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Laser Machining

Theory and Practice

With 164 Illustrations



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2 Lasers for Machining

The laser is clearly the most critical component of any laser machining system. This chapter provides an overview of the operation of the various types of lasers used in machining. First, the basic mechanisms required to produce laser light, such as stimulation, amplification, and population inversion are explained. The unique properties of laser light, including monochromaticity, coherence, diffraction, and radiance are also described. Lasers can be classified by the type of lasing medium used: solid, liquid or gas. The beam each type of laser produces has a characteristic wavelength and power range. The most common types of lasers used for machining are CO₂, Nd:YAG, and excimer lasers. Possible configurations for these three laser types are detailed.

2.1 Lasers and Light: A Historical Perspective

Any discussion of lasers and laser light must begin with an introduction to ordinary light. In 1704, Newton characterized light as a stream of particles because of its tendency to travel in a straight line [7]. However, he also recognized that light possessed certain wavelike properties. Nevertheless, Newton's description of light as a stream of particles was accepted for the next century. Early in the nineteenth century, new evidence again showed that light had wavelike properties. In 1803, an experiment by Young, a London physician, provided conclusive evidence. Monochromatic light was passed through two pinholes, resulting in an interference pattern resembling waves in water or pulses of sound. Concurrently, Fresnel and Arago correctly interpreted an experiment by Huygens, who had shown early in the seventeenth century that light transmitted through calcite crystals was polarized, convincing him that light was composed of waves. Fresnel and Arago re-examined this experiment and explained that light waves were transverse waves oscillating perpendicularly to the direction of propagation and were not longitudinal waves, as Huygens had postulated.

The discovery of polarity complimented the electromagnetic theory proposed by Maxwell, who described light as rapid variations in the electromagnetic field due to the oscillation of charged particles [7]. Thus, light was classified as merely one form of the radiant energy which ranged in form from radio waves to X rays; these forms were all phenomena relating to electromagnetism.

The interpretation of light as wavelike was challenged with the advances of physics in the twentieth century. In 1900, Planck began an investigation of emissions from hot bodies [7]. According to electromagnetic theory, the intensity of emissions at a particular frequency should be proportional to the square of the emitted frequency. This would mean that an almost infinite amount of energy would be radiated at higher frequencies; however, markedly different results were obtained in actual experimentation. Planck

derived an empirical formula to explain the relationship between intensity and the frequency of the emitted radiation; he reasoned that light must exchange energy with matter in quanta or “packets”. His equation showed that the energy of each packet was related to the frequency of the light by a constant ($h = 6.63 \times 10^{-34}$ joule-sec), a fundamental constant of nature now known as *Planck’s constant*.

In 1905, Einstein further extended the quantum concept of light. He noted that electromagnetic theory failed to explain the photoelectric effect, in which negatively charged metal plates lost their charge when exposed to radiation of sufficient energy [7]. The electrons in the metal absorbed radiant energy and attained enough excitation to leave the plate. If the energy of a light wave were distributed over its entire length, an amplitude of radiation, which would be below the threshold energy level for ejecting an electron, should have existed, and the metal would have required a period of exposure to ‘charge up’ before emitting any electrons. However, no such amplitude or delay was detected, and Einstein maintained that the quantization of light was the only possible explanation.

Light, then, possesses certain wavelike properties, such as polarization and interference, but it can also behave as if composed of individual particles, called photons, which possess a discrete amount of energy or quanta. In the 1920’s, an understanding of these phenomena was first developed, and the field of *quantum mechanics* was formed. This theory describes light as composed of particles which do not obey deterministic laws of motion, as in classical mechanics. Thus, the motion of a particle in a known force field cannot be determined exactly, but rather its wavelike behavior is an expression of the probabilities that govern its motion. This can be dramatically demonstrated by an interference experiment where a single photon is in motion on the pickup screen. The pattern of the first photons appears to be random, but with long exposures, the expected interference pattern develops.

Although special in many ways, laser light does comply with the basic laws of quantum mechanics and exhibits both wavelike and particle-like properties. LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. Laser light differs from ordinary light in that *it consists of photons that are all at the same frequency and phase (coherence)*. A laser’s ability to produce *coherent* light is based upon the principle that photons of light can stimulate the electrons of atoms so they emit photons of the exact same frequency [17]. This occurs when a photon passes close to the electron, and can be explained using quantum mechanics. The possibility of stimulation was first postulated by Einstein in 1917, but the first working laser was not built until almost half a century later.

2.2 Basic Mechanisms in Lasers

Since the central component of any laser machining system is the laser itself, it is necessary to understand the mechanisms which cause laser light when discussing laser machining. Lasers convert electrical energy into a high energy density beam of light through *stimulation* and *amplification* [17]. *Stimulation* (Fig. 2.1) occurs when electrons in the lasing medium are excited by an external source such as an electrical arc or flash lamp, resulting in the emission of photons [3, 15]. The energy required to raise an electron from one energy state to another is provided by an excitation process, or *pumping*. This is achieved by the lasing medium's absorption of energy from mechanical, chemical, electrical, or light sources. The rate of power input to the excitation process must exceed the output power of the laser, since there are many losses associated with the lasing process. The lasing medium typically contains ions, atoms, or molecules whose electrons are conducive to changes in energy level. According to quantum mechanics, atoms or molecules in the lasing medium have discrete electron energy levels. Laser light is created by the transition from a higher to a lower energy level, and the wavelength produced is a characteristic of the lasing medium. At the beginning of the lasing process, photon emissions are random in nature. As each photon stimulates other excited electrons to emit photons, however, the new photons will have similar wavelength, direction, and phase characteristics as the initial photon. Eventually, a stream of photons with identical wavelength, direction, and phase will be produced.

The *amplification* of light in a laser is accomplished by an optical resonator, which is composed of a cavity with the lasing medium set between two high-precision, aligned mirrors [3, 15]. One mirror is fully reflective, and the other is partially transmissive to allow for the beam output. The mirrors channel the light back into the lasing medium; as the photons pass back and forth through the lasing medium, they stimulate more and more emissions. Photons that are not aligned with the resonator are not redirected by the mirrors to stimulate more emissions, so that the cavity will only amplify those photons with the proper orientation, and a coherent beam develops quickly (Fig. 2.2).

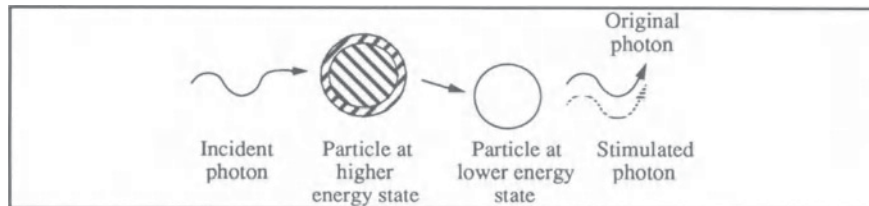


FIGURE 2.1 Stimulation

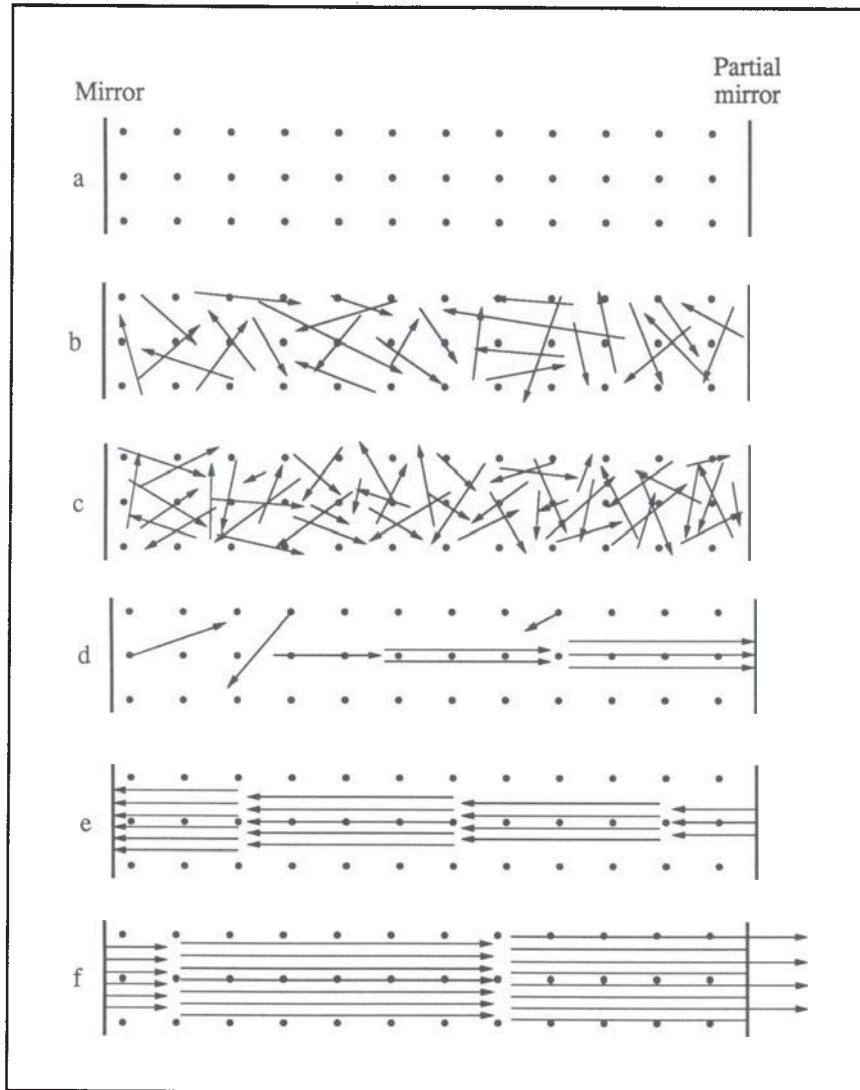


FIGURE 2.2 Amplification States (a) Laser Off, (b) and (c) Initial Random States, (d) Initial Stimulation, (e) Amplification and (f) Coherent Beam

Population inversion [15] is another necessary condition for the lasing process (Fig. 2.3). When the lasing medium or lasant is in equilibrium, the population of electrons at any energy state is determined by the Boltzmann equation. For a medium with two energy states, the relationship between energy and electron population is:

$$\frac{N_2}{N_1} = \exp - \left(\frac{E_2 - E_1}{kT} \right) \quad (2-1)$$

where N_1 and N_2 are the number of electrons at Energy States 1 and 2 respectively, E_1 and E_2 are the energy values for States 1 and 2, T is the absolute temperature of the medium, and k is Boltzmann's constant. Since the ratio of population of any two energy states is related to the exponential of the inverse of the difference between the energy states, higher energy states always possess a smaller population than lower energy states under equilibrium conditions. The goal of choosing a lasing medium and an excitation method is to induce a non-equilibrium state that contains more high energy state than lower energy state electrons. Under the condition of a population inversion, sustained lasing action is possible because statistically more electrons are available to provide stimulated emissions than there are ground state electrons, which have the tendency to absorb the emitted photons (State 3 in Fig. 2.3). Theoretically, only a slight population inversion is required to achieve lasing; however, with other energy losses also occurring, there must often be several excited electron states for every equilibrium state electron. The product of the actions of stimulation, amplification and population inversion is to produce a stream of photons with common characteristics, namely a laser beam. This laser beam possesses temporal, spatial and energy properties which are different than diffuse light. These properties make the laser beam useful for many applications in communications, measurement, and materials processing.

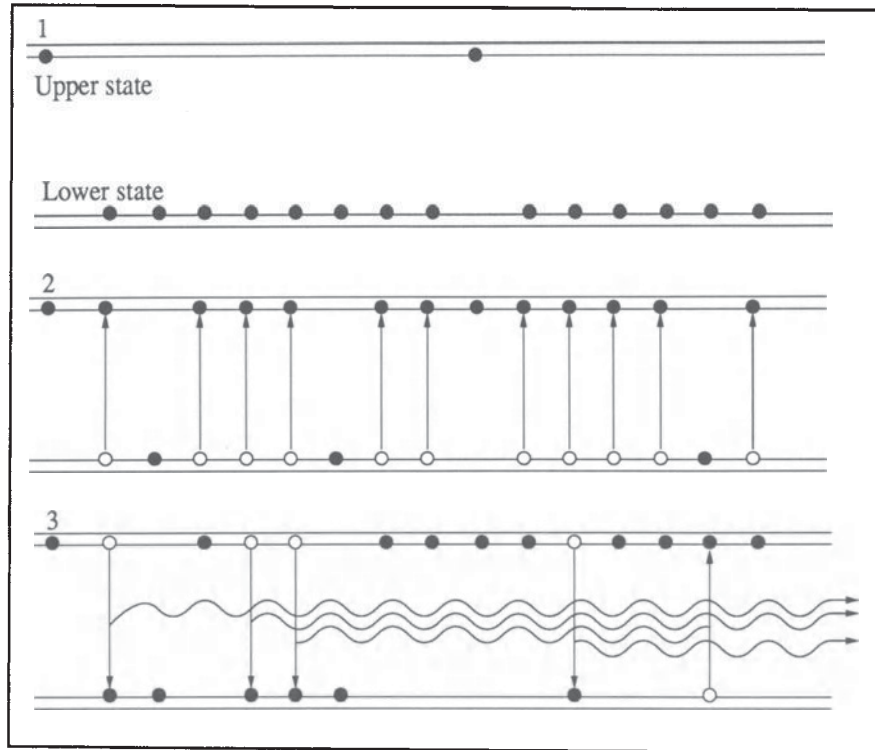


FIGURE 2.3 Population Inversion

The first type of laser developed was the ruby laser, invented in 1957 by Townes and Shawlow. The ruby laser consists of a ruby lasing rod which has mirrored ends that form the optical resonator (Fig. 2.4) and a helical flash lamp which surrounds the ruby rod and provides excitation [17]. The ruby lasing medium is composed of aluminum oxide (Al_2O_3) with a small amount of dissolved chromium oxide (Cr_2O_3). The Cr^{3+} ions in chromium oxide give ruby lasers their distinctive red color and also allow for the generation of laser emissions (Fig. 2.5). In the $\text{Cr}^{3+}:\text{Al}_2\text{O}_3$ system, the initial or *ground state* of the Cr^{3+} ion when the laser is turned on is known as $^4\text{A}_2$. The helical flash lamp is used to raise or *pump* the electrons in the Cr^{3+} ions to the higher energy states of $^4\text{T}_2$ and $^4\text{T}_1$. Then, the energy levels for these excited electrons are lowered through a process which produces no radiation to an intermediate ^2E state, which is composed of two sublevels called $2\bar{\text{A}}$ and $\bar{\text{E}}$. The emission from the $\bar{\text{E}}$ sublevel to the ground state produces the characteristic 694.3 nm laser light of a ruby laser.

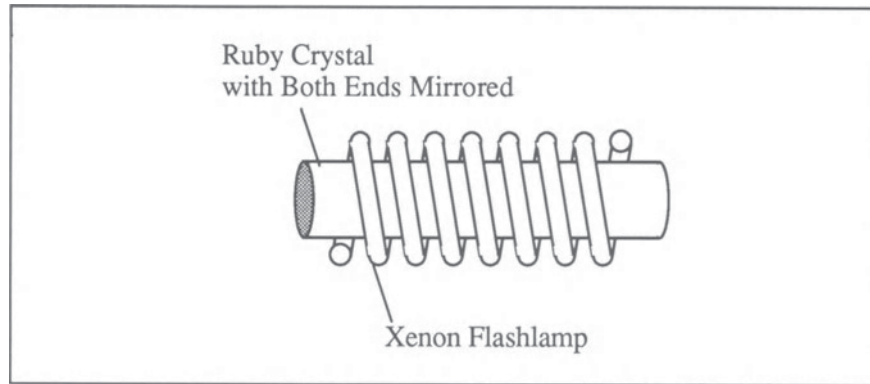


FIGURE 2.4 Ruby Laser

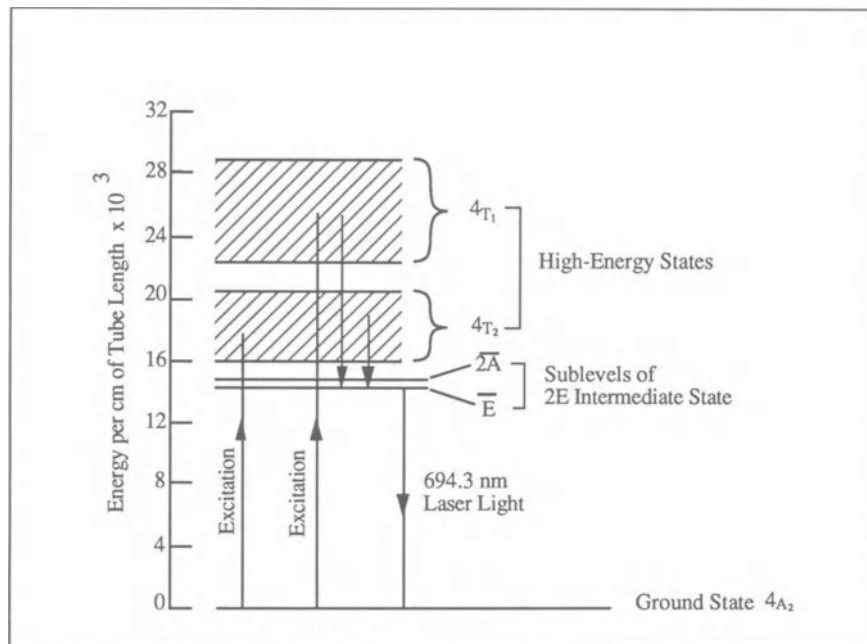


FIGURE 2.5 Chromium Ion Energy Levels

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Ruby lasers are typically operated with a pulsed emission of the laser beam in order to obtain a high energy density because the energy efficiency ($\sim 0.1\%$) is too low for uninterrupted beam output. This creates leading edge spikes in the pulse output, because the stimulation of emissions rapidly depletes the stores of electrons in the ${}^2E$ state. In addition, the pumping of electrons to higher energy states is slow; therefore, pulse repetition rates are slow. The rate and efficiency of energy transfers to and from the excited electron energy states greatly influences the operating characteristics of any laser.

2.3 Laser Light: Properties

Simply illuminating a piece of paper can illustrate the inherent differences between laser and ordinary light. In ordinary light, a sheet of paper appears as a flat, smooth surface. The reflection of the light appears to be identical over the entire surface of the sheet, and the image does not vary greatly with changes in viewing angle. Under laser light, the paper will have a small illuminated area with a grainy appearance. This small illuminated area is due to the small divergence properties of the laser beam. The energy of the ordinary light source is spread over the entire piece of paper and most likely over the rest of the room. Laser light does not spread or diverge, and the spot on the paper is not much larger than the diameter of the beam at the output of the laser.

The grainy appearance of the paper under laser light is composed of contrasting regions of darkness and light, and the grainy pattern changes as the viewing angle is altered. This change is due to the scattering of the laser light by microscopic irregularities within the paper surface. Bright points appear in areas of constructive interference, while dark areas are created in areas of destructive interference. The uniform wavefronts of the laser beam make these interference patterns possible. In ordinary light, the wavefronts are unordered and produce chaotic interference patterns that have no discernible patterns.

The unique properties of laser light can be quantified by examining the optical properties of *monochromaticity*, *coherence*, *diffraction*, and *radiance*.

High *monochromaticity* implies that the range of frequencies emitted by the light source is small; this is often evaluated by measuring the spectral line width [23]. Laser light typically contains a single or a few spectral lines of very narrow widths (Fig. 2.6). Ordinary light sources have multiple wide lines. Monochromaticity is most important in applications such as interferometry, holography, velocimetry, isotope separation, and communications in which the frequency content of the laser beam is of great importance. It is generally not a critical factor in laser machining.

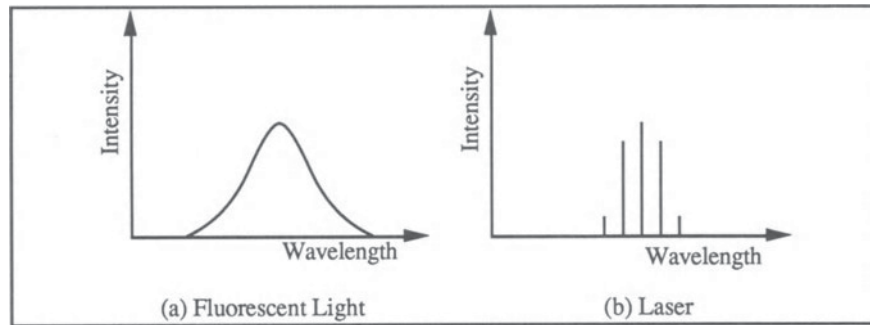


FIGURE 2.6 Monochromaticity

Spatial and temporal *coherence* refers to the relationship between the electric and magnetic components of an electromagnetic wave (Fig. 2.7) [17]. When these components are all aligned, the beam is said to be coherent. Spatial coherence refers to the correlation of phases at different points in space at a single moment in time; temporal coherence refers to the correlation of phases at a single point in space over a period of time. An analogy to coherence can be made with a marching band. Looking at a row marching at a given moment, the members should all be aligned shoulder to shoulder; this is spatial coherence. Looking at a single column for a minute, the spacing between the members should be consistent; this is temporal coherence. An ordinary light source would more resemble the people at the intersection of several hallways in a building. The motions recorded for any area or point in time would be random. Since monochromaticity is required for good coherence, the applications that are critically dependent on coherence are similar: interferometry, holography, velocimetry, and communications.

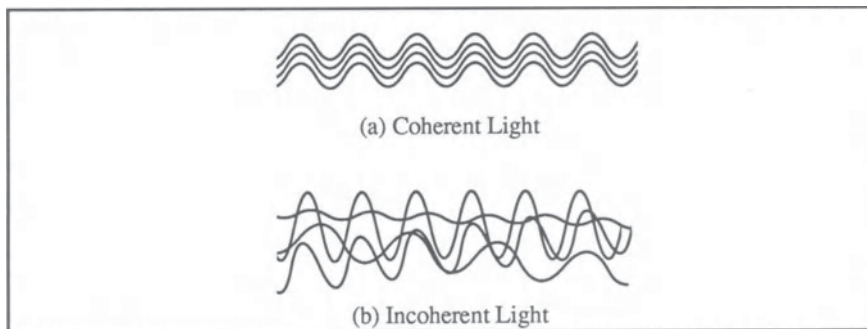


FIGURE 2.7 Coherence

Diffraction is the phenomenon by which light bends around sharp-edged objects [17]. When ordinary light is projected over a distance, a substantial amount of diffraction or scattering of light occurs, resulting in a loss of light intensity as the distance from the light source increases. One advantage of laser beams over ordinary light is that lasers produce beams with very limited diffraction. Low-diffraction light of this type can often be described as a *collimated beam*. Therefore, a laser beam can be projected over a distance with little divergence of the beam or loss in beam intensity. Typical beam divergence angles range from 0.2 milliradians for HeNe lasers to ten milliradians for Nd:YAG lasers. This property of laser light produces a directional energy source which can focus a large amount of luminous energy on a small area. In machining applications, this directional characteristic allows precise control of the laser beam direction relative to workpiece position. For the focussing of laser light, the diffraction effect is related to the ratio between focal length and aperture or beam diameter.

The *radiance* of a light source is the amount of power per unit area emitted by the light source for a given solid angle (Fig. 2.8) [15]. Typical units of radiance are Watts per square meter per steradian. The solid angle can be thought of as the cone through which the light passes. Lasers have high output powers for the small areas which they use to emit the beam. In addition, the beams possess low divergence, which causes them to be transmitted over a small solid angle. Thus, laser light sources possess extremely high radiance. A typical helium-neon laser with a one mW output possesses a radiance two orders of magnitude greater than that of the surface of the sun, which has a power output of 4×10^{26} W. The radiance of a source cannot be increased by optical manipulation; the high radiance capabilities of laser beams are influenced by the design of the laser cavity.

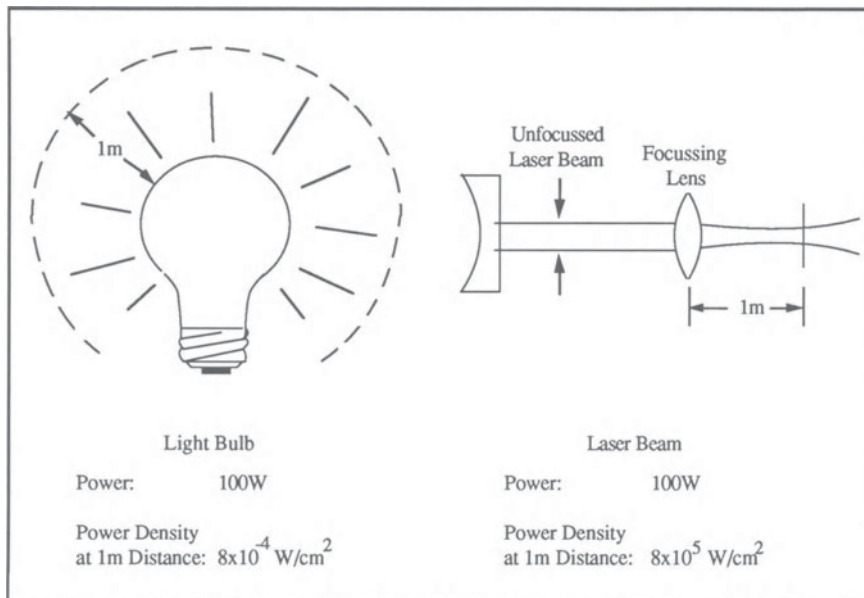


FIGURE 2.8 Radiance

While high monochromaticity, high coherence, and low diffraction individually are not critical factors for laser machining, the combination of these characteristics make the laser beam a powerful tool for machining. High power and energy density can be achieved on the surface of the workpiece, which leads to quick phase change of the workpiece material and to subsequent material removal.

2.4 Laser Types

Lasers can be categorized most easily according to their lasing mediums, which are divided into three basic categories as defined by the state of the lasing material: *gas*, *liquid*, or *solid*. Furthermore, all laser types operate in one of two temporal modes: *continuous wave* (CW) and *pulsed* modes. In CW mode, the laser beam is emitted without interruption. In pulsed mode, the laser beam is emitted periodically.

2.4.1 Gas Lasers

Gas lasers (Fig. 2.9) are further divided into three subgroups based on the composition of the lasing medium: neutral atom, ion, or molecular [19]. The helium-neon (HeNe) laser is a typical neutral atom gas laser and is the most popular visible light laser; it can be tuned from infrared to various visible frequencies, with the most common being red at a wavelength of 0.6328 μm . The actual lasing occurs during an electron transition in the neon (Ne) atom, but the presence of helium (He) is essential since it is excited first by an electrical discharge, and then its energy is transferred to the Ne atom through kinetic interactions. Excitation is provided by DC electrical discharge in a low pressure discharge tube. There are four possible high energy states that electrons in the lasing medium can achieve upon excitation. Since the lasing action has an energy efficiency of 0.1% or less, the laser beam energy is approximately three orders of magnitude lower than the electrical discharge energy. Emissions typically have a Gaussian energy intensity distribution with a maximum power of 50 mW. Areas of applications for neutral atom gas lasers include holography, scanning, alignment, measurement, vision, and optical-fiber communications, which all require a low-powered source of directional energy.

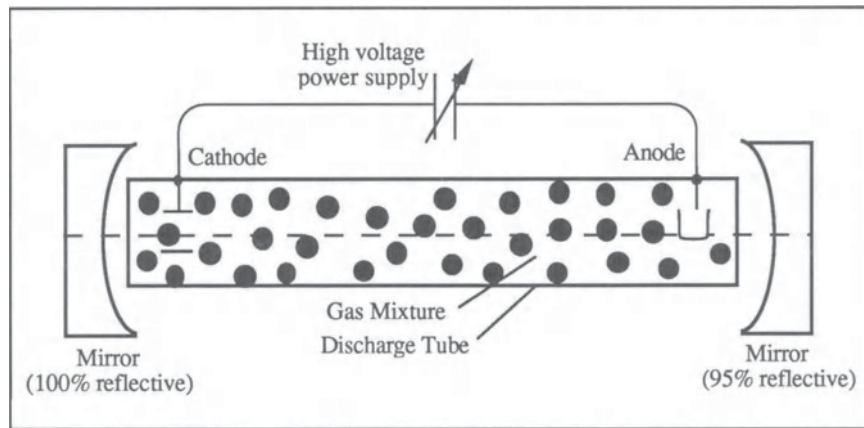


FIGURE 2.9 General Schematic of a Gas Laser

Ion gas lasers use an ionized gas such as argon (Ar), krypton (Kr), and xenon (Xe) as a lasing medium to produce laser beams with wavelengths ranging from 0.5 to 1.0 μm [15]. Excitation is initiated by an electrical discharge, which is achieved in two stages: first the gas is ionized, and then the electrons are brought to the excited state. The resulting laser beam can achieve power levels of up to several Watts. Typical applications include surgical applications and spectroscopy, which both require higher power levels than those achievable with neutral atom lasers.

Molecular lasers use gas molecules as the lasing medium, whereby the molecules are excited and the vibrational mode of the molecules change [15]; these transitions between different vibrational modes produce photons. Carbon monoxide (CO), hydrogen fluoride (HF), and carbon dioxide (CO_2) lasers are examples of this type, which is by far the most common type used for laser machining and which will be discussed in detail.

The *carbon dioxide laser* emits light at a wavelength of 10.6 μm in the far infrared region of the electromagnetic spectrum [10]. The lasing medium is a combination of the gases carbon dioxide, nitrogen, and helium. The lasing mechanism in a carbon dioxide laser differs from the solid or ion lasers. Excitation of the carbon dioxide is achieved by increasing the vibrational energy of the molecule. The actual pumping is achieved by an AC or DC electrical discharge. Only a small percentage of the carbon dioxide is excited directly by the electrical discharge; most of the electrical energy is absorbed by nitrogen gas. The vast majority of carbon dioxide molecules achieve excitation by colliding with the nitrogen molecules, which transfer their added vibrational energy (Figure 2.10). This is an extremely efficient and selective energy transfer because nitrogen is a dimer with one vibrational mode and only one excitation state ($V=1$ state). This excited state is very close to the required excitation state of the carbon dioxide (State 001). Once excitation is achieved in the CO_2 molecule, the electrons can release energy through collisions with other CO_2 molecules still in the ground state; these collisions lower the excited electrons to intermediate Energy States 100, 020, and 010. Of these energy changes, only the transformation of electrons from State 001 to State 100 releases energy in the form of 10.6 μm laser light.

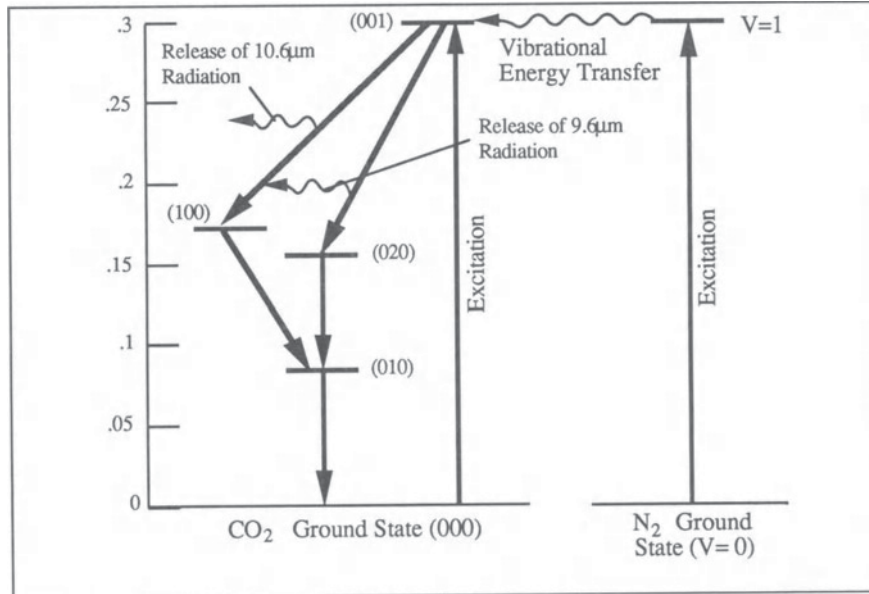


FIGURE 2.10 Carbon Dioxide Energy Levels

The remaining energy between the intermediate states and the ground state is lost through kinetic energy transfer, which generates heat instead of light. For CO₂ molecules, the rate of energy release through heat is much lower than energy release through light, so the energy efficiency for producing a laser beam is high compared with other lasing materials. In comparison, helium has a very high thermal diffusivity; therefore, with its addition to the lasing gas mixture, the rate of energy release through heating is extremely high. This combination of lasing interactions makes the carbon dioxide laser suitable for industrial applications both in terms of the energy efficiency (up to 10%) and the high output beam powers achievable.

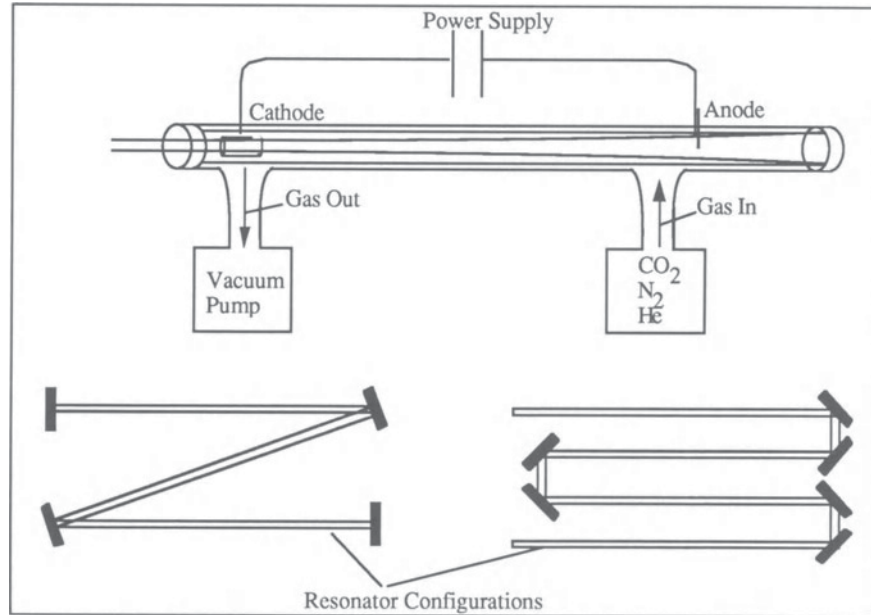
Several different geometries of electrical discharge and gas flow are available. This contributes to the wide range of laser beam power levels which are available, from several Watts to 15 kW. High power carbon dioxide lasers typically operate with mixed energy intensity distributions; the beam profile may vary with time between several possible configurations [10]. Medium and low-powered CO₂ lasers are more stable and maintain a Gaussian intensity distribution. CO₂ lasers are widely used in industry for applications in laser machining, welding, and heat treating.

The properties of a carbon dioxide laser are primarily determined by the method of gas flow [10]. The three main types of gas flow are *sealed discharge tube*, *axial flow*, and *traverse* or *cross flow*. The flow method determines how fast the post-stimulation carbon dioxide gas can be removed from the optical cavity so that new ground state carbon dioxide gas can be introduced for excitation and stimulation.

The *sealed discharge laser* contains a fixed lasing gas mixture sealed in the laser cavity; therefore, it does not require a gas supply or gas handling system. However,

because there is no gas flow, output powers are limited to about 50 W (since used CO_2 cannot be discharged and replenished with new CO_2), and the lifetime of the laser is limited by the disassociation of the carbon dioxide into oxygen and carbon monoxide.

The second type of CO_2 laser is the *axial flow laser*. This is the most widely used type of CO_2 laser, in which the gas flows along the axis of the optical cavity (Fig. 2.11) [1]. Axial flow allows the depleted gas to be replaced by new gas. Laser beam powers of up to 4 kW of continuous wave output can be achieved. Laser beams with pure Gaussian intensity profiles can be generated for power levels up to about one kW, while beams with power above one kW generally have a mixed mode output containing two or more different intensity profiles. Since the used gas is either exhausted immediately or is reused after removing any contaminants, this system requires a constant supply of gas and a gas handling system. Axial flow lasers can be further classified by the speed of gas flow, namely *low-speed flow* and *high-speed flow* lasers. Low-speed flow lasers attain power outputs of about 50 W to 70 W for each meter of cavity length. To produce a compact package, the optical cavity is folded so that longer discharge lengths can be obtained in a smaller assembly. The low flow speed causes the laser to heat up considerably, and the relatively low conductivity of the gas mixture limits the bore size of the lasing tube. Heating of the resonator cavity causes distortions in the resonator optics due to thermal expansion; these distortions affect the beam intensity profile and beam stability. However, with external cooling for the resonator and optics, beam outputs with good adjustability and stability can be generated. High-speed flow models typically have a gas velocity of 60 m/s. Thus, the carbon dioxide molecule only has time for one excitation/stimulation cycle before exiting the optical cavity. Typical outputs are 600 W per meter of cavity length, with total laser beam outputs available up to 6 kW. Due to the convective cooling of the high-speed flow, the thermal distortions in the resonator optics are minimized and larger bore diameters can be used to produce intensity profiles which are nearly Gaussian in shape.

FIGURE 2.11 Axial Flow CO₂ Laser

The third type of CO₂ laser is the *transverse flow laser*, in which the gas mixture of He, N₂ and CO₂ flows perpendicular to the optical cavity axis (Fig. 2.12) [3]. The gas flow is maintained by a blower and is cooled by a heat exchanger. The electrodes are arranged on either side of the cavity, and relatively small voltages are required in order to maintain high current discharge due to the small separation distances. The beam is usually reflected or folded several times within the cavity, creating a compact design which can achieve outputs of one to 10 kW per meter of cavity length and total outputs greater than 15 kW. However, beam quality deteriorates at higher power levels and beam output can shift between several possible beam intensity profiles.

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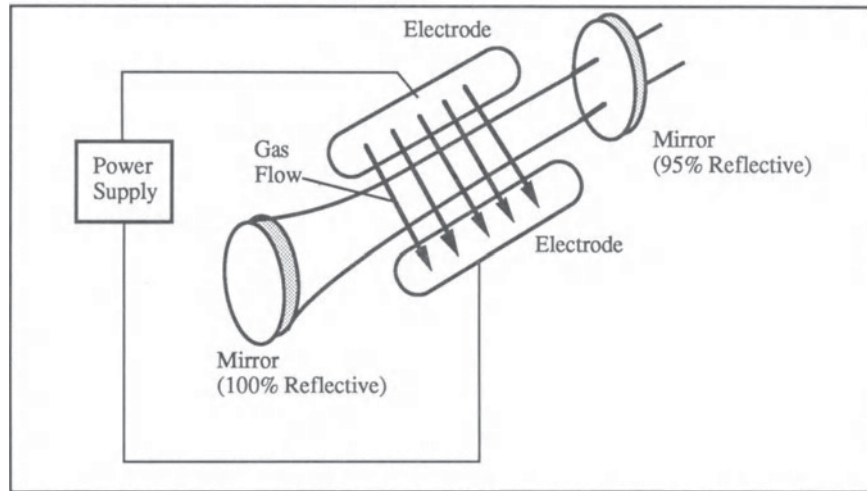


FIGURE 2.12 Traverse Flow CO₂ Laser

For all types of gas lasers, the electrical discharge is either AC, DC, or AC/DC biased [10]. A pulsed output is attainable for almost any of the carbon dioxide laser types; however, the ratio of peak to average power is relatively low due to the limited energy storage capability of the gaseous medium. A constant supply of gases is required for the carbon dioxide lasers, except for the sealed discharge tube models, which must be replenished periodically. The cost of the gas is minimal, except for helium, which can be expensive. Optics are made from Zinc Selenide (ZnSe), Gallium-Arsenide (GaAs) or from various salt crystals (NaCl or KCl). The salts possess poor hygroscopic properties and are limited mainly to research applications. Optical fiber technology has not yet been developed for beam delivery in gas lasers; however, flexible metal conduits with mirrored interior surfaces have been developed to carry up to 2 kW of laser power.

The *excimer laser* is an increasingly popular type of gaseous laser. The term “excimer” originates from “excited dimer,” a compound of two identical species which exists only in an excited state [9]. Some excimer lasers use xenon (Xe₂) and fluorine (F₂) as the lasing material, but the majority of excimer lasers use an excited complex (exciplex) of a noble gas and halogen atom as the actual lasant. Typical excimer complexes include argon fluoride (ArF), krypton fluoride (KrF), xenon fluoride (XeF), and xenon chloride (XeCl). These compounds only exist temporarily when the noble gas is in an excited electronic state. The bond is very strong but lasts only a few nanoseconds. When the noble gas atom is no longer excited, each compound molecule dissociates into its elemental components; this dissociation is accompanied by a release of the binding energy in the form of a photon. The output wavelengths of the excimer lasers vary from 0.193 to 0.351 microns in the ultraviolet to near-ultraviolet spectra (Fig. 2.13).

ArF	.1933μm
KrF	.2484 - .2495μm
XeF	.3490 - .3540μm

XeCl 3080 μm

These compounds can be formed by inducing the Noble gas (Ar, Kr, or Xe) of the compound into an excited state with an electrical discharge, an electron beam, or a combination of the two. In the electrical discharge method, an electrical discharge provides the initial energy for excitation of the noble gas [24]. The discharge also initiates an ionization process in the halogen atom, which releases energy to sustain the excitation of the noble gas electrons. The electron energy of the discharge is small (four to six electron-volts); consequently, the ionization process is the dominant mechanism for excitation. Through repetition of high power pulses, a set of electrical discharges is sufficient to maintain a high average power in the laser beam. In the method involving electron-beam pumping, the high energy of the electron beam (1-2 MeV) results in ionization of atoms. The ionized atoms attract neutral atoms to form ionized molecules which lose some energy and become excimers. The electron beam provides sufficient energy to sustain continuous excitation in the noble gas, so ionization of the halogen does not have a significant influence on excitation.

The excimer is usually formed in a rectangular resonator cavity. The output beam originates from the resonator and the discharge is transverse. The emission spectrum of photons is a wide (100-200 $\text{\AA}$) continuous band [24]. This width causes the stimulated cross section to be small, so that high excimer concentrations are required for amplification. Often, all the gases may be used with a single excimer laser; however, the laser must be conditioned between each gas. The halogens react with the materials of the laser, so an inert gas such as He or Ar needs to be flushed through to break up the compounds.

Excimer lasers produce high-powered, pulsed beams, with average power over 100W and average pulse repetition rate of 1000 pulses per second. The problem with a

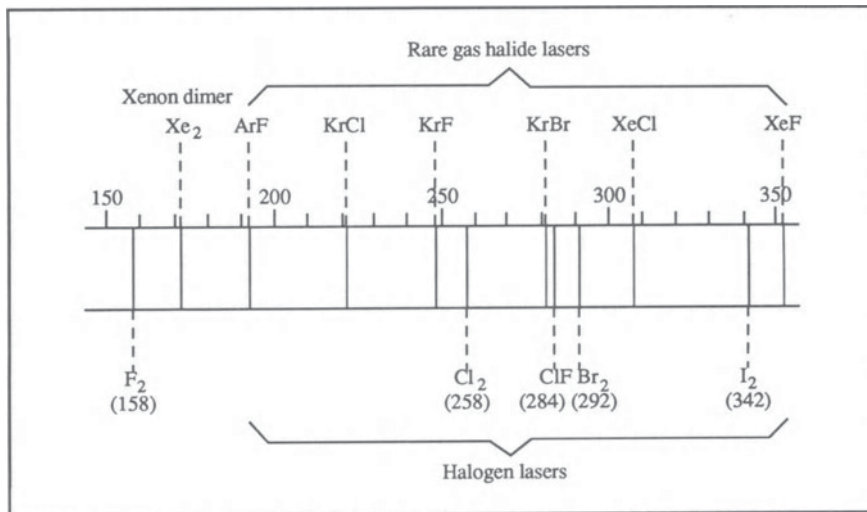


FIGURE 2.13 Spectra for Different Types of Excimer Lasers

high average power is that the lasing medium and the resonator cavity are both heated during the lasing process. At the same time, high power levels must be reached in order to achieve reliable periodic switching [9]. In the excimer compound, both intermediate products (F^+ , Ar_2^+ , etc.) and active states of the molecule (KrF^* , XeF^* , etc.) absorb the laser radiation with an absorption coefficient between $1 \times 10^{-3} \text{ cm}^{-1}$ and $5 \times 10^{-3} \text{ cm}^{-1}$. This fact limits the length (L) of the laser to 2-3 m because the coefficient $\times L$ must be less than or equal to one; otherwise, all of the beam energy will be absorbed by the excimer and no laser beam can be produced. This shorter length limits the maximum output energy of the excimer laser, which makes the range of materials it can process much narrower than that for the CO_2 laser. The average power of an excimer laser pumped by an electrical discharge is limited by the instability of the discharge, the inhomogeneity of the excimer, and the chemical and thermal effects on the medium. In KrF , XeF , and $XeCl$ lasers, this problem is addressed by driving the gas mixture rapidly and perpendicularly to the discharge zone.

Excimer lasers are used to machine solid polymer workpieces, remove polymer films from metal substrates, remove metal films from polymer substrates, micromachine ceramics and semiconductors, and mark thermally sensitive materials, among other things [9]. The characteristics of the excimer laser beam make it ideal for some material removal applications. The high energy of each photon from an excimer laser reduces the interaction time between the irradiated and bulk material of the workpiece; therefore, the heat affected zone is minimized. This is extremely desirable for surgical and polymer processing applications and can be applied to other materials such as ceramics as soon as higher average power models are developed. The use of excimer lasers for cutting, drilling and marking has increased since their development in the 1970's. Processing with excimer lasers results in higher precision and reduced heat damage zones compared with CO_2 and Nd:YAG lasers. The increased demand for excimer lasers in recent years has resulted in the development of more reliable lasers by manufacturers. The fact that industry has become more aware of the applications of excimer lasers has caused their use in materials processing to become more acceptable.

The physics of the material removal process for excimer lasers is different than that for CO_2 or Nd:YAG lasers. Instead of removing material through melting or vaporization, where the material is heated from solid to liquid and/or gaseous states, the excimer laser removes material through ablation, breaking the chemical bonds of the material until it dissociates into its chemical components. In ablation, no liquid or gaseous phases of the material are present. The ablation process occurs as the UV pulses of radiation from the excimer laser make contact with the workpiece surface. Organic materials absorb photons in a thin layer near the surface, which break the bonds in the organic compounds. When the rate of bond breaking exceeds a critical value, the material decomposes. In this manner, the pulse of the excimer beam removes a fraction of a micrometer-thick piece of material layer by layer.

Another difference between excimer and CO_2 or YAG lasers is that the latter focus the beam to a small area and traverse the workpiece. Excimer lasers produce large area beams that are masked through a template to achieve the desired cutting area (Fig. 2.14). After being passed through a mask, the beam is focused onto the workpiece through a lens. From optics:

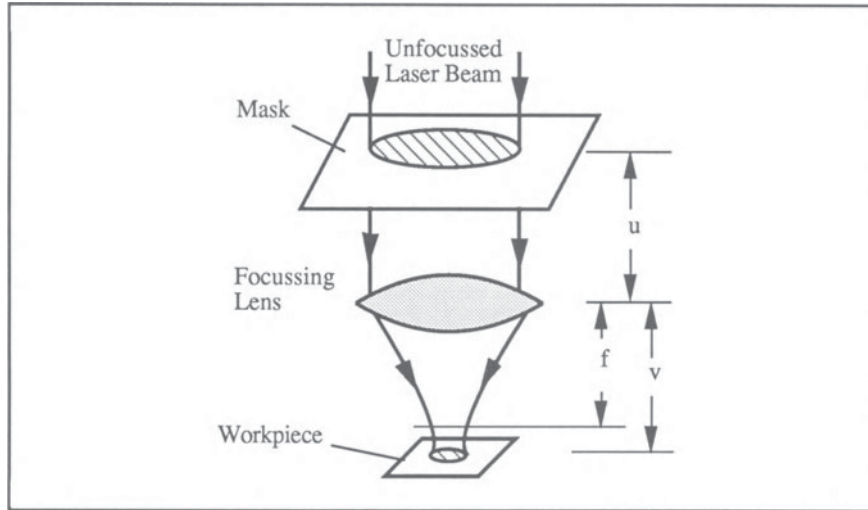


FIGURE 2.14 Configuration for Laser Machining With an Excimer Laser

$$1/u + 1/v = 1/f$$

u = distance from mask to lens

v = distance from lens to workpiece

f = focal length of lens

For values of u greater than $2 \times f$, the image on the workpiece will be inverted and demagnified, with a demagnification factor $d = |u/v|$. The energy density of the laser beam on the workpiece is proportional to the square of the demagnification:

$$ED_w = ED_0 d^2 \quad (2-2)$$

where ED_w is the energy density at the workpiece and ED_0 is the energy density of the unfocused beam. The energy density at the workpiece can be changed by adjusting the degree of demagnification. For example, high material removal rates for etching with an excimer laser can be achieved at $ED_w < 1 \text{ J/cm}^2$ [9]. Since unfocused excimer laser beams usually have energy densities from 100 to 200 mJ/cm², processing of polymers, for example, requires a demagnification factor of two to three. An added advantage is that the dimensional accuracy of the shape machined in the workpiece is high compared with the template shape, since there is no relative motion between the beam and the workpiece.

The mask is made of a metal that reflects most of the incident laser irradiation, so the material underneath the mask is not removed in the cutting process. Excimer lasers are excellent for machining repetitive patterns because the use of the mask allows for a series of holes or slits to be processed at the same time. This method is much more efficient than the use of a CO₂ or Nd:YAG laser, whose use requires that each hole or slit be cut individually. For example, an excimer laser can drill 5000 holes in a polyimide sheet in

approximately three seconds, while the same process would require about 50 seconds with a CO₂ or Nd:YAG laser [9].

If the area of the workpiece to be processed exceeds 1cm x 1cm, or the patterns to be cut are not repetitive, contact masking is used, where the mask is held close to the surface of the workpiece while the laser beam passes over it. The material exposed to the beam through the mask openings is ablated. Another method for machining large areas is conformal masking, where a thin metal layer mask is deposited on the workpiece.

2.4.2 Liquid Lasers

Liquid lasers are primarily *dye lasers* which utilize large organic dye molecules as the lasing medium (Fig. 2.14) [19]. The dyes can absorb radiation from a wide range of frequencies and have hundreds of overlapping spectral lines from which they can lase. These lasers are designed so that the frequency at which they lase can be varied, and are called "tunable." The spectral ranges of the dyes encompass the visible spectrum and parts of the infrared and ultraviolet spectra. The dyes are normally circulated axially through a discharge tube. Continuous operation is difficult to achieve because population inversion is difficult to maintain; therefore, a pulsed mode of operation with an average power up to 10 mW is generally used. Excitation is usually provided transversely by another pulsed laser (typically Ar, N₂, or Nd:YAG), pulsed flashlamp, or focussed continuous laser. The tunability of these lasers makes them desirable for spectroscopic investigation or photochemical applications.

2.4.3 Solid State Lasers

Solid lasers use ions suspended in a crystalline matrix to produce laser light as shown in Figure 2.15. The ions or *dopants* provide the electrons for excitation, while the crystalline matrix propagates the energy between ions. The two main classes of dopants in the laser medium are Chromium (Cr³⁺) for ruby lasers and Neodymium (Nd³⁺) for Nd:YAG and Nd:glass lasers [20]. Ruby lasers generally are no longer used because of low energy efficiency and low achievable beam power. The Nd:YAG and Nd:glass lasers are in general very similar to each other in structure and lasing action. Excitation is achieved by krypton or xenon flash lamps, and an output wavelength of 1.06μm in the near infrared region of the spectrum is obtained. The Nd:glass laser uses a glass host material for the neodymium ions. The glass rods have the advantage that they can be grown to larger sizes more economically than the YAG crystals, but glass has a lower thermal conductivity which limits the pulsed operation of the Nd:glass laser. Therefore, Nd:glass lasers are used in applications which require low pulse repetition rates and high pulse energies (up to 100 Joules per pulse) [20]. In general, the pulse operation of the neodymium lasers make them desirable for hole piercing and deep keyhole welding applications.

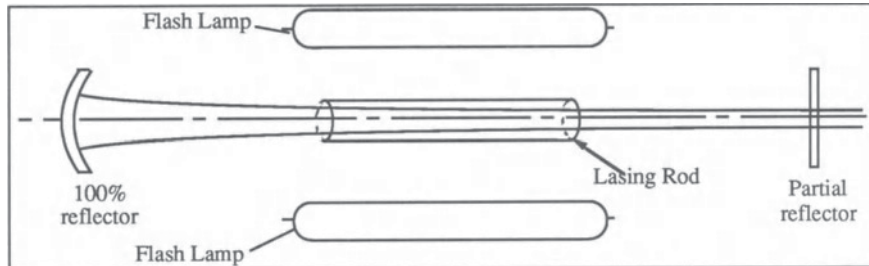


FIGURE 2.15 Schematic of a Solid Laser

The host material in Nd:YAG lasers (Fig. 2.16) is a complex crystal of Ytttrium-Aluminum-Garnet (YAG) with the chemical composition $\text{Y}_3\text{Al}_5\text{O}_{12}$. The YAG crystal has a relatively high thermal conductivity which improves thermal dissipation in the laser cavity, so continuous wave operation up to a few hundred Watts is possible [15]. When operated in a pulsed mode, high pulsing rates can be achieved, and average powers of up to 1 kW are available. The actual lasant is the Nd^{+3} ions which have been doped into a YAG crystal. The YAG crystal is transparent and colorless. When doped with approximately 1% Nd, the crystal takes on a light blue color.

Solid-state lasers usually use krypton or xenon flashlamps for optical pumping. Krypton flashlamps have low operating current and high energy efficiency, so they are useful for continuous wave operation. Xenon flashlamps have a better spectral coupling with the energy states of the neodymium ions than their krypton counterparts; therefore, they can support the higher current density discharges required for pulsed mode operations. The optical pumping cavity is most commonly shaped as an ellipse, where the lasing rod and the flashlamp are each placed at one of the foci of the ellipse. The distance between the lasing rod and the flashlamp is minimized so that the direct coupling between the two is maximized. In addition, any light radiated by the flashlamp that is not directed at the lasing rod is reflected off of the walls of the elliptical cavity at the lasing rod. This combination of direct and indirect pumping results in low electrical power requirements and an acceptable energy efficiency for both continuous wave and pulsed operation.

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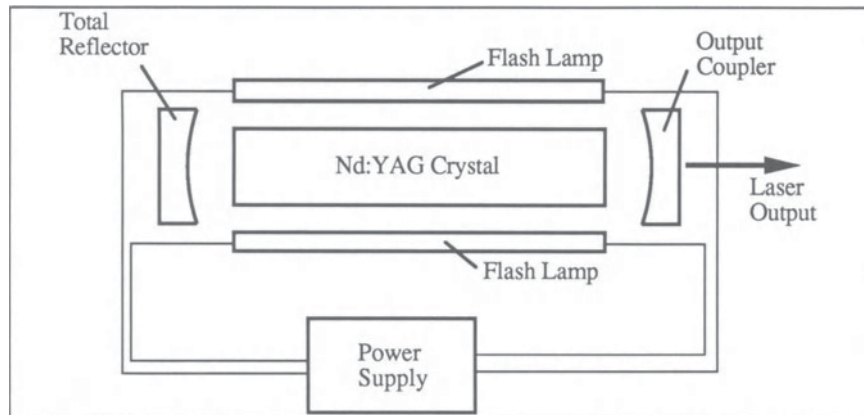


FIGURE 2.16 Schematic of a Nd:YAG Laser

Generally, a cooling system is required for operation of Nd:YAG lasers. With an efficiency of about 3%, a typical Nd:YAG produces thirty times as much waste heat as laser output; this heat must be removed in order to ensure proper laser operation. Flooding the optical compartment with water can remove waste heat; however, the water absorbs a significant amount of the flashlamp energy, and the turbulence of the water can produce optical distortion and imaging problems. These problems can be overcome by flowing water over the outside of the optical cavity and by encasing the lasing rod and flashlamp with transparent cooling jackets. This arrangement minimizes the amount of water that the flash light must travel through and allows better control of the water flowing in the optically distorting areas between the flashlamp and the lasing rod. Furthermore, the flashlamp electrode assemblies should be cooled to prevent thermal loading, and deionized water should be used to prevent any electrical conduction through the water.

The output characteristics of a Nd:YAG laser can be altered by varying the pumping discharge waveform. For high pulse energy in a pulse time of one millisecond, a long lamp pulse is used to obtain a six to seven Joule pulse composed of many spiked oscillations within the pulse. Such a laser can operate at several hundred cycles per second and is useful in laser cutting applications. Laser beam pulse frequency and shape can be tailored by using *Q switching*, where a shutter moves rapidly in and out of the path of the beam. In this manner, beam output is interrupted until a high level of population inversion and energy storage is achieved in the resonator. If the optical cavity is switched from no reflections (low Q) to near total reflection (high Q), the cycle can be optimized to build up the maximum population inversion before the pulse is generated (switched from low to high Q). This results in a beam pulse with a high energy (up to one joule) and a short pulse period (down to 10 ns), which is especially useful for deep hole drilling applications.

Continuous wave laser operation using a continuous flashlamp can be applied to laser cutting. Some cutting and marking operations require a higher peak power, so a pulsed beam output using *Q switching* is sometimes used. Average output power is comparable to similar continuous outputs. Pulse durations from 10-200 ns are used with pulse

frequencies up to 5 kHz, resulting in peak power levels which are a few orders of magnitude greater than average beam power.

The operating cost for a Nd:YAG laser includes the replacement of the flashlamps, which cost \$100-150 and last from 50,000 to 200,000 hours [20]. Optics suitable for transmitting light at a wavelength of 1.06 μm are made from fused quartz, which is a commonly used optical material and is relatively rugged compared to the transmissive optical materials required for carbon dioxide laser emissions. Also, fiber optic materials for beam delivery with good hygroscopic properties and flexibility have been developed for Nd:YAG laser radiation.

2.5 Laser Equipment Characteristics

After the use of laser machining has been decided upon, a suitable laser must be selected. Since industrial laser systems have high capital and operating costs, the choice of a particular laser must be carefully matched with both the machining application and the materials to be processed in order for the operation to be economically viable. The five major characteristics of the laser beam which are critical in determining the type of laser to use for a particular application are *the beam's power, wavelength, temporal mode, spatial mode, and focal spot size*. Other practical and economic considerations include the output stability of the power and TEM mode, the physical size of the unit, projected lifetime of the laser, gas or flash lamp consumption, availability of service and parts, the power requirements, and the efficiency of the laser. These secondary characteristics vary widely depending on the make and model of the laser. Detailed information can be found in the service manual for the specific laser.

2.5.1 Laser Power

Output power is the most basic characteristic of a laser. Purchase of an under-powered laser system will result in increased processing time or an inability to perform machining operations on the desired materials. Capital expenses for a laser system increase with laser power, and purchase of an over-powered laser system may result in excessive expenses. In general, the highest continuous wave power is obtained from CO₂ lasers, while Nd:YAG lasers provide the highest peak power for pulsed operation. The amount of laser power required is determined by examining the optical and thermal properties of the workpiece material or group of materials to be machined. The *thermal* properties can be divided into two basic categories: *fixed* and *loss properties*. The first category determines the amount of energy required to melt and vaporize the material. This includes heat capacity, latent heat, and heat of vaporization. For example, ceramic materials generally require higher laser power to machine than plastics due to their higher latent heats. *Loss properties* are important because they determine the energy transmitted to the surrounding material during processing. Thermal diffusivity is most important in transient operations, while thermal conductivity is more important in steady-state applications.

The laser's optical properties affect the surface of the workpiece where the laser beam impinges. Of the optical material properties, the *absorptivity of the material* has the largest influence on laser power requirements. The material absorptivity determines the fraction of the impinging radiation energy that is actually absorbed by the material. The remainder of the beam energy is reflected back into the environment. Thus, laser power must be adjusted so that the required amount of power for achieving the desired material removal at the desired processing rate is absorbed by the surface, instead of only impinging on the surface. The absorptivity value can vary depending on the wavelength of the beam impinging on the surface, surface roughness, temperature, phase of the material, and the use of surface coatings. The process rate also is related to the required laser power; however, this relationship is complex, since the process rate will also affect the energy losses of the process and the power will affect the material/laser coupling. Estimation of power requirements can be performed by using models of the specific laser machining process to relate the material properties, operating parameters such as laser power and process rate, and material removal characteristics such as depth of cut, hole depth, and the shape of the cut.

2.5.2 Wavelength

The *wavelength* is the characteristic spatial length associated with one cycle of vibration for a photon in the laser beam. The optical resonator of the laser must be properly designed to produce the correct wavelength; the length of the resonator must be such that the laser beam traverses an integral number of half wavelengths of the desired frequency. Any variations in this distance due to thermal expansion or mechanical vibrations may cause the laser to vary its output wavelength, mode or efficiency. Thermal expansion of the resonator components can be controlled by water cooling. Large mechanical structures are used to provide a stiff base for dampening mechanical vibrations to the resonator, particularly to the mirror components. The selection of optical accessories such as lenses, mirrors, polarizers, and windows also depend upon the wavelength of the laser. If fiber optics are intended for beam delivery, suitable optical fiber materials are available for only a few specific laser wavelengths.

The absorptivity of materials can be highly dependent on the wavelength of incident light, and thus certain lasers will be more suitable for the processing of different classes of materials. For example, some metals such as aluminum and copper show low absorptivity at a wavelength of $10.6\mu\text{m}$, which is the characteristic wavelength for CO_2 lasers. Therefore, in order to machine these materials effectively, either a high power laser or one with a different wavelength must be used. Materials can be machined more effectively by using a Nd:YAG laser with a $1.06\mu\text{m}$ wavelength, whereby the copper and aluminum absorptivity values are much higher.

2.5.3 Temporal Mode

Lasers can operate in either a continuous wave (CW) mode or a pulsed beam mode (Fig. 2.17). In continuous wave mode the laser beam is emitted without interruption. In the pulsed beam mode, the laser beam is emitted periodically. Pumped energy is stored until a threshold energy is reached, and then the stored energy is discharged rapidly into the laser cavity. Through this process, short duration pulses with high energy densities can be generated from lower levels of continuous electrical power. CW operation offers the advantage of smooth surfaces after machining. However, the surface quality improvement is offset by the high electrical power input required to maintain a continuous beam. Pulsed beam operation allows deeper drilling or cutting depths to be achieved compared to a continuous beam operating at a given beam power, but pulsed operation may result in larger surface irregularities in the machined parts due to a periodic beam output.

The temporal mode capability of a laser depends greatly on the lasing medium. Typically, solid lasers operate best in pulsed mode and at relatively lower powers in continuous mode. The solid lasant provides a large population of excited ions because of the relatively high density of the material; however, there is a limited ability to regenerate these excited ions due to the amount of time needed to return them to the ground state. Thus, high energy pulses can be generated by the rapid stimulation of the entire lasing medium. Continuous output is limited by the inability to quickly return ions to the ground state for re-excitation. Also, there are thermal limits to the amount of heat the lasant can absorb and the rate the heat can be removed; these limits affect pulse repetition rates and continuous power ratings.

Gas lasers typically operate in a continuous mode with limited pulse capability. The gas lasant does not contain as many excitation sites as a solid lasing material, and therefore, the pulse energy is limited. Typically, the continuous power ratings are also limited by the low density of the laser medium for lasers in which the gas in the laser cavity is

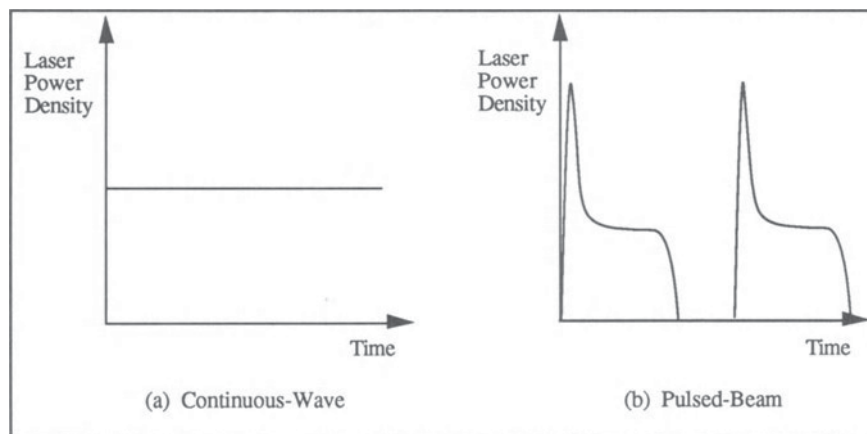


FIGURE 2.17 Laser Beam Temporal Modes

not replenished. This can be increased many orders of magnitude by continuously flowing new lasing material into the optical resonator. The incoming gas is in the ground state and is always ready for excitation and stimulation. Also, gases which have undergone stimulation and need to return to the ground state are removed from the laser cavity. The flow of gas effectively reduces the cycle time of the emission process and greatly increases the power potential of the laser. This technique also improves the pulsing capability, as do altering of the lasing gas mixture and using specialized electrical pumping techniques.

The selection of a laser and an operating mode will depend strongly on the desired machining operation. Pulsed operation is usually best for deep penetration processes. The concentration of energy in each pulse leads to a small percentage of energy lost through conduction into the workpiece or dissipation to the environment. In addition, the coupling of the material and the laser may require the use of higher power densities available only by pulsing. For the same reason, pulsing is used to minimize the heat affected zone in materials that are sensitive to elevated temperatures, such as polymers. Continuous power operation is used when high average power is required, which is important for achieving high material removal rates. When material/laser coupling is good, continuous power operations will not suffer from large losses. Also, surface finish is often an important concern. Continuous operation provides smooth cutting surfaces, while pulsing can create a wavy surface due to its periodic nature.

2.5.4 Spatial Mode

As mentioned above, resonator design is crucial to the production of the proper wavelength of light. Similarly, the phase of the electromagnetic wave may differ by resonator design, resulting in changes in the laser beam spatial profile. The beam profile can be characterized by its *Transverse Electromagnetic Mode* (TEM) [3]. TEM modes are normally written in the form of TEM_{nm} . The subscripts n and m denote the number of nodes in directions orthogonal to the beam propagation, such as TEM_{00} or TEM_{01} (Fig. 2.18). TEM_{00} has a Gaussian spatial distribution and is usually considered the best mode for laser machining because the phase front is uniform and there is a smooth drop off of irradiance from the beam center. This minimizes diffraction effects during focussing and allows the generation of small spot sizes. Correct resonator design can minimize non-Gaussian modes. Higher order modes have more rapid diffraction characteristics. In a resonator designed to produce a beam with a TEM_{00} spatial mode, a large part of the higher order modes is diffracted beyond the reflection mirrors and discarded. In order to minimize the occurrence of higher-order modes in the laser beam, an aperture can be used at the midpoint of the resonator. The aperture is designed so that it is large enough to pass the Gaussian components, but higher order modes are attenuated because they diverge after hitting the reflecting mirrors and cannot pass through the narrow diameter of the aperture. In some applications such as welding or heat treating, use of higher-order modes is desirable because these applications require uniform heating over the surface area more than localized high energy densities. By using a higher-order mode beam, energy can be distributed evenly over a larger spot size.

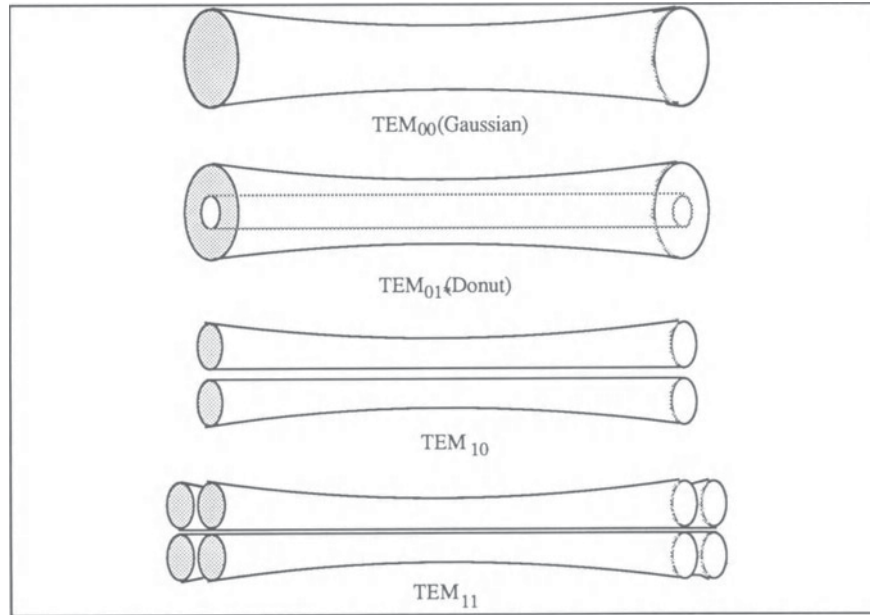


FIGURE 2.18 TEM Modes

2.5.5 Focal Spot Size

In materials processing, *irradiance (power per unit area)* of the laser beam at the material surface is of prime importance [15]. Irradiances great enough to melt or vaporize any material can be generated by focussing a laser beam. The maximum irradiance is obtained at the focal point of a lens, where the beam is at its smallest diameter (Fig. 2.19); the location of this minimum diameter is called the *focal spot*. Irradiance values of billions of watts per square centimeter can be obtained at the focal spot. The imperfections of the optical components and diffraction effects limit the size of the obtainable focal spots.

Several factors influence focal spot size. First, focal spot size is directly related to the quality of the incoming beam, which can be quantified by the divergence of the beam (Fig. 2.19). A laser beam with a small divergence can be focussed to a smaller spot than a beam with high divergence [3]. Second, focal spot size is influenced by diffraction. When focussing a diffraction-limited laser beam with a lens, a longer focal length or higher f-number corresponds to a larger focussed spot diameter. Finally, the diameter of the incoming laser beam affects the focal spot size. When restricted to specific optics, the only method of producing smaller focal spot sizes is to *increase* the incoming laser beam diameter.

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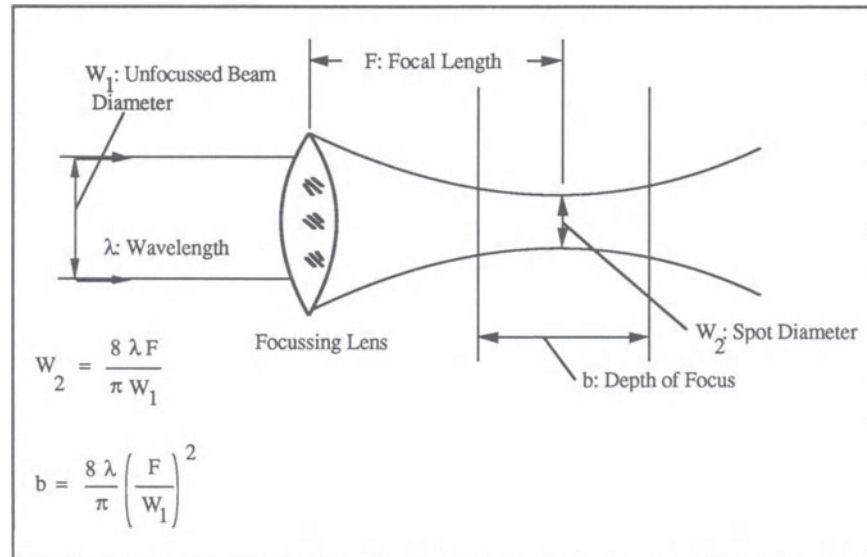


FIGURE 2.19 Calculation of Focal Spot Diameter and Depth of Focus

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