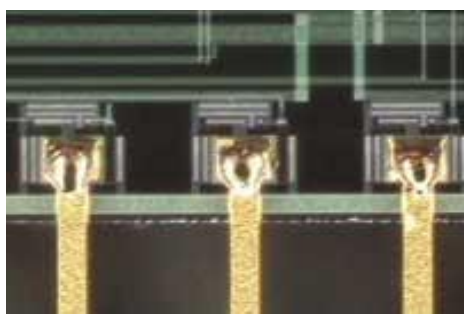


Spot welds on bar copper by pulsed 1064 nm and 532 nm Nd: YAG laser.

Pulsed green lasers address material reflectivity issues

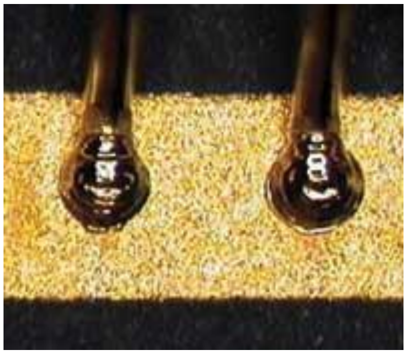
Reducing laser wavelength from 1064 nm to 532 nm significantly reduces the reflectivity of copper and other conductive materials. The 532 nm (green) wavelength enables consistent coupling into the copper and stabilizes welding. Using the process of second harmonic generation (SHG), 532 nm lasers light can be produced from a 1064 nm lamp-pumped solid-state (LPSS) laser. The SHG process uses a frequency-doubling crystal that operates as a nonlinear optic. One 532 nm laser welder is capable of up to 4 J pulses, which covers the majority of microwelding applications. Such a laser was developed by placing the crystal within the cavity and with careful control of polarization and beam power density on the crystal. In the final version, the 532 nm pulsed Nd: YAG welding laser is capable of 1.5 kW peak power with up to 5 ms pulse width. This provides enough weld energy to penetrate approximately 350 µm thick oxygen-free copper, which is sufficient for many micro-conductor welding applications. All the benefits of a regular pulsed YAG laser are maintained, including real-time power feedback, flat-top modes, fiber delivery, and time and energy shared outputs.

Material reflectivity must be addressed to achieve a good, strong laser micro weld on copper. As shown in the table above, reducing the wavelength from 1064 nm to 532 nm significantly reduces the reflectivity of copper and other conductive materials. The 532 nm wavelength enables consistent coupling into the copper and stabilizes welding.



0.015-in. thick gold coated copper flat wire welded to metalized pads.

At 532 nm, the laser couples into copper as 1064 nm couples into steel. Therefore, successful micro welding of copper can be achieved if a 532 nm laser is used. This wavelength can be achieved in two ways. Most common is to use a q-switched laser, but such a laser does not have sufficient pulse energy to weld. A more novel approach is to use a regular pulsed Nd: YAG laser, which offers 532 nm light at 1.5 kilowatt (kW) peak power with up to a 5 milliseconds (ms) pulse width. This provides enough weld energy to penetrate approximately 350 microns thick copper, which is sufficient for most micro welding applications. Another additional benefit of using a pulsed Nd: YAG laser delivered through a fiber is that the beam has low brightness. This promotes even absorption across the focus spot, preventing hot spots at the center of the weld that may cause instability.



Solid 0.004-in. diameter gold wire welded to gold plated metalized pad.

Examples of green laser micro welding applications

Electrical connections come in many different sizes, shapes, and materials. The requirement for high quality, reliable terminal connections occur in many industries. The welding of electrical contacts needs to be a seamless process to the operation of the part, such that the joint performs as a single solid continuous component. Laser welding offers this potential. For example, the automotive industry has seen a significant increase in sensor technology to monitor car performance, functionality and environment. Each sensor has many terminal connections that must survive for the lifetime of the car. In this arena, laser micro welding provides a viable option, and the laser provides a great tool for high speed high quality welding.

0.01-in diameter silver wire welded to nickel plated copper terminal.

Connection requirements are also critical in the medical industry, for example in implantable devices, sensing and monitoring instruments, where each connection is critical to maintaining part functionality and performance, and thus requires a highly stable joining technology. Similarly, in the communications industry, signal strength and integrity are crucial to maximize part performance and ensure that the joint is not a limiting factor to the part's design. There are a number of electrical contact configurations that are needed across all industries chosen according to specific part and component design. A few of these connection options that can be accomplished using the pulsed green laser are shown below:

- A common connection in the electronics industry is when 0.00150 inch thick gold coated copper flat wire is bonded to metalized pads. Ideally the pad thickness is at least 1.5 times the thickness of the ribbon, because this creates a good thermal balance between the wire and the pad preventing the pad from overheating.

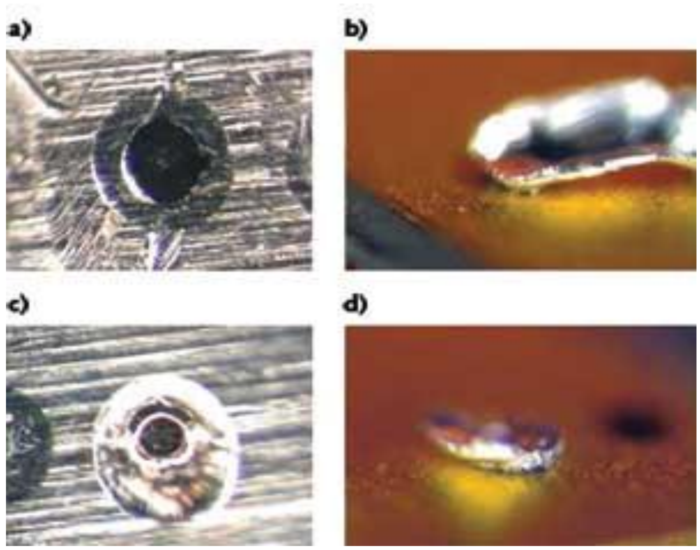
- Joining solid and stranded wires is another common terminal configuration for power electronics. By suitable positioning of the laser to the tip of the wire and the pad, the wire is effectively reflowed on the pad. Also note in FIGURE 6 the absence of heat effect on the pad itself. As shown on FIGURE 7, a stranded wire is also highly weldable. The key in welding the stranded wire is maintaining the tip to ensure the strands are closely packed. This can be achieved by compacting, dipping in a plating or using a short cut back distance to the insulation.

- The flexibility of the laser is extremely valuable in welding different joint geometries and terminal shapes. FIGURE 8 shows a weld between a gold-plated copper connector of rectangular cross section to a silver-plated copper wire. The weld is a butt with wire position in relation to the terminal showing some variation plus the gap between the wire round and the square edge of the terminal. The controlled and consistent absorption of the laser power to both parts enables the weld to be made reliably.

- Welding multiple joints on lead frames is all about quality and speed. Being a non-contact process, laser welding lends itself to volume manufacturing. It can execute many welds per second, according to the motion integration. The figure below shows a flat wire welding to a copper lead frame.

0.2mm thick copper flat wire welded to 0.2mm thick copper lead frame

- Power application that require less than 50mAh for such applications as wireless products, smart cards, or RFID tags, generally use either lithium ion or lithium polymer battery technology. For these applications that require the battery terminal to be connected, there are a number of special challenges. Each terminal is made of copper and aluminum, which are both problematic to weld. The terminal material is also very thin, sometimes less than 0.001 in. In some applications, ultrasonic welding is used, but laser welding is also an option, and may be especially well suited to joining terminals to PCB metalized pads. FIGURE 10 shows several views of laser welding of thin copper and aluminum to gold coated copper pads.



Laser welding of thin copper and aluminum to gold coated copper pads, a) Top view of the 0.01-in. thick aluminum terminal welded to gold coated copper pad; and b) side view of the pull-tested aluminum weld showing nugget formation; c) a) top view of the 0.01-in. thick nickel coated terminal welded to gold coated copper pad; and d) side view of the pull-tested copper weld showing nugget formation.

Micro welding of dissimilar materials

When welding materials with different levels of absorption, there is a tendency to overheat the more absorptive materials, causing excessive spatter and porosity. This is usually overcome by favoring one material. However, for small parts, this may not be sufficient because even the tiniest absorption imbalance can create an overheated weld. At 532 nm wavelength, the reflection of both parts becomes closer; therefore the weld energy balances more consistently, significantly improving weldability.

Laser welding - viable method for high volume micro welding of copper

Micro welding of such conductive materials as copper is a difficult proposition, but laser welding offers a useful non-contact joining method, well geared for automation. In the past, copper's reflectivity at the 1064 nm wavelength has always been the barrier to implementing laser welding. By using a 532 nm green Nd: YAG laser welder, this barrier has been removed, offering a viable method for micro welding copper and other conductive materials in high volume.

Surface Treatment

Surface treatment employs lasers of varying energies. For example low power density processes of transformation rely on surface heating without melting and include hardening, bending, laser chemical vapor deposition. Moderately higher power densities, which rely on melting, include surface homogenization, laser glazing, surface alloying and cladding. Much higher power densities rely not on melting but also on evaporation and these processes include instant ablation, shock hardening.

Laser processing, ablation and deposition

Pulsed-laser radiation is absorbed through various energy transfer mechanisms, leading to thermal and non-thermal heating, melting, and finally ablation of the target. Laser ablation is one of the most efficient physical methods for micro, and more recently, nanofabrication, due to the high resolution capability, low heat deposition in the target and high level of flexibility. On the other hand, the ablation of the target yields to an ejection of its constituents and to the formation of nano-clusters and nanostructures on the PLD process. When the target is ablated in vacuum or in a residual gas, the nano-clusters can be deposited on a substrate, placed at some distance from the target, leading to the formation of a thin nano-structured film. The properties of synthesized nanostructures can be efficiently controlled by parameters of laser ablation (fluence, pulse duration, wavelength) and properties of the environment.

Femto-second (fs) laser ablation is opening up new perspectives in the ultra-precise processing of organic materials and in the PLD synthesis of thin films with tailored structure and composition. Focusing fs laser pulses into a target leads to optical breakdown and generation of a micro-plasma. Because of the nonlinear nature of plasma formation, very fine and highly localized laser effects can be induced while minimizing thermal and mechanical damage to the surrounding material. For fs pulses, the pulse energy threshold for material modification is reduced by some orders of magnitude compared with ns or ps pulses. Pulsed lasers of ns (Excimer and Nd:YAG lasers) and fs pulse duration to process and ablate different types of target materials including semiconductors, polymers and biopolymers under vacuum, in air or in the presence of pressures of a background gas. We are interested in studying the fundamentals of the ablation process by investigating the influence of laser parameters and target properties.

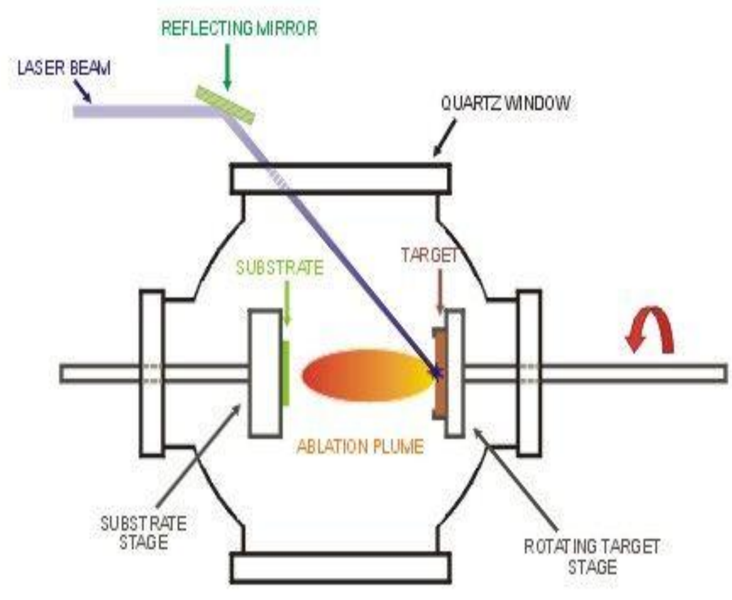
We aim at the assessment of mechanisms and to the optimization of the processing in different applications. We are also interested in using ablation plumes as nonlinear media for harmonic generation.

To investigate the ablation process, the ablation plume is analyzed by mass spectrometry, wavelength, spatially and temporally resolved optical emission spectroscopy and laser-induced fluorescence (LIF). We also investigate the target after irradiation with a variety of techniques, including optical and scanning electron microscopy's, colorimetry, Raman and FTIR, etc. We are interested in studying:

- Laser ablation of inorganic compounds: SiO, semiconductors, inorganic salts, etc.
- Effect of molecular weight on the UV/IR laser ablation of polymers.
- Laser processing of biopolymers.

Pulsed Laser Deposition (PLD)

In PLD the material ejected in the ablation plume is deposited on a substrate placed in front of the target as shown in the scheme of the typical set up. PLD provides a method of depositing thin coatings, of a wide range of target materials, on different substrates. We focus in the understanding of the mechanisms of laser-target interaction in the characterization of the properties and dynamics of the ablation plume and finally in the process of deposition on the substrate. Finally our research focuses on determining characteristics of the deposited film, morphology and composition.



SCHEME OF VACUUM CHAMBER WITH A PLD SYSTEM

Other Industrial Applications of Lasers

- Enhanced electroplating
- Surface texturing
- Laser chemical vapor deposition
- Laser physical vapor deposition
- Non-contact bending
- Magnetic domain control
- Laser cleaning and paint stripping
- Surface roughening
- Micro-machining
- Laser marking
- Shock hardening
- Stereo-lithography
- Laser direct casting
- Process control using lasers

2. Laser Medical Applications

I. Interaction of Laser Radiation and Biological Tissue

A. Optical properties of tissue:

1. Absorption

The absorption depends on the type of tissue and the wavelength of incident laser. Proteins, hemoglobin and melanin account for absorption of UV and visible lasers while absorption by water is dominated in the IR range. Transmission (T) of laser light through a tissue is given by the initial laser intensity (I_o), the absorption coefficient (μ_a) and the tissue thickness (d) according to Lambert-Beer law,

$$T = \frac{I_T}{I_o} = e^{-\mu a.d}$$

2. Scattering

There are 2 types of scattering;

- Elastic scattering (no loss of energy) is described by Rayleigh scattering (particles causing the scattering are smaller in size than the wavelengths of radiation in contact with them. This type of scattering is therefore wavelength dependent. As the wavelength decreases, the amount of scattering increases. It is responsible for the blue appearance of the sky) and Mie scattering (particles causing the scattering are larger than the wavelengths of radiation in contact with them. It is responsible for the white appearance of the clouds).
- Inelastic scattering (loss of energy of photon and change of wavelength). Inelastic scattering on tissue occurs in the following processes:
- Fluorescence, Phosphorescence
- Brillion scattering (adiabatic density fluctuations)
- Raman scattering (molecular and lattice vibrations and /or electronic transitions)

The scattering coefficient μ_s is:

$$\frac{dI}{dZ} = -\mu_s I(z)$$

Total attenuation of laser light is; $\mu_t = \mu_a + \mu_s$. Scattering power, $\propto$ is then,

$$\propto = \frac{\mu_s}{\mu_t} = \frac{\mu_s}{\mu_a + \mu_s}$$

Mean free path (δ_a) is the depth where incident laser intensity has been reduced by 1/e ≈ 37%.

$$\delta_a = 1/\mu_a$$

The maximum penetration depth of laser is in the visible and NIR. The depth decreases for longer/shorter wavelengths in IR/UV. Intervention in lower tissue layers are performed using visible-NIR lasers while the treatment of surface tissue employs IR-UV lasers. There are 5 types of interactions between laser light and tissue;

1. **Photo-mechanical:** acoustic wave generated by sudden heating of tissue leads to a shock wave and mechanical disruption of tissue e.g. destruction of kidney stones.

2. **Photo-thermal:** heat generated in tissue causes a change in tissue, e.g. tissue welding or cell death. Most effects are due to HEAT and when tissue absorb laser light ➔ heated Tissue may be:

- Ablated (removed) – high power and energy.
- Charred.
- Coagulated (cooked or welded).
- Bio-stimulated – low power and energy.

Mechanism of photo-thermal tissue effects comprises 3 steps:

1. Absorption of radiation
2. Conversion of the laser energy absorbed into heat
3. Temperature-related tissue changes

Laser light excite vibrational-rotational states of molecules in the tissue. Absorbed laser energy is converted to heat energy within ps – ns and heat can be transported either by conduction (most significant) or by convection and radiation. Heat conduction is given by heat conductivity (k) and thermal diffusivity (N) of the tissue. At temperature difference (ΔT), the deposited heat energy (Q) diffuses according to:

$$\frac{\mathrm{dQ}}{\mathrm{dt}} = k\frac{\mathrm{A}}{\mathrm{d}}\Delta\mathrm{T}$$

Where (A) is the surface through which heat flux flows over a depth (d). The higher heat conductivity of a tissue volume, the faster heat flows away from that tissue volume. For example: water conducts heat better than fat, meaning for fixed laser power, more energy is deposited in fatty tissue than in water-containing tissue. The spatial temperature change is:

$$\frac{\mathrm{dT}}{\mathrm{dt}} = N\Delta^2\mathrm{T}$$

Thermal diffusivity is a function of heat conductivity (k), tissue density (ρ) and specific heat (c):

$$N = \frac{k}{\rho c}$$

Time required for dissipating a temperature gradient along a characteristic length ($x = \frac{1}{\alpha}$), where (α) is the absorption coefficient, is called the relaxation time and is given as: T_R

$$T_R = \frac{1}{4N\alpha^2} = \frac{\rho c}{k\alpha^2}$$

T_R is very important in pulsed lasers to estimate if there is relevant temperature conduction during the laser pulse itself. Heat conductivity and heat diffusivity are not constant parameters and are rather a function of absolute temperature. The exact effect of laser depends on energy and temperature produced. There are 4 types of impact that need to be differentiated:

- Heating
- Coagulation
- Carbonization
- Vaporization

Coagulation occurs at high laser intensities where thermal effect can burn the irradiated cells. This process describes structural change of bio-molecules in particular proteins leading to a detachment of epidermis. The absorption of laser light will deposit heat energy in the tissue. At 60 ^{o}C, skin whitens and when temperature reaches 90 ^{o}C the cells ultimately dry up and shrink leading to the formation of dark scars. This process can be applied in:

A. Dermatology:
- Coagulate blood vessels
- Removal of pigmented spots
- Destruction and removal of subcutaneous (under the skin) pigment
- Destruction of hair roots
- Treatment of psoriasis
- Smoothing wrinkles

B. Laser-induced thermotherapy:

This is minimally invasive for local treatment of malignant hepatic tumors. 1064 nm Nd: YAG laser energy is transported, via a glass optical fiber, to tumor tissue to heat tumor and destroy tumor cells.

Vaporization is facilitated by strong absorption of laser radiation by water and therefore by tissue as well. Laser energy is deposited in relatively small tissue volumes which are then evaporated. The high laser energy density can generate very high temperatures of up to several hundred ^oC at which carbonization is formed. This process can be utilized in laser cutting of tissue and is achieved in the area of the laser focus.

3. Photo-chemical interaction with tissues

This interaction can be utilized even at relatively low intensities. It involves the excitation of molecules by laser light followed by a chemical reaction. In photo-induced synthesis, the irradiated molecules are excited and made to form bonds to each other. Examples of this process are: photosynthesis in plants and the tanning effect of UV light on human skin. In isomerization process, a molecule is laser-excited and made to change its atomic arrangement. This process can be utilized for the treatment of jaundice which is caused by brilirubin, an elevated concentration of hemoglobin degradation product. Brilirubin can be made excretal in the urine and eliminated by isomerization. PDT utilizes laser excitable dye to destroy tumor tissues. Tumor tissue must first be labeled with sensitizer dye (which accumulates in this tissue) then exposed to laser light of a wavelength that matches the absorption peak of the dye. Electrons of the dye molecules will get excited into short-lived triplet states (intersystem crossing). Energy of triplet states is transferred to oxygen (ground state; $^3O_2$) forming very reactive, high energy singlet oxygen ($^1O_2$). In turn, ($^1O_2$) reacts directly with bio-molecules to form peroxides and endoperoxides. Reaction with water can form radicals which can oxidize bio-molecules or attack redox system of the cells; changing its membrane permeability and killing it.

4. Photo-ablation of tissues

Direct photo-ablation is based on direct molecular dissociation caused by absorption of photons. Laser intensity threshold for this type of interaction is ~ 10^7-10^8 W/cm^2 for ns laser pulses and the t issue depth ablated per pulse is determined by the laser pulse energy. Laser fluence threshold $F_{thr.}$ below which no material is ablated is:

$$F_{thr.} = F_o e^{-\mu d}$$

The geometry of the cut is determined by spatial parameters of the laser beam. Advantages of this technique are its high cutting precision, high predictability, and minimum thermal damage to surrounding tissue. The dissociation process proceeds in two steps: sufficient energy absorption of UV laser to reach an electronic state that exceeds the chemical bond energy followed by molecule dissociation. Average electron excitation by laser must happen more rapidly than thermal relaxation time T_R, i.e. pulse duration (τ_r) < T_R. Photo-ablation process is specifically used in dentistry and lithotripsy.

<u>Photo-ablative dental laser</u> should be characterized by its short pulse duration and high intensity. Er: YAG laser operating at 2900 nm wavelength matches the main absorption peak of water. Virtually all laser pulse energy is deposited in the tooth tissue which is

heated up very quickly so that adsorbed water as well as O-H groups evaporates in the form of micro-explosions, i.e. tissue removal.

Lithotripsy is used to disintegrate gallstones, urinary calculus, cholesterol, cystine, etc. Optical quartz fiber is introduced while monitoring and advancing to a location next to the stone to be disintegrated. When a laser pulse transported through the fiber is focused onto the surface of the kidney stone, rapid evaporation of the stone surface will take place. This produces a shock wave in the surrounding liquid which destroys the stone after multiple pulses. 10-400 µs duration and 5 mJ -2 J Ho: YAG or Nd: YAG lasers are employed for this application.

5. Photo-disruption of tissue

Above 10^{11} W/cm^2 of laser intensity, there will be a strong non-linear increase in the laser light absorption even in transparent media accompanied by a white flash of light and an acoustic signal. This is an optical break-through meaning plasma is produced. The ionization is due the absorption of multiple photons, i.e. is a non-linear process. This effect is strongly intensity dependent. Plasma production commences after the laser-induced break-through. The start electrons are accelerated by inverse Bremsstrahlung absorption which produces secondary electrons by the collision avalanche ionization until the plasma is generated at a temperature ~ 15000 K and a pressure of 20 – 60 bars. The functional principle of photo-disruption is:

- Focused laser pulse ($I > 10^{11}$ W/cm^2)
- Non-linear break-through
- Plasma bubble ($d \approx$ 1-100 µm)
- Shock wave
- Cavitations'' bubble ($d <$ 2 mm)
- Continuing shock wave

Human Skin

Human skin is a remarkable organ, the body's largest, but it is often taken for granted. Most people are content to let skin be until dryness, oiliness, a rash or a wrinkle rouses attention. But once they understand how skin functions, many reconsider the importance of the skin and the quality and content of the skin care products they use. Using natural skin care can make more of a difference than most folks realize.

Consider the following facts:

1. An adult's skin comprises between 15 and 20 percent of the total body weight.
2. 1cm^2 has 6 million cells, 5,000 sensory points, 100 sweat glands and 15 sebaceous glands.

Skin is constantly being regenerated. A cell is born in the lower layer of the skin called the dermis, which is supplied with blood vessels and nerve ending. The cell migrates upward for about two weeks until it reaches the bottom portion of the epidermis, which is the outermost skin layer. The epidermis doesn't have blood vessels but does have nerve endings. The cell spends another two weeks in the epidermis, gradually flattening out and continuing to move toward the surface. Then it dies and is shed.

Two billion to 3 billion skin cells are shed daily. The body expends this effort to replace skin every month because the skin constitutes the first line of defense against dehydration, infection, injuries and temperature extremes. Skin cells can detoxify harmful substances with many of the same enzymatic processes the liver uses. The unbroken surface also prevents infectious organisms from penetrating into systemic circulation. As gatekeeper, the skin absorbs and uses nutrients applied topically. Because it cannot completely discriminate, the skin may absorb the synthetic chemicals often present in soaps and lotions and other skin care products, which at best it has no use for and at worst can be toxic or irritating.

Most of our site visitors are committed to natural foods and remedies, but many aren't as selective when it comes to personal skin care products. These otherwise savvy shoppers might purchase any sale shampoo, skin care cleanser or lotion. But because new skin is constantly being generated and because it plays such an important protective role, it makes sense to choose nourishing natural skin care products.

The Epidermis

The epidermis is the topmost layer of the skin. It is the first barrier between you and the outside world. The epidermis consists of three types of cells keratinocytes, melanocytes and Langerhans cells. Keratinocytes, the cells that make the protein keratin, are the predominant type of cells in the epidermis. The total thickness of the epidermis is usually about 0.5 - 1 mm. At the lowermost portion of the epidermis are immature, rapidly dividing keratinocytes. As they mature, keratinocytes lose water, flatten out and move upward. Eventually, at the end of their life cycle, they reach the uppermost layer of the epidermis called stratum corneum. Stratum corneum consists mainly of dead keratinocytes, hardened proteins (keratins) and lipids, forming a protective crust. Dead cells from stratum corneum continuously slough off and are replaced by new ones coming from below. The skin completely renews itself every 3 - 5 weeks. Most mild peels work by partly removing the stratum corneum and thus speeding up skin renewal.

Another significant group of cell in the epidermis is melanocytes, the cells producing melanin, the pigment responsible for skin tone and color. Finally, Langerhans cells are essentially the front door of the immune system in the epidermis. They prevent unwanted foreign substances from penetrating the skin. The condition of epidermis determines how "fresh" your skin looks and also how well your skin absorbs and holds moisture. Wrinkles are formed in lower layers.

The epidermis consists of many layers:

The stratum corneum or outer layer**:** This layer is made of flattened epithelial cells in multiple layers. These layers are called keratinized layers because of the buildup of the protein keratin in those cells. Keratin is a strong protein that is specific to the skin, hair and nails. This layer of skin is, for the most part, dead. It is composed of cells that are almost pure protein.

The translucent or transitional layer**:** This is a translucent, thin layer of cells. This layer is sometimes visible in thick skin; however, nuclei and other organelles are not visible. The cytoplasm (the amorphous area between the nucleus and the outer membrane of the cell) is mostly made of keratin filaments.

The suprabasal layers**:** This is three to five layers of flattened polygonal cells that have granules in the cytoplasm. Below them is a layer of cube-shaped cells that also contain bundles of keratin filaments.

The basal or cell-division layer**:** This layer is just above the basement membrane and the dermis. It is a single layer of cells that undergo cell division to renew the upper layers of the epidermis.

Human skin interaction with laser light

Human skin is the first line of defense against environmental effects. It is made of many thin sheets of layers of flat, stacked cells in which nerves, blood vessels, hair follicles, glands, and sensory receptors are found. It is constantly regenerated where cells created in the lower layer of the skin (dermis) migrate to the bottom of the upper layer (epidermis). Epidermis strongly absorbs UV radiation which causes sun tanned skin while NIR penetrates deeply into the skin tissue. The relative effectiveness of optical radiation in penetrating the epidermis and dermis is proportional to cosine the angle of incidence. Collagen fibers are triple-helical amino acid compounds that are strengthened by cross-linking of prolene and hydroxyprolene.

There is an increasing interest in non-ablative skin resurfacing at a time where the ablative laser technique is declining due to the prolonged after-treatment medical care required. Non-ablative laser skin resurfacing creates a controlled injury to certain target structure in the dermis while completely sparing the epidermis from damage. This technique stimulates collagen generation and/or removes irregular pigmentation and enlarged vessels from the skin. Non-ablative technique can be employed either by heating the papillary dermal layer through the effect of water absorption spectrum or through the hemoglobin absorption of laser light with partial coagulation of papillary dermis.

Photo aging is the main factor of aging signs in which normal elastic fibers accumulate in an abnormal way while collagen fibers decrease in number and become disorganized. Non-ablative skin resurfacing is wavelength-dependent allowing different wavelengths to target different structures. Penetration is also a wavelength-dependent which increases from several (μm) in the UV to several (mm) in the IR. For non-targeted tissue, the laser pulse duration should be longer than its relaxation time, but to deliver all laser energy to the target tissue before it has a chance to cool down, the laser pulse duration must be shorter than the relaxation time of the target tissue.

Severe pain could be induced in human skin tissue when heated to a temperature of 45 ºC; this corresponds to an injury threshold. When targeted tissue reaches ~60 ºC, coagulation occurs. Laser light can exert its effect on selected tissue by thermal, mechanical and photochemical means. Mechanical effect of lasers on tissue-selective photothermolysis can target pigmented cells. When a Q.S. laser pulse is used to treat pigmented tissue, a photo-acoustic shock wave is created, fragmenting the pigment into smaller particles i.e. loosing its coloring property. In the case of photochemical injury, a single photon has sufficient quantum energy to convert individual molecules to one or more different chemical molecules. The yield of the photochemical reaction products is proportional to the photon flux. Thermal energy depends on energy absorbed per unit volume (or mass) to produce a critical temperature elevation. Injury threshold depends on exposure time, the longer the length of exposure, the lower the temperature required to coagulate proteins and destroy tissue by elevated temperature.

Non-ablative effect of lasers on tissues

Skin resurfacing is one way to treat skin aging caused by many environmental, dynamic and gravitational effects. It allows gradual attenuation in the signs of skin aging. Clinical signs of aging include the appearance of wrinkles, skin laxity, increased visible vascularity and pigmented spots. Improving skin texture is achieved by collagen remodeling. This is based on generating new fibers in the dermis to give the skin back its elasticity and can be triggered by heating the dermis and collagen fibers to a certain temperature.

Papillary dermal layer is heated due to the effect of water absorption of certain laser wavelengths, (1200 nm - 2000 nm) but this requires many sessions. Laser light absorption by hemoglobin is another approach to change the skin metabolism. This can help increase the blood supply to the targeted tissue resulting in microvasculature renewing, fibroblasts stimulation and new collagen production. Nd: YAG laser emitting at 1064 nm has deep penetration (~4 mm) with negligible absorption by the melanin and water, thus making micro-vascular hemoglobin the main target for fibroblast activation. Heat is generated in the papillary layer and spreads to the surrounding tissue. Epidermal temperature increases to (43-48) ºC which means that the treatment doesn't require stringent anesthesia or cooling. An epidermal surface temperature of (40-48) ºC is ideal since this correlates with dermal temperature of (55-65) ºC that is needed for collagen re-modeling. Laser pulse energy and duration are arranged for each patient to find the mildest mode for microvasculature treatment.

Non-ablative resurfacing induces a dermal healing response without notable injury to the epidermis. Improving the appearance of the skin is done by a sub-threshold laser-induced injury to the dermis and/or the dermal vasculature which results in a wound repair response and activation of the dermal fibroblasts. An inflammatory response within the dermis to the laser generated heat initiates a reaction that leads to collagen remodeling and an improvement in the appearance of the skin.

Cooling the skin surface during laser exposure is essential to protect the epidermis and superficial dermis from photo-thermal effects.

Laser beam interaction with material can introduce either thermal or wave effects but for dermatology, thermal effect is the dominant factor although wave aspects need more attention in this field. Not all lasers are useful to treat skin conditions or disorders, only those which have wavelengths that are absorbed efficiently in the targeted tissue are employed. It is not very clear to many users which laser is best for a specific case. Lasers can emit in a wide spectral range, and nowadays there are lasers emitting in the x-ray, ultraviolet, visible, near infrared (NIR), mid infrared (MIR) and far infrared (FIR) spectra. Each laser is specified by its mode of operation (pulsed or continuous), output energy, duration & repetition frequency for the pulse types and average output power for the continuous types. Emitted wavelength or wavelengths in the case of the tunable lasers, line width which defines the temporal coherency of the beam, spatial content which shows the way the beam's energy is distributed, plane of oscillation or polarization of the beam and the beam spot size are other important aspects that have to be selected carefully. Based on the principles of selective absorption, the recommended lasers for non-ablative resurfacing are those of wavelengths absorbed by hemoglobin, water, melanin and pigments. Therefore dye lasers emitting at 532 nm/585 nm/595 nm, semiconductor lasers emitting at 810 nm/1450 nm, Nd: YAG lasers emitting at 1064 nm/1320 nm and Er: Glass lasers emitting at 1540 nm are preferred. Green 532 nm and yellow 585 nm & 595 nm and to a lesser extent NIR 810 nm laser are strongly absorbed by hemoglobin and melanin. The heating effect in the dermis stimulates collagen remodeling and tightening. Non specific thermal injury initiates a wound repair response including fibroblasts activation and new collagen generation. The NIR 1064 nm has a very deep penetration into the skin and weak absorption by the melanin making it an ideal candidate for treating deep skin layers with little effect on the epidermal layer. For stronger absorption by water and much weaker absorption by melanin MIR 1330 nm, 1450 nm and 1540 nm lasers perform better than the 1064 nm.

II. Photomedicine

1. Introduction

Photomedicine includes both the study and treatment of diseases caused by exposure to light and the diagnostic and therapeutic applications of light for detecting and curing disease. Light energy causes heating, mechanical effects and chemical reactions. We need to answer the following questions:

- **Why do identical photons produce harmful medical effects (as in skin cancer), but helpful effects (as in vitamin D production)?**
- **Can we control the effects of the light energy in Photomedicine?**
- **What light sources are beneficial in Photomedicine?**
- **How do we maximize beneficial effects, while minimizing bad effects?**

2. Diseases Caused by Light

Sun light wavelength distribution and their intensities depend on latitude on the earth they inhabit, the time of day, and the season of the year. Sunlight is more intense near the equator, near to midday, and the near to midsummer. Short wavelengths dominate at midday and longer in morning and evening. Passing through the atmosphere selectively absorbs ultraviolet and blue wavelengths, leaving the red.

UV light is damaging to the skin. People who live nearer to the equator tend to have darker skins with more of the protective pigment called melanin. Skin diseases could be caused by chronic sun exposure.

The two dominant diseases caused by chronic sun exposure are photo aging (leathery wrinkled skin), and the induction of skin cancer (both the dangerous malignant melanoma and the less dangerous non-melanoma skin cancer). Harmful acute effects of sun exposure include sunburn and various photodermatoses.

The interaction of UV light with the skin causes a cellular damage and repair, pigmentation changes, vascular and immune suppression effects. The chemical reaction caused by the UV absorption results in the formation of several types of DNA lesions, including thymine-thymine dimers.

Few minutes of exposure each day over the years can cause noticeable changes to the skin. Freckles, age spots, spider veins on the face, rough and leathery skin, fine wrinkles, loose skin, actinic keratoses (thick wart-like, rough, reddish patches of skin), and skin cancer can all be traced to sun exposure.

Photo aging describes aging caused by sun exposure. Its level depends on: 1) person's skin color, and 2) his history of long-term or intense sun exposure. Fair skin people develop more photo aging signs than those with dark skin. Darkest skin signs are limited to fine wrinkles, and a mottled complexion. Photo aging occurs over a period of years.

Repeated UV exposure breaks down collagen and impairs the synthesis of new collagen. The sun also attacks our elastin. When unprotected from sun light, skin becomes loose, wrinkled, and leathery at early time. Deep wrinkles, age spots, and leathery skin indicate premature aging caused by years of unprotected exposure to the sun.

Using sunscreens and limiting sun exposure are two approaches for mitigating the chronic adverse effects of sun exposure. UV from sun light delivered to the skin increases the biosynthesis, i.e. the conversion of provitamin D3 to previtamin D3 which is then thermally converted to vitamin D3 in the skin, which is then transported to the liver on the vitamin D-binding protein.

3. Photo-protection

In order to mitigate the effects of UV damage to the skin received from the sun, modern practice is to encourage the use of sunscreens. Absorbers and reflectors of UV radiation are used. Antioxidants, such as vitamins E and C do not absorb or reflect UV radiation but enhance the ability of skin cells to repair damage induced by UV radiation. Effective sunscreen should protect against UVA (penetrate to deeper layers of the skin) and UVB (causes sunburn). Many sunscreens are a mixture of UVA and UVB-absorbing chemicals, or physical blocking agents such as zinc oxide.

4. Cancer diagnosis.

Optical diagnosis relies on the structural and biochemical differences between cancer tissue and normal tissue that can be probed with visible or NIR light. Exogenous substances that accumulate in tumor tissue can enhance the optical contrast between tumors and normal surrounding tissue.

Cancerous cells are more active and reproduce at an abnormally high rate. They have larger and more numerous nuclei. On the tissue level, tumors have immature collagen as well as a pronounced network of immature blood vessels (higher blood content).

Fluorescent dyes delineate tumor borders or detect otherwise invisible lesions. They are chemically attached to some targeting vehicle that recognizes specific molecules or markers expressed or over-expressed on tumors. Targeting vehicles include: peptide sequences (bind to tumor cell receptors), antibodies, vitamins such as folic acid, and certain sugars. Fluorescent dyes used for diagnosis should have low intrinsic toxicity, resist photo-bleaching, and absorb and emit in the INR spectrum; such as quantum dots, gold nano-shells, and oxygen sensitive phosphorescent dyes.

5. Phototherapy

Phototherapy involves the transformation of light energy to chemical, kinetic or heat energy in order to achieve a desired physiological result. Light energy must be absorbed by an atom or molecule of specific chromophore in order to initiate a physical or chemical process. Chromophore may be endogenous (naturally occurring in cells or tissue), or exogenous (added to cells or tissue for a therapeutic purpose), Table 1.

The absorbed energy by the tissue is largely converted to heat which is removed by the vascular system from the treated area over a period of time. If the heat builds up quickly, when using a large optical power, sections of the tissue may boil, vaporize burn or even explode. Same total amount of light applied very slowly allows heat dissipation by the vascular system leading to primarily photochemical reactions.

6. Laser Medicine

Dermatology

Absorption of green light produced by argon (488 nm), KTP (532 nm) or dye lasers (570 nm) by hemoglobin is the basis for treatment of vascular lesions. These comprise port wine stains, telangiectasia and varicose veins, etc. Visible and near-infrared lasers are also used for the removal of pigmented lesions such as lentigines نمش and mole شامة

Hair removal (photo-epilation):

Melanin is the primary chromophore for all hair removal lasers. It absorbs all wavelengths in the visible and NIR. There are two types of melanin in hair: eumelanin (gives hair brown or black color) and pheomelanin (gives hair blonde or red color). Because of the higher absorption of laser photons by eumelanin, black or brown hair is much easier to remove than blond hair. Laser works best with dark coarse hair and light skin, but new lasers are now able to target dark black hair even in patients with dark skin.

Tattoo removal.

Tattoo removal uses lasers that are "tuned" to the color of ink used in the tattoo. Pulsed laser fragment the tiny ink particles via photothermal expansion, and these tiny particles are removed from the skin by macrophage cells, that engulf them, and then migrate to draining lymph nodes, (Figure 5).

Wrinkles and resurfacing:

Ablative laser skin resurfacing is used to damage a large surface of skin with a CW CO_2 (10600 nm) laser to allow forming new epidermis. Although highly effective, it has a high risk of unwanted thermal damage and scarring. Short-pulse (~1 ms), high-peak power, rapidly scanned CW CO_2 (10600 nm) and normal mode Er: YAG (2940 nm) lasers provide the ability to accurately thermally ablate controlled layers of tissue.

Non-ablative rejuvenation uses Nd: YAG laser at 1320 nm with pulse duration of 200 microseconds and the diode laser at 1450 nm. The healing time is much shorter than ablative resurfacing.

Scar removal:

585 nm PDL lasers are standard for the treatment of hypertrophic scars and keloids Atrophic scars are treated with ablative CO_2 (10600 nm) and Er: YAG (2940 nm) lasers, but non-ablative and fractional laser procedures can be used.

Dentistry

Lasers are used by dentists to treat cold and canker sores gum disease, and tooth sensitivity or decay. Each wavelength has a unique effect on dental structures, due to the specific absorption of that laser energy in the tissue. Some lasers are only absorbed by blood and tissue pigments, while others are only absorbed by water as well as "hard" tissue. The temperature (as a result of laser light absorption) will rise. Non-sporulating bacteria are deactivated at temperatures of 50^{o}C. The inflammatory soft tissue in periodontal disease can be removed at 60 ^{o}C; moreover, homeostasis can also be achieved within the same heat parameters. Soft tissue excision or incision surgery is accomplished at 100 ^{o}C, where vaporization of intra- and extra cellular water causes ablation, or removal of biological tissue. The aqueous component of tooth structure and bone also boils at this temperature; thus cavity preparation, calculus removal, and osseous contouring can proceed.

Ophthalmology:

Lasers allow non-invasive treatment of diseases of the eye as well as vision correction. Vision correction utilizes an ultraviolet Excimer (193 nm) laser to reshape the cornea in a process known as laser-assisted *in situ* keratomileusis (LASIK). Near-infrared Nd-YAG lasers (1064 nm) or argon lasers (488 nm) are used to treat glaucoma by relieving intra-ocular pressure. Argon lasers (488 nm) are also used to treat abnormal retinal blood vessels that are common in diabetics, glaucoma, mild-to-moderate nearsightedness and astigmatism, and other conditions that impair sight. Macular degeneration can also be treated with lasers. Age-related macular degeneration (AMD) is a disease that results in a breakdown of the macula accompanied by a loss of central vision. "Wet" AMD is characterized by leaky blood vessels. Nd-YAG (1064 nm) laser photocoagulation is used to seal the blood vessels and restore vision.

Hair removal

1. Tweezing: for removing single hairs, but stimulates new hair growth and can create post inflammatory hyper pigmentation, and scarring (rarely).
2. Shaving: for large surface area but causes skin erosion, hyper-pigmentation and stimulates rapid re-growth of darker, thicker hair.
3. Waxing (hot or cold): Hair re-growth is slow, but painful, causes irritation, pigmentation, scarring, new hairs are darker and coarser.
4. Chemical depilatories: Employs strontium sulfide which dissolves the hair above the skin but causes irritation.
5. Electrolysis: Employs weak DC current → permanent hair follicle destruction in 15-80% of patients by forming free radical, toxic NaOH.
6. Electro-thermolysis: Uses AC current → direct thermal destruction of the hair follicle but slow, painful, with risk of scarring and pigmentation

Growth cycle of hairs consists of an Anagen (growth) phase, Catogen (transitional) phase, and Telogen (resting) phase. Anagen phase contains 85-90% of hair follicles and can last 2-3 years on the adult scalp. While some hair follicles are in anagen, others are in telogen or catogen. This requires multi hair-removal sessions for complete removal. Two main theories are concerning follicular regeneration:

- Dermal papilla is the crucial site for induction of new hair re-growth.
- Cells in the area of insertion of hair muscle are responsible for hair regeneration.

Hair destruction rests in bulge region (200 microns below the skin surface) or dermal papilla (2-5 mm deep).Melanin is present in the hair shaft, and in the dermal papilla.

The principle to for hair removal is selective photothermolysis. Melanin in hair absorbs laser pulses which destroy of hair shaft. To localize thermal effects, laser pulse duration ≈ thermal relaxation time. Much shorter laser pulses cause insufficient heating while much longer ones cause non-selective damage to surrounding dermis.

Before after

Hair growth is a cyclic process through 3phases: Anagen: is growing phase during which hair matrix cells are actively dividing and lengthening hair shaft. Catogen: is brief breakdown phase during which hair papilla retract towards area of plug. Telogen: resting stage begins when papilla reaches its final destination. When this phase ends, hair bulbs produce new hairs.

Laser systems

Choice of a laser system with appropriate parameters (energy fluence, spot size, wavelength, and pulse width) should be made with respect to patient's skin color (Fitzpatrick photo-types, hair density, type of hair, hair shaft diameter, hair color).Epidermal protection during laser treatment is essential. It can be achieved by using longer wavelengths, long ms pulses and use of cooling.

Laser hair re-growth

Hair loss is caused by heredity, diet, medications, postpartum & menopausal changes and stress. Lasers stimulate cell metabolism to repair them. It increases micro-circulation in hair follicles for nutrients and oxygenated blood access hair follicles, i.e., the stimulation of natural hair growth.

Before after

Laser treatment of wounds and burns

Clinical observations have suggested that lasers can stimulate wound and burn healing. The best conditions will be the one that heals at short time with no scar. The influence of laser radiation on the acceleration of skin burn healing at adequate wavelength, intensity, and dose can accelerate tissue repair. Polarized light can survive through long propagation distance in biological tissue. Skin wound repair depends on polarization orientation with respect to a referential axis as the animal's spinal column. In addition it will depend on wavelength, power, energy fluence and irradiation time.

III. Laser radiation hazards and control

1. Ionizing Radiation and Non-Ionizing Radiation

Ionisation is an electrical process in which an electron is knocked out of its orbit. Ionising radiation is radiation that is energetic and capable of causing atoms and molecules in its path to split into positive and negative ions. Ionising radiation include alpha, beta and gamma rays that are arisen by the decay of radioactive substances and X-ray that is produced electronically by X-ray machines. Alpha and beta are particulate radiation while gamma and X-rays are electromagnetic radiation of wavelengths from 100 nm to 10^{-5} nm. Alpha, beta & gamma rays are resulted from spontaneous re-arrangements within unstable nuclei but X-rays are produced by electrons jumping between orbits close to the nucleus or by electrons losing energy when passing through the strong electric field close to the nucleus. Unlike the radiation from radioactive sources, the X-rays can at anytime be "turned off" by merely disconnecting the high voltage. Alpha and beta are sub-atomic particles while gamma and X-rays are electromagnetic rays similar to light. These radiations differ in their penetration abilities as follows:-

- Alpha radiation is completely absorbed by a sheet of paper or a few centimetres of air,
- Beta radiation is completely absorbed by a few cm of wood, glass, water or several meters of air,
- Gamma & X-ray radiation are difficult to be absorbed completely, but their intensity can be reduced significantly by a few mms of lead, or a few cm of concrete or brick, for low energy radiation and by 10 or more cm of lead or a meter or so of concrete or brick for high energy radiation.

Non-ionising radiation refers to the radiation that the energy is not capable in causing ionisation but is capable in causing other injuries to the body. It includes the electromagnetic radiation and fields with wavelengths greater than 100 nm and acoustic radiation and fields with frequencies above 16 kHz. Examples are microwaves, ultraviolet, visible, infrared, laser and ultrasound radiation.

Non-ionizing radiation (μm)					**Ionizing radiation (μm)**
RF	MW	IR	Vis	UV	X& Gamma Rays
10^{10}	10^{7}	10^{3}	0.75	0.4 – 0.04	10^{-8}

Electromagnetic radiation is created by oscillating electric charges. The frequency of oscillation determines the kind of radiation that is emitted. Electromagnetic radiation can be considered as a stream of particles called photons. Each photon has associated with it an amount of energy hν, where h is Planck's constant (6.626×10^{-34} Joule.sec or 4.1357×10^{-15} eV. sec). The frequency of the wave motion can be used to calculate the energy of the emitted photon; thus, radiation has a dual wave-particle character.

	Region	**Type of Radiation**	**Frequency**	**Wavelength**	**Photon Energy**
Ionising Radiation	Ray Region	Gamma Rays	$> 10^{19}$ Hz	< 0.03 nm	> 40 keV
		X-rays	$3 \times 10^{15} - 10^{19}$ Hz	0.03 -100nm	12.4 - 40 keV
Non-Ionising Radiation	Optical Region	Ultraviolet	$0.75 - 1.67 \times 10^{15}$ Hz	100- 400 nm	3.1 - 6.9 eV
		Visible	$4.3 - 7.5 \times 10^{14}$ Hz	400 -700 nm	1.77 - 3.1 eV
		Infrared	$3 \times 10^{11} - 4.3 \times 10^{14}$ Hz	700 - 1 mm	0.00124-1.77 eV
	Wave Region	Microwave	300 - 300 GHz	1 - 1 m	$10^{-6} - 10^{-3}$ eV
		Radio-wave	< 300 MHz	> 1 m	$< 10^{-6}$ eV

The biological effect, due to the non-ionising electromagnetic Radiation, is very different from the effects due to the X-rays and gamma radiation. The effect mainly is thermal and it has no cumulative effect. However, with sufficient energy, the non-ionising radiation can cause injuries to the human body. For example, high power lasers can produce skin burn and eye injury, over exposure to UV radiation can cause skin cancer, exposure to extremely high intensity ultrasound can elevate the tissue temperature and create tiny bubbles of gas or cavities in the body.

2. Laser Radiation

a. Physical characteristics

The name **"LASER"** is an acronym for "Light Amplification by Stimulated Emission of Radiation". Light from a conventional light source radiates in all directions at various wavelengths that reinforce or cancel each other. Light from a laser travels in one direction in straight line and in a specific wavelength only; thus, the laser is a very narrow beam.

Laser radiation is released either as a pulse or a continuous wave. Typical power output ranges from 0.02 watt to 100,000 watts. With the aid of a "Q-switch" device, the laser pulse-width could be much shortened whereby producing extremely high power pulses.Laser beams are not limited to visible wavelengths only. Though a laser beam produces only one wavelength, laser units can be designed over a wide range of frequencies, from infrared to ultraviolet regions.

b. Laser Sources

Basically, a laser system consists of two accurately parallel reflecting end-plates between which the active lasing material is placed, one plate being slightly transparent. The active lasing material is pumped by exciting its atom or molecule to an excited state. A light wave is then emitted when an excited atom falls from the excited energy state to a lower energy state. Light waves emitted parallel to the axis of the active lasing material are reflected back and forth between the two end-plates and stimulate other atoms or molecules to emit light wave of the same frequency. When amplification is great enough, a laser beam would pass through the partially reflecting end plate.

There are four types of lasing systems

- i solid state, i.e. ruby crystal is most common,
- ii gaseous state, i.e. CO_2 and He-Ne are most common,
- iii semiconductor, GaAlAs gallium-arsenide junction is common,
- iv liquid state, organic dyes lasers.

c. Classification of Lasers

The hazard classification specified for laser is defined by the output parameters, i.e. emission wavelength, emission duration, power output, and accessible emission levels

(AELs) of laser radiation. The maximum accessible emission levels for various classes of lasers are specified in the Second Schedule to the No-Ionizing Radiation Protection Regulations 1991. The classes are:

Class 1 laser systems are safe by virtue of their power output or engineering design. These lasers cannot be considered as hazardous even if all of the accessible laser radiation output is to direct to the eye's pupil or focus into one mm spot on the skin for a day. These lasers are considered as non-risk lasers, or exempt lasers. The wavelengths could range from ultraviolet, visible to infrared region. Class I continuous visible laser should not have the accessible laser output of more than 0.39 microwatts.

Class 2 laser systems are those emitting visible laser radiations, in the wavelength range from 400 nm to 700 nm, in pulse or continuous wave. This is a class of low-power and low-risk lasers. These laser systems are normally not hazardous by virtue of normal aversion responses. They are not capable of causing any eye injury within the duration of a blink of 0.25 sec. For class 2 continuous visible laser devices, the power emitted should not exceed one mW, bar code scanner at the check out point in supermarket and laser pointer in class room are good examples for class 2 laser. Any low-risk laser devices, by virtue of enclosure, should have warning labels indicating "High-risk class when access panels are removed".

Class 3 laser systems are considered to be medium-power and moderate-risk laser. Generally, they do not present any diffuse reflection hazard, skin hazard for unintentional exposure, or fire hazard. These lasers could present a serious potential eye injury resulting from intra-beam viewing of the direct beam and specula reflections. Class 3 lasers can be further sub-divided into two subcategories, namely, class 3a and class 3b lasers.

Class 3a lasers are capable of emitting visible and/or invisible laser radiation with the maximum accessible emission levels as specified. As for visible Class 3a laser devices, they operate in a power range of 1 -5 mW, which have an irradiance in the emergent beam of not more than 25 W/m^2. This class of laser are not capable of damaging the eye because of the person's normal aversion response to bright light, unless the radiation is stared at for a long time, or unless binoculars or optical instruments are used. Many construction alignment laser falls into the class 3a category.

Class 3b lasers are medium-power and moderate-risk laser devices that are capable of emitting ultraviolet, visible or infrared laser radiation with specified maximum accessible emission levels. It can be in continuous wave or pulsed mode and operating in a power of 500 mW or less for emission duration of longer than 0.25s, or a radiant exposure of (100 kJ/m^2) or less for emission duration shorter than 0.25 sec. These lasers are capable of causing accidental injuries by exposure from the direct or a specularly reflected beam. Diffuse laser beam reflections from class 3b are not hazardous, but may be so if focused to the eye with optical instruments. Therapeutic laser, acupuncture laser, bio-stimulation lasers, military laser range finders and designator are **class 3b**.

Class 4 lasers are high-power and high-risk lasers that are capable of emitting ultraviolet, infrared or visible laser radiation at levels exceeding the accessible emission levels for class 3b. The average power output is 500 mW or greater for periods longer than 0.25s, or a radiant exposure of (100 kJ/m^2) within exposure duration of 0.25 sec or less. These lasers can produce a hazardous direct or a specularly reflected laser beam. A potential fire and skin burn hazard exist as the possibility of hazardous diffuse reflections occurs.

d. Laser applications

Forty three years after Einstein first introduced the concept of stimulated emission of radiation by atomic systems in 1917, the first working laser, ruby crystal laser, was produced in 1960. Few months later, the first He-Ne laser was then produced at Bell.

To date, more than forty years after the invention of the first ruby and He-Ne lasers, lasers have found their applications in medical and industrial fields.

i. Industrial

High power lasers are used in industrial cutting (300 - 1500 W), drilling, welding (500 - 600 W) and micro-machining. It has also been used to project a reference line for construction equipment (2 mW) in such operations as dredging, tunnelling, pipe laying and bridge building. Other industrial applications include trimming, marking, curing and entertainment laser light show.

Common high-power industrial lasers are,

- Industrial cutting
- Drilling, welding
- Marking
- Engraving
- Micro-machining
- Communications field
- Entertainment lasers

Other low-power industrial lasers are,

- Construction alignment lasers
- Dredging
- Tunnelling, pipe laying
- Bridge building
- Military applications

- Scanners for deciphering coded package markings
- Low power Entertainment laser

ii. Medical

Lasers that are manufactured for purpose of in vivo diagnostic, surgical, therapeutic laser irradiation of any part of human body are classified as medical lasers. Medical lasers are used in areas of plastic surgery, ophthalmic, physiotherapy, obstetrics and gynaecology. Photo-coagulator laser (1 - 3 W) is used by some surgeons to repair torn retinas. A limited beam laser has also been used to kill malignant tissue, remove birthmarks or burn away warts. Statistics, in 2007, show that there were 518 units of medical lasers and 779 medical laser users in Singapore. Out of these medical lasers, about 453 units were class 4 high power surgical lasers and they were being used by 692 medical practitioners and surgeons in various major hospitals and clinics. Acupuncture and cosmetic lasers are categorised as medical lasers.

High-power medical lasers are used in,

- Surgery
- Excision of malignant or non-malignant tissues
- Plastic surgery
- Removal of birthmarks
- Obstetrics and gynaecology
- Burning away warts
- Photo-coagulator for torn retinas by ophthalmologist

The low power medical lasers and they are,

- Acupuncture lasers
- Physiotherapy lasers
- Cosmetic lasers

ii. Research

Lasers are also used in Singapore for research and educational purposes. In 2007, there were about 362 researchers involved in using about 328 lasers for their projects. Most of the lasers are less than 5 W and they can be as high as 1000 W, i.e. class 4 CO_2.

e. Laser radiation hazards and its exposure limits

Ocular Exposure to Laser Radiation

Lasers can be hazardous due to its great brightness of beam. The main concern is with the eye damage, as it is capable of increasing the laser light intensity many thousands of times by its focusing power. Parallel rays of a laser may be focused to a point image by the eye while rays from a conventional lamp can produce a sizeable and less dangerous image at the retina. Light from a laser entering the eye is concentrated 100,000 times at the retina. Thus, the eye is the organ of the body most subject to damage.

Skin Exposure to Laser Radiation

Injury to skin is seldom of concern except in dealing with very high-powered lasers. But with ever increasing laser intensities encountered, skin damage is becoming a concern.

Exposure limits

The unit used to describe the radiation exposure from laser radiation is completely different from the units for ionising radiation exposure. The common units are Watts (W) or milliwatts (mW) for the power or W/m^2 or mW/cm^2 for the intensity. The exposure limits (ELS) should be used only as guidelines for controlling human exposure to laser radiation. They should not be regarded as thresholds of injury or as sharp demarcations between "safe" and "dangerous" exposure levels. Exposure at levels below the ELs should not result in adverse health effects. They incorporate the collective knowledge generated world-wide by scientific research and laser safety experience, and is based upon the best available published information. In 1985, International Non-ionising Radiation Committee (INIRC) of the International Radiation Protection Association (IRPA) published a set of guidelines on limits of exposure to laser radiation of wavelengths between 180 nm and 1 mm. They are used as for given wavelength ranges. ELs for the eye are always specified at a plane tangent to the cornea at the point of the optical axis of the eye. In addition to the exposure limits, all precautions must be observed during laser operation.

f. Safety guides against laser radiation

(a) Laser should be discharged in a non-reflective and fire-resistance surface.

(b) The area should be cleared of people for a reasonable distance of laser.

(c) Attach warning sign to laser equipment and around to indicate eye hazard.

(d) Looking into primary or specular laser beam should be avoided.

(e) Avoid aiming laser with eye and prevent looking along the axis of the beam.

(f) Work area needs high illuminations to constrict pupils and limit energy enter eyes.

(g) Operators should be aware of eye hazards and have periodic eye examinations.

(h) Safety eyewear designed to affords partial protection.

(i) Don’t uses binoculars or aiming telescopes to view direct or reflected beam.

At its maximum emission capacity, a high power laser should operate in such a manner that the intensity of laser radiation at all accessible locations, when measured within a stationary circular area of 0.385 cm^2 and averaged over that area does not exceed the following limits

- at time interval < 18 □sec ➔ integrated irradiance of 5.0×10^{-3} J/m^2
- at time interval > 18 □sec but ≤ 10 sec ➔ an integrated irradiance of $18\ t^{0.75}$ J/m^2
- at any time > 10 sec but ≤10,000 sec ➔ an integrated irradiance of 100 J/m^2
- at any time interval > 10,000 sec ➔an irradiance of 10 mW/m^2

Since high power lasers are capable of cutting and burning, certain form of control in operating these lasers is required. Only the trained and qualified persons are allowed to use the high power lasers in most of the advanced countries. As for the use of low power lasers, it can also cause injury to the eyes if they are handled and used incorrectly by untrained personnel; restrict its users to trained personnel only.

3. Laser - Optical Fiber Communications

1. Introduction

Fiber optic communication systems have become the backbone of the long distance communications network with their ability to carry data at rates of several Gbits/s. The high bandwidth capability of the fiberoptic systems makes it possible to offer the variety of services we typically associate with information superhighway. Cables consisting of several strands of fibers, each of diameters in the range of a few hundred microns, have been laid across the United States and other countries. The cables are also laid on the bottom floor, completing the network linking several continents, making it possible transmit information instantly from one end of the world to the other.

Information transmission is not the only area in which optical fibers have found a unique place. Optical fibers are also used as sensors to detect and measure various physical, chemical, biochemical and biomedical parameters of interest. These parameters include: pressure, temperature, presence and absence of certain chemicals/biochemicals. The inert nature of the optical fiber allows it possible for use in environments having strong electrical fields, making it an ideal choice within fighter planes, power plants etc. to monitor what is going on. We will, however, limit ourselves to the understanding of optical fibers in communications.

Light modulation is employed to carry the information we want to send. Varying one of the following parameters; associated with the carrier wave, is needed to enable information to be carried:

- Amplitude
- Intensity
- Frequency
- Phase
- Polarization

These parameters can all, in principle, be used but since light detectors respond to intensity, therefore, intensity modulation is most popular.

In analog modulation, the primary signal (time varying electric voltage) continuously varies light intensity. In digital modulation, on the other hand, the signal amplitude is "sampled" at regular intervals, and information is sent by means of series of pulses. Timing and width of pulses are fixed but their amplitudes can take "0" or "1"

"1" is when the voltage level> predetermined value, and

"0" is when the voltage level< predetermined value.

To reproduce the signal, the sampling rate of the signal must be twice that of the highest frequency component in the signal.

Example: In telephone alls, the highest frequency is 4 KHz. When sampling an 8-bit number, the bit rate must equal to 2x8-bitx4KHz = $64KBs^{-1}$. Practically, the frequency band-width required to transmit a bit rate B is:

$$\Delta f = B/2$$

1.1 Light Propagation in Optical Fibers

An optical fiber is a cylindrical structure made up of pure silica. As light is launched into the fiber, the light is confined to the fiber by virtue of the phenomenon of Total Internal Reflection (TIR). To understand TIR, we need to look at the transmission of light through materials having different refractive indices. The refractive index determines the speed of the wave inside the material. The speed of light **v** inside any material is given by the following expression,

$$v = \frac{c}{n} \qquad (1)$$

Where **c** is the velocity of light in free space (3×10^8 m/s) and **n** is the refractive index. We can now explain the phenomenon of total internal reflection using Figure 1. In Figure 1a, a ray of light is going from a medium of lower index (**rarer**) to one of a higher index (**denser**). As the ray enters the second medium it moves **towards** the normal (the dotted line). In Figure 1b, light goes from a higher index to a lower index and the light moves **away** from the normal. As the angle of incidence θ_i is increased and becomes equal to θ_c, the light in the second medium grazes the interface (Figure 1c). We now have total internal reflection if the angle of incidence goes above θ_c, known as the critical angle. All the light now stays in the medium of higher index.

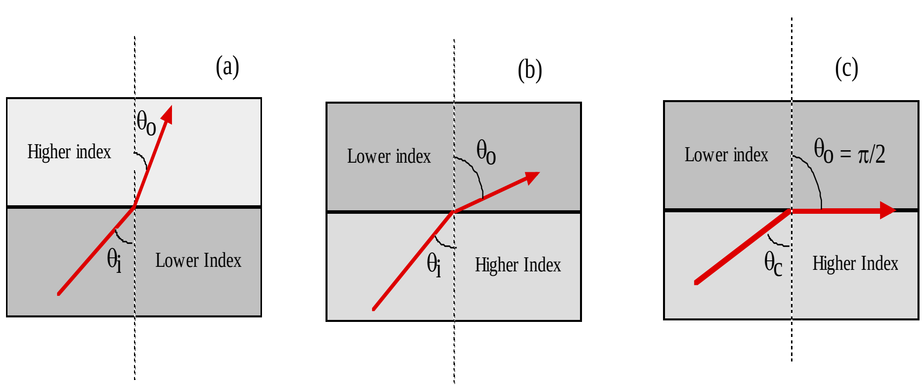


Figure 1 Reflection at an interface (a) Lower index to higher index (b) Higher index to lower index (c) Higher index to lower index at critical angle θ_c.

Condition of TIR allows light to be guided. To understand this, consider a simple experiment as shown in Figure 2. A beaker full of water has a glass tube on the right through which water can flow out freely. A beam of laser light is allowed to enter from the left as shown. If the water is now allowed to flow out, the water will appear red as it flows freely out of the tube. The higher index water (1.33) surrounded by lower index air (1.0) creates TIR conditions, and the light that was present in the beaker is now provided guiding conditions as it comes out because of water being surrounded by air.

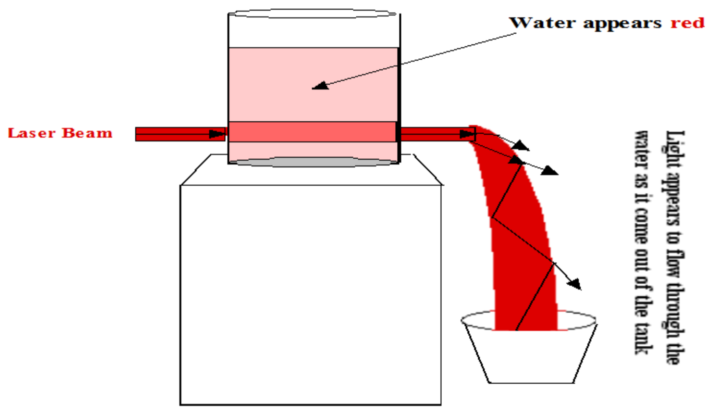


Figure 2: Concept of Total Internal reflection

The conditions of total internal reflection in optical fibers are created by having the fiber with an inner core of high index silica glass surrounded by silica glass of slightly lower index. A number of ways exist for the creation of the required index difference between the core and cladding. Thus there are a number of index profiles that are used in the fabrication of fibers. Some of these are shown in Figure 3.

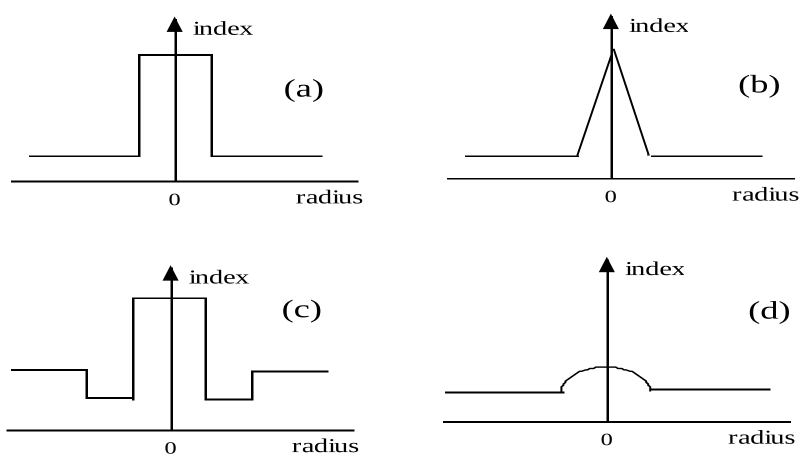


Figure 3: Index profiles: (a) Step Index (b) Triangular (c) W-type (d) Graded Index

The structure of step-indexed fiber is shown in Figure 3a. The index of the core is n_c and index of the cladding is n_{cl}. Note that air has refractive index of unity, water has a refractive of 1.33, and ordinary glass has a refractive index of around 1.45. A cut out of the fiber is shown in Figure 4. Thus, if we have an inner cylinder (core) made up of a higher index, surrounded by material (cladding) of lower index, total internal reflection conditions can be met. Indeed, the material, Silica, is used for the core and cladding. By doping the core with a small percentage of Germanium, the index of the core region can be increased by about 10^{-3} to 10^{-4} above the cladding index (~1.456). We now have three physical parameters that characterize the fiber, the radius of the core (a), the index of the core (n_c), and the index of the cladding (n_{cl}). We will normally assume that the cladding is infinitely thick.

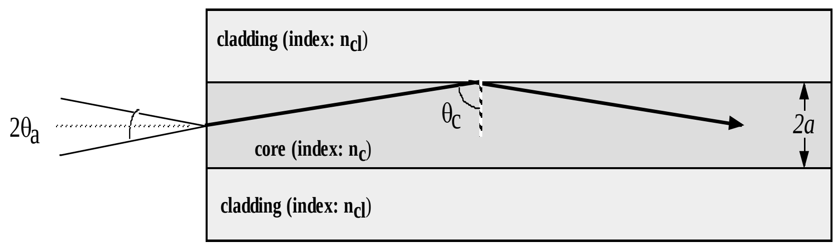


Figure 4: Critical angle at interface of core/cladding is □c.

This determines the maximum angle (□a) for accepting light into the fiber. Light beyond the cone of 2□a will be lost. The acceptance angle θ_a is determined by the indices of the core and cladding and is given by

$$\theta_a = \sqrt{n_c^2 - n_{cl}^2}\ rad\ . \qquad (2)$$

The acceptance angle expressed in radians is also known as the **Numerical Aperture** (NA) of the fiber. Higher values of numerical apertures point to better light gathering capacity of the fibers. Note that NA does not depend on the radius of the fiber. The coupling efficiency of light into fiber core is given as:

ή = $(NA)^2 . A_{core}/A_{light}$

Where; A_{core}/A_{light} are the cross-sectional areas of fiber core and light beam respectively.

Example: A fiber has a core index of 1.458 and a cladding index of 1.451. What is the numerical aperture? Work out the coupling efficiency when 850 nm LED light is incident on the core if the core cross-sectional area is one half of that of the laser beam.

Answer: Acceptance angle $= \sqrt{1.458^2 - 1.451^2} = 0.1427\, rad\ or\ 8\ deg$.

ή = $(NA)^2 . A_{core}/A_{light} = (0.1427)^2 \times 0.5 = 1\%$

1.2 Modes in Fibers

An optical mode refers to a particular solution to the equation governing the propagation of light inside the fiber, subject to the boundary conditions existing from the physical properties of the fiber such as the core diameter, index of the core, index of the cladding and the operating wavelength. The mode has the property that its spatial distribution does not change with length or distance. The only effect of propagation is a change in the instantaneous phase or a change in amplitude induced due to losses. No change in shape of the spatial distribution (i.e., in a direction at right angle to the propagation) takes place. A fiber can support many modes. We can also fabricate a fiber that only supports a single mode. Such a fiber is known as single mode fiber. If we take a multimode fiber and reduce the radius of the fiber, the number of modes supported in the fiber goes down, and, it is possible to reach a point when only a single mode can be supported. Before we look at the simple equations governing the number of modes supported by the fiber, let us try to understand the concept of modes using a simple analogy of a 'highly flexible vertical rod' in a long box. Let us look at Figure 5. If the box is small in height (box aa), then the rod that can be fitted in the box can only take one possible shape (mode 1). If we increase the height now to bb, it can fit mode 1 and another shape (mode 2). For the box of height cc, the rod can also take another shape (mode 3). Thus, the transverse dimensions determine how many different 'shapes' can be present in the box. These shapes can be identified as the modes in an optical waveguide.

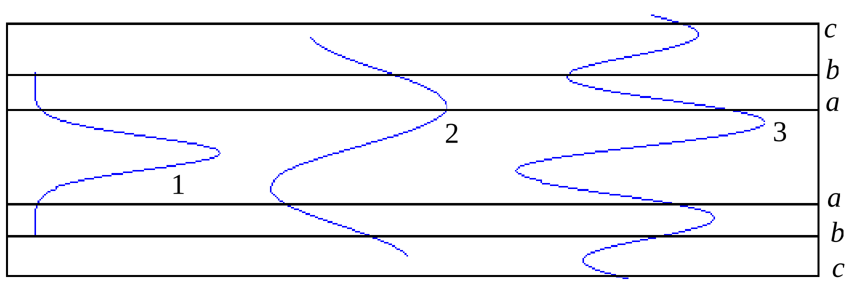


Figure 5: Concept of modes

The number of modes and their shapes will be determined by the cross sectional geometry of the fiber. The parameter that determines whether a fiber is single mode or multimode is referred to as the V parameter of the fiber given by

$$V = \frac{2\pi}{\lambda} a \sqrt{n_c^2 - n_{cl}^2}\ . \qquad (3)$$

Making an approximation that the indices are very close,

$$V = \frac{2\pi}{\lambda} a\, n_c \sqrt{2\Delta}\ , \qquad (4)$$

Where Δ is the index difference defined as

$$\Delta = \frac{n_c^2 - n_{cl}^2}{2n_c}. \qquad (5)$$

If the V value is less than 2.405, the fiber is considered to be a single mode fiber. The number of modes, N, supported in a step index fiber is given by

$$N = \frac{V^2}{2}. \qquad (6)$$

It might appear that for V=2.405, N~2. This is **not** a mistake. It simply reflects the fact that the single mode contains two polarizations, which are indistinguishable from each other because of circular symmetry of the optical fiber. In other words, a single mode fiber contains two modes that are together and cannot be separated. One way to separate them is to use an elliptical fiber. An elliptical fiber cross section is shown Figure 5 which has the capability of separating the two modes of a single mode fiber. These fibers are also known as polarization preserving single mode fibers. Such fibers are used in coherent fiber communications and in fiber sensors.

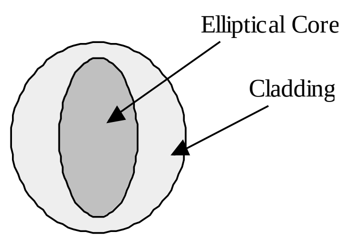


Figure 5: A typical elliptical fiber cross section. It allows the LP01 modes to become two separate modes, LP_{01}^{x} and LP_{01}^{y}.

A few modes of an optical fiber are shown in Figure 6. As the mode order increases, the patterns become more and more complex. The lowest order mode has almost a Gaussian field pattern as shown in Figure 7.

The pattern of the lowest order shows a 'guided' part of the mode inside the core and an 'evanescent' part in the cladding which has an exponential decay in the radial direction. The lowest order mode intensity profile can be approximated to a Gaussian pattern. As the V –value increases, the fundamental mode becomes 'tighter and tighter' and all most all the power in the lowest order power stays within the core. In the case of a single mode fiber of a step index fiber (V<2.405), about 85% of the power travels through the core and the rest travels through the cladding.

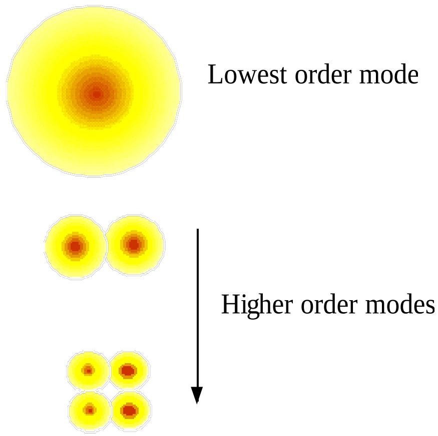


Figure 6 Modes in an optical fiber

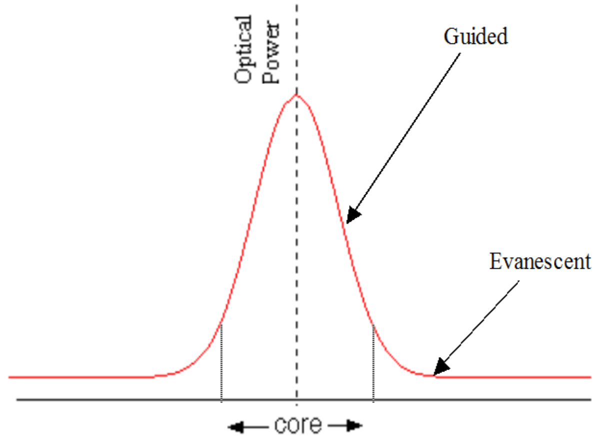


Figure 7 Intensity (power) profile of the fundamental mode

Example:

A step index fiber has a core radius of 8 microns. The core and cladding indices are 1.458 and 1.44 respectively. What is the V value of the fiber if the operating wavelength is 1300 nm? How many modes will be supported in the fiber? For a single mode fiber operating at 1500nm, with the indices as given, what must be the radius of the fiber?

Answer: $V = 2\pi \frac{a}{\lambda}\sqrt{\left(n_c^2 - n_{cl}^2\right)}$= 8.83.

Number of modes supported $N = \frac{V^2}{2} = 39$.

For single mode operation V=2. 405

$$a = \frac{2.405\lambda}{2\pi\sqrt{\left(n_c^2 - n_{cl}^2\right)}} = 2.5\mu\text{m}.$$

The fiber should not have a radius > 2.5 μm for single mode operation at 1500 nm.

1.3 Power Loss in Fibers

As the light travels through the fiber, power is attenuated because of scattering and absorption. These two phenomena are wavelength dependent, resulting in strong attenuation peaks around 1250 nm and 1400 nm. These peaks arise from the presence of water (OH) content during the fabrication. Minimum attenuation is around 1300 nm and 1500 nm. Most of the fiber communication systems operate around these two wavelengths. The attenuation is around (0.22 dB/Km) in the 1500 nm region and about (0.5 dB/Km) in the 1300 nm. The attenuation characteristics are shown in Figure 8.

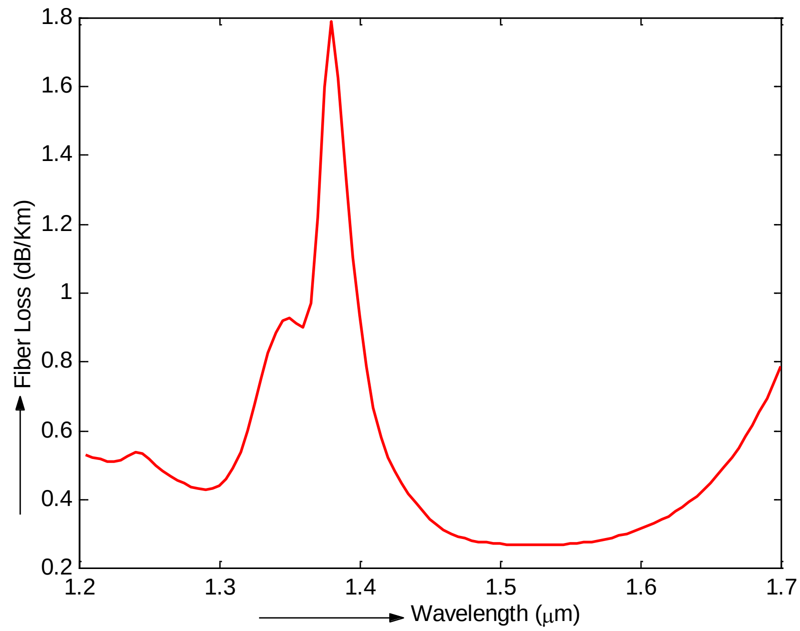


Figure 8: Power losses in optical fibers; showing 2 low-loss regions at 1.3µm and 1.5µm**.**

1.4 Dispersion in Fibers

One of the major limitations of fiber communication systems is the pulse broadening introduced by dispersion. Dispersion is present in both single mode and multimode fibers.

If a fiber is multimode, it supports a number of modes. Each of these modes will travel down the fiber at different speeds, resulting in a significant difference in times of arrival of the modes at the output end. Consider now the launch of a single pulse of light as shown in Figure 9. As soon as the pulse enters the fiber, replicas of the pulse will be created corresponding to each of the modes. Since these replicas will arrive at the receiver at different times, the resultant pulse will be broader (dark line envelope of the replicas at the output). The broadening of the pulse is the result of differential time delays and is said to come from the multimode dispersion in the fiber.

The dispersion in multimode fibers limits the data rate of transmission. As the transmission distance increases, two adjoining pulses transmitted through the fiber broaden and it becomes difficult to separate the pulses.

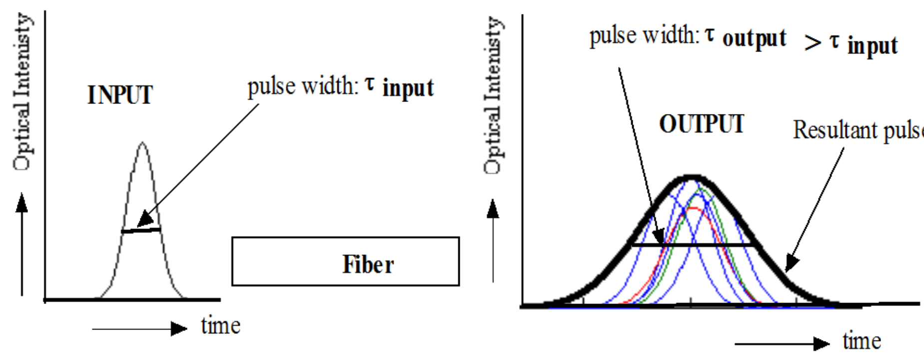


Figure 9 Pulse broadening in fibers is shown. The output pulse is an envelope of all the replicas and is thus, broader than the input pulse.

For a multimode fiber, the upper limit of the distance-bit-rate product BL is given by

$$BL < \frac{8c}{n_c \Delta^2} \text{ Bits/s.Km} \tag{7}$$

Dispersion also is present in single mode fibers. The primary cause of dispersion in single mode fiber is the dispersive nature of the refractive index of glass. A material is considered to be dispersive if the speed depends on the wavelength. The refractive index of glass indeed is a function of wavelength, i.e., $n \equiv n(\lambda)$. Since all the optical sources have a finite spectral width, the dispersive nature of the index in conjunction with the finite spectral width of the source leads to dispersion in single mode fibers. We can go back to Figure and visualize that each of the replicas of the pulses now correspond to the individual wavelengths that constitute the spectrum of the source, the output pulse will certainly be broadened. The pulse broadening in single mode fibers will be much smaller than the corresponding value in multimode fibers.

There are two components to the dispersion in single mode fibers. One is the material dispersion, determined purely by the material properties. The other one, waveguide dispersion is dependent on the waveguide parameters such as the V-value, the index profile and the core diameter. This also means that while material dispersion remains a constant for a given material, the waveguide dispersion can be tailored by the choice of an appropriate index profile and diameter. The material and waveguide dispersion are interdependent. The total dispersion is the sum of these two and is shown in Figure along with the material and waveguide dispersion. The point at which the dispersion value is zero gives the operating wavelength for minimum dispersion. If the waveguide dispersion is not tailored, the fiber operated around this wavelength is referred to as a zero dispersion fiber (typically around 1300 nm). If the waveguide dispersion is tailored, the zero dispersion point can be moved and fibers operated at such a wavelength is identified as dispersion shifted fiber (around 1500 nm). By having negligible dispersion around a band wavelengths we can have a dispersion flattened fiber (around 1500 nm). The dispersion characteristics of a typical single mode fiber are shown in Figure 10 and Figure 11. The unit of dispersion (D) is $ps/nm^{-1}.Km^{-1}$. Figure 10 shows the two components of the dispersion in single mode fibers. Since they are interdependent, the total dispersion in single mode fibers is given by

$$\delta\tau_{total} = \delta\tau_{mat} + \delta\tau_{waveguide}. \qquad (8)$$

If we have a multimode fiber, the total dispersion in a multimode fiber sill be given by

$$\Delta\tau_{total} = \sqrt{\delta\tau_{total}^2 + \delta\tau_{mod\,al}^2}, \qquad (9)$$

Where; the first term is the contribution from the material and waveguide dispersion, while the second term is arising from the multi-modes.

Material dispersion, also called group velocity dispersion, (D) is given as:

$D = (\lambda/c).(d^2n/d\,\lambda^2)$

Time pulse spreading $\Delta\tau$ is:

$\Delta\tau = L.\ (\lambda/c).(d^2n/d\,\lambda^2).\Delta\lambda$

Where; $\Delta\lambda$ is the spectral width of the laser line used.

Example: Pulse spreading in a dispersive wave-guide

60 nm spectral width LED drives a 10 Km single mode fiber and has a material dispersion = ($-100\ ps/Km^{-1}nm^{-1}$) for the wavelength centered at (λ = 800 nm).

a. If the LED is pulsed on and off in 5 ns, work out the pulse length when it arrives at the end of the waveguide.
b. What is the maximum practical pulse rate for this system, if the received pulses are to be distinguishable from one another?

Solution:

a. For single mode fiber, there will be no modal dispersion. The 5 ns pulse contains a wavelength spread of ± nm about the center of 800 nm. The group velocity pulse spreading will be:

$\Delta\tau = L.\ (\lambda/c).(d^2n/d\,\lambda^2).\Delta\lambda$

$= (10\ Km).\ (-100\ ps/Km^{-1}nm^{-1}).(60\ nm)$

$= -60\ ns$

Since we are dealing with a relative change between the two frequency extremes of the pulse, the negative sign means nothing. The pulse has increased its time width by 60 ns.

b. The maximum pulse rate is determined by the condition that the subsequent pulses do not overlap each other at the end of the optical fiber. In this case we would want to delay 60 ns before sending a second pulse. Therefore the maximum pulse rate would be 1 pulse every 60 ns or $\approx 17 \times 10^6$ pulses per second.

Figure 11 compares the dispersion characteristics of the three single mode fiber types. The dispersion flattened fiber has very low dispersion over a broad range of wavelengths. These fibers will find applications in wavelength division multiplex fiberoptic systems. The 'nm' (nanometer) refers to the spectral width of the source and the 'Km' refers to the transmission distance in kilometers. The pulse broadening is given by

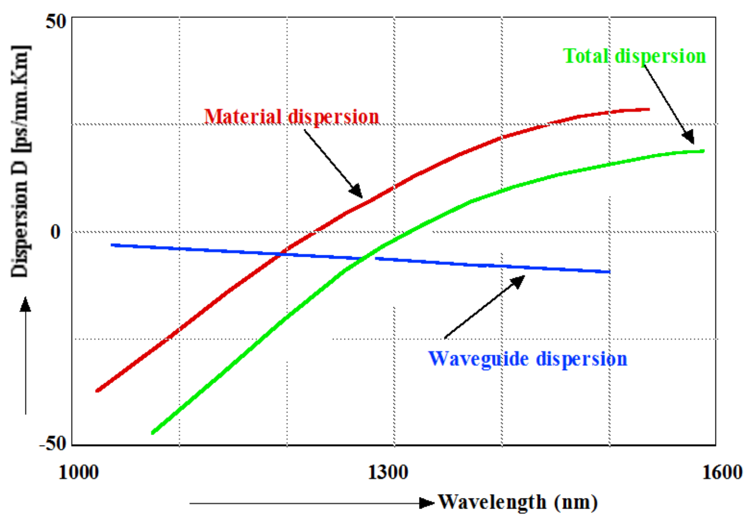


Figure 10: Material and waveguide dispersion with total dispersion is the sum of the two.

Dispersion limits the ability to transmit data at high rates over long distances. As the data rate-distance product increases, we will be dealing with a weaker signal as the transmission distance increases. We also will be facing increased dispersion leading overlapping of the adjoining bits resulting in inter-symbol interference as shown in Figure 11. The ISI will increase the likelihood of errors in the detection of 0's and 1's. The weaker signal also increases the likelihood of increased errors because the signal-to-noise ratio may fall below the threshold value required for acceptable performance. This means that the optical signal needs to be detected, pulses reshaped, and retransmitted. This is accomplished by using a repeater. Repeater is a receiver/transmitter combination. Before we look at a repeater

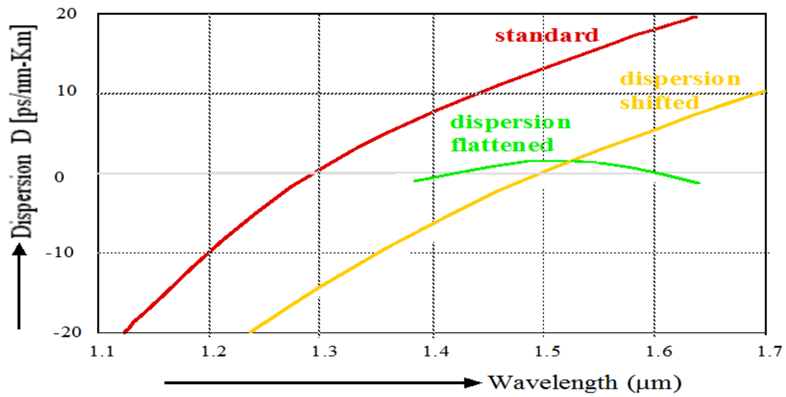


Figure 11 Dispersion in single mode fibers

Figure 12 shows the problems arising out of dispersion. As the pulses travel down the fiber, they broaden and start overlapping. It becomes difficult to separate the two adjoining pulses, increasing the error at the receiver. Reducing the data-rate-distance product will help alleviate the problem. However, this reduces our ability to transmit data at higher rates over long distances. Repeater or a soliton based communication system can overcome the limitations imposed by dispersion.

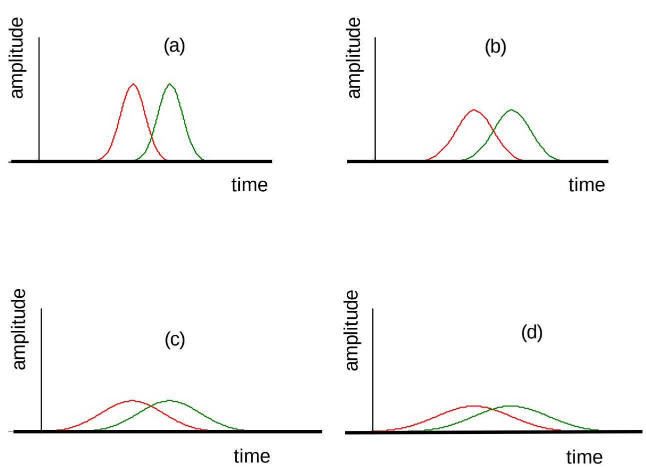


Figure 12: Injected pulses into the fiber broaden when transmit the fiber: (a) closest to the input end, (b) away from the input end, (c) further away, (d) farthest from the input end.

1.5 Data Transmission

Fiber optic communication systems allow us to transmit data at rates higher than coaxial or microwave systems. The ability of traditional fiberoptic communication systems has been extended multifold using soliton based systems. A standard fiberoptic communication system is shown in Figure 14. It consists of a source (typically a laser diode) that can be directly modulated in accordance with the data to be transmitted, fiber, and photodiode which demodulates and converts the data back to electrical/electronic form. The laser diodes are modulated directly by applying the data signals to the bias circuit of the laser diode. When the signal strength becomes weak and pulses broaden, there is a need to amplify the signals, 'put the pulses back in shape' or equalize and retransmit. This is accomplished using a repeater as shown in Figure 13b. A repeater is of regenerative type, it detects the signal, generates the electrical pulses, equalizes them to correct for the pulses distorted from dispersion. These amplified and equalized pulses are applied to the laser diode (transmitter).

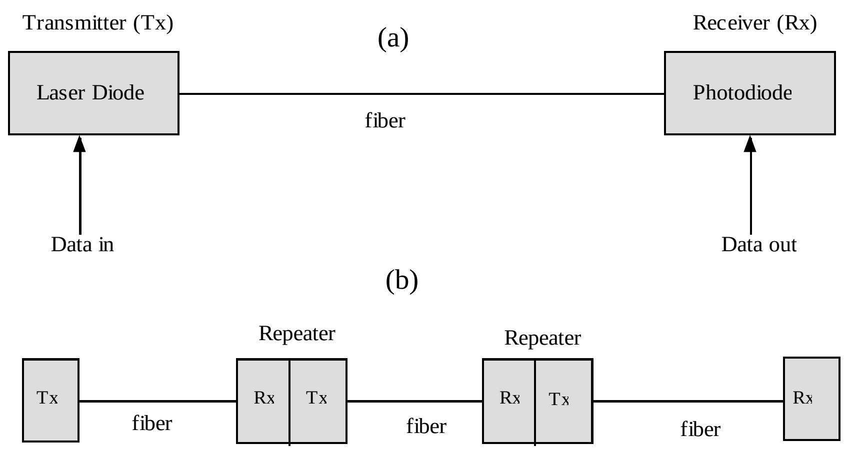


Figure 14: (a) A generic fiber optic communication system (b) A long distance fiber optic communication system showing repeaters

The laser diodes must have very narrow spectral widths to reduce dispersion, since the dispersion goes up with the spectral width of the source. A few typical laser diode intensity profiles are shown in Figure 15.

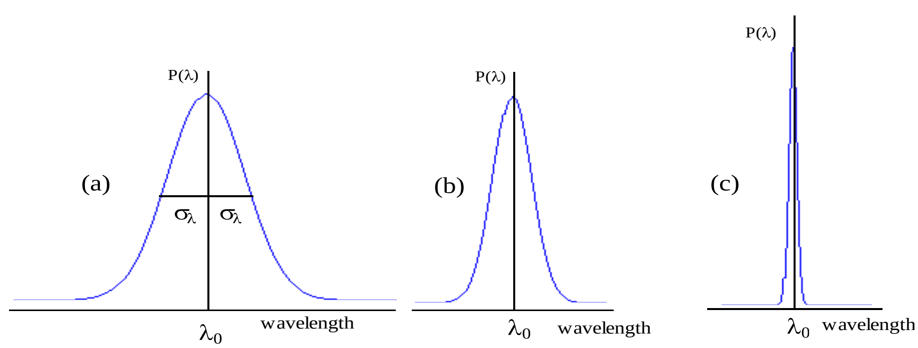


Figure 15: Intensity (power) profiles of three different types of lasers

$$P(\lambda) = \frac{1}{\sqrt{2\pi\sigma_\lambda^2}} exp^{-\left(\frac{\lambda-\lambda_0}{\sigma_\lambda\sqrt{2}}\right)^2}$$

λ_0 is the mean wavelength and σ_λ is the standard deviation. (a) Low data rate modulation, (b) Higher data rate modulation (c) Highest data rate modulation

As the spectral width of the sources goes down, the modulation capability of the source goes up. Spectral widths of the sources can be as small as 10^{-7} nm, allowing the operation at very high data rates. It is also possible to modulate the laser beam indirectly. Low spectral widths alone would not assure higher data rate capabilities. Fibers must have **low attenuation** and **low dispersion** at the operating wavelength. The photodiode must be able to have sufficient sensitivity at the operating wavelength. The first undersea fiberoptic systems became operational (1988) is the TAT-8 (Transatlantic) system. It connects United States with Europe. The data rate was 280 Mbits/s with a repeater spacing of about 50 Km. Repeater used here were of the regenerative type operating at 1300 nm wavelength. Significant improvements in the performance of the fiberoptic systems were realized after using coherent fiber systems.