Extract from

INDUSTRIAL STRENGTH LASER MARKING

Turning Photons Into Dollars

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Chapter 1 - Principles of Laser Amplification

The word "**LASER**" is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Simply stated, the laser is nothing more or less than a light amplifier.

Lasers amplify light by absorbing and emitting energy. The means of absorption can be either electronic on the atomic level or rotational/vibrational on the molecular level. The emitted energy is a high-intensity beam of laser light. To understand the mechanics of amplification in Nd:YAG lasers, we must look to the transitions that occur between energy levels of the atom (atomic level).

Absorption, Emission, and Energy Levels

Atoms consist of a positive charged nucleus surrounded by a cloud of negatively charged electrons orbiting the nucleus (fig.1). Each electron travels in its own unique orbit at a diameter corresponding to the excitation state (energy level) of the electron. The energy that is absorbed by an atom goes to the electrons, either increasing the speed of the electrons' travel or enlarging the diameter of the electrons' orbit. When energy is subsequently emitted by an atom, the electron returns to either a slower speed or a smaller diameter orbit. We will focus on the energy transitions which occur with increasing and decreasing electron orbits.

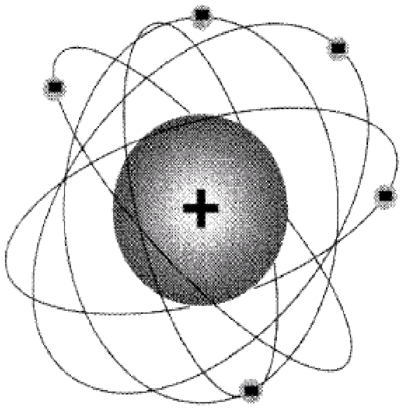


Fig. 1. Positive nucleus surrounded by a cloud of negatively charged electrons.

An interesting property of atoms is that only energy of specific amounts can be absorbed and emitted. The electron orbits can only increase and decrease to specific levels (diameters). In other words, the energy potential for any given atom is *quantified*. For example, an atom may absorb energy at l.5 electron-volts but it will not absorb 1.45 or l.55 electron-volts. After the energy is absorbed, the energy is also lost only in certain amounts because the electrons may only return to allowed orbits.

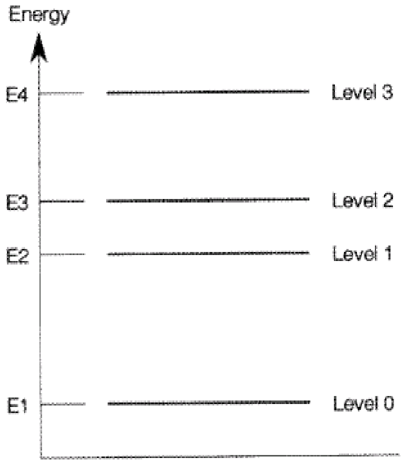


Fig. 2. Energy level schematic with multiple energy levels.

The energy levels for a specific atom can be shown with an energy level schematic (fig. 2). Here, the allowed energy levels for the atom are represented by different levels on the diagram. An atom in the ground state has energy level E^0 while an atom in the first excited state has energy level E^1, etc.

As an atom absorbs energy, the absorbed energy must be equal to the difference between the allowed energy levels. An atom may absorb energy equal to the difference between E^0 and E^1 and move to the first excited state (level 1) but it cannot absorb energy less than E^0-E^1. it can also absorb energy equal to E^0 - E^2 and move to the second excited state (level 2). However, it cannot absorb energy equal to E^2 - E^1. Correspondingly, when an atom loses energy, it must also lose energy in amounts equal to the difference between levels.

Photon Absorption

One method in which an atom may gain energy is to absorb a photon of light. To be absorbed, the photon must contain energy equal to the difference between two of the allowed energy levels of the atom. Because a photon's energy determines its wavelength, the atom will only absorb light of specific wavelengths which are equal to the allowed energy levels.

Spontaneous Emission

There are two ways in which an atom can subsequently lose energy: by transfer to another atom or by emitting a photon of light. When emitted as light, the emitted photons wavelength will correspond to the energy lost by the atom as it moves from a high energy level back to a lower level. The light emitted by an atom must correlate with the allowable energy levels for the atom.

Normally an atom will absorb energy, raising it to a higher energy level, and will remain in that energy state for some period of time (nanoseconds or milliseconds). This period is the *"spontaneous"* or *"upper-level"* lifetime of the atom. Eventually the atom will spontaneously emit a photon of light in a random direction and return to the ground state. This is *spontaneous emission* (fig. 3).

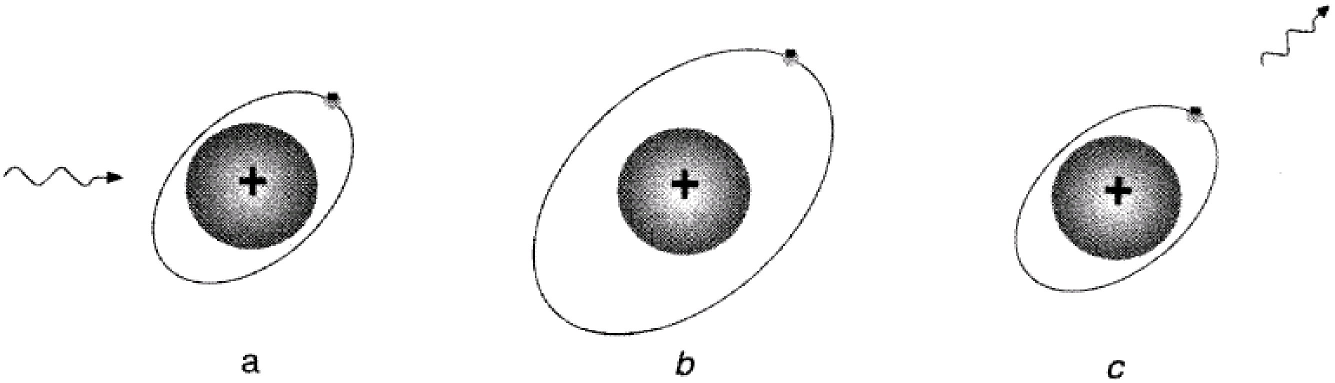


Fig. 3. An atom absorbs a photon (a), remains in an energized state for a period of time (b), and decays emitting a photon of light (c).

Stimulated Emission

Another mechanism by which an atom can emit light is by *stimulated emission* (fig. 4). During the spontaneous lifetime while the atom is in an upper level state before spontaneous emission can occur, the atom can be stimulated to release its photon of light my interacting with another passing photon. The passing photons' wavelength must be equal to the difference of the electron's upper and lower energy levels to stimulate the atom to emit a photon. Because the emitted photon's wavelength is determined by the difference between the same energy levels, the passing and emitted photons will be the same wavelength. In addition, both photons will travel in the original direction of the passing photon and will be in phase. With equal properties of wavelength, direction, and phase, the photons constitute *coherent light*. This stimulated emission of coherent light is crucial to the operation of a laser. In fact, this is the stimulated emission referred to in the acronym "LASER".

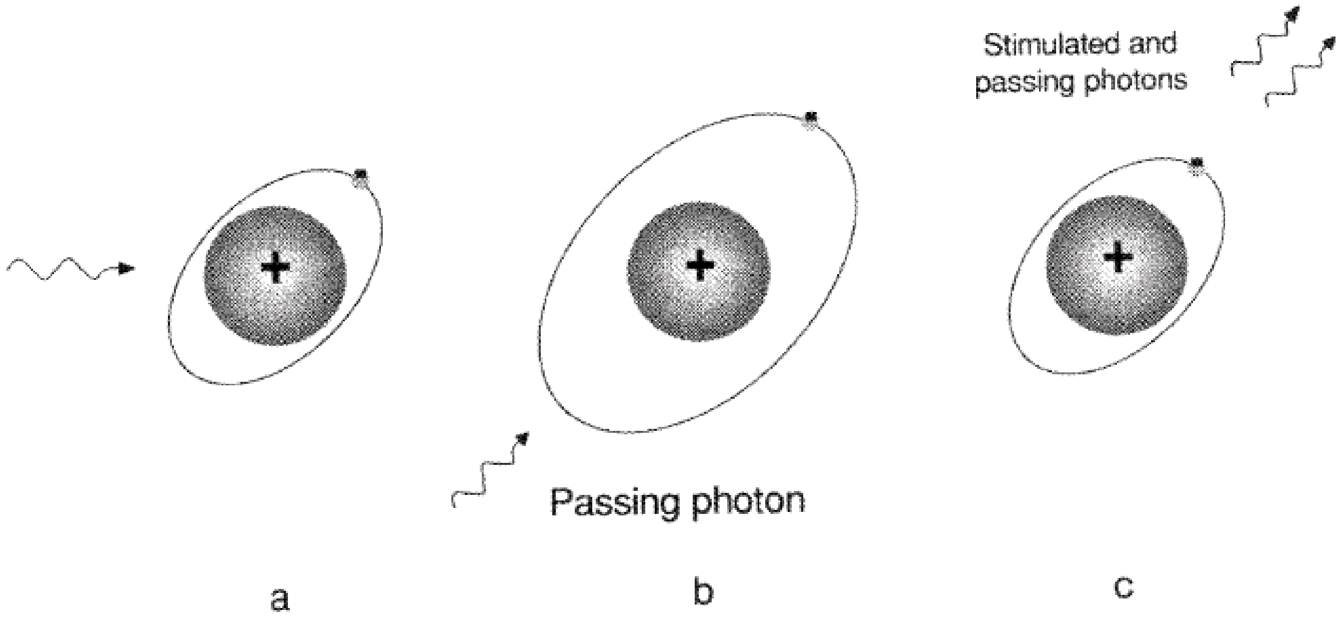


Fig. 4. An atom absorbs a photon (a), is stimulated by a second passing photon (b), and emits its photon (c).

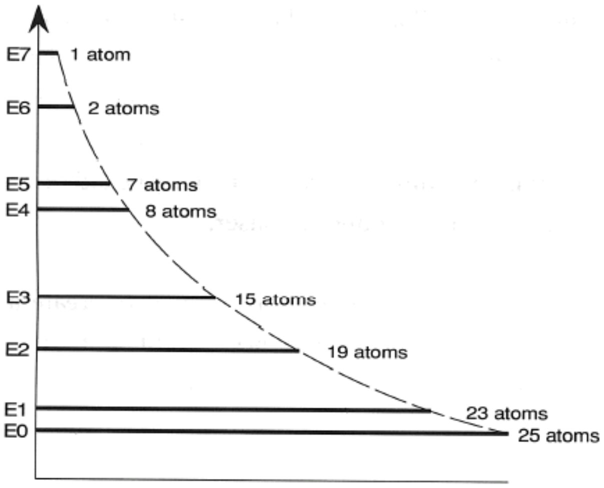


Fig. 5. Energy distribution as defined by Boltzmann's law.

Population Inversion

Up to now, we have looked at the energy transitions of a single atom. What of the energy distribution of a large population of atoms?

In any substantial population of atoms, the majority of the atoms will be in the ground state. The remaining atoms will be distributed among the higher energy levels in decreasing quantities. The population at each level is dictated by *Boltzmann's law*, one of the fundamental laws of thermal dynamics. In figure 5, each energy level for a specified atom is represented on the vertical axis of the diagram while the population for each level is represented by the length of the corresponding horizontal lines. As described by Boltzmann's law, each ascending level will have fewer atoms than the preceding level. The population of atoms is in a *thermal equilibrium distribution*. Applying heat to the population to increase the energy will subsequently increase the number of atoms above the ground state but will not change the overall distribution (i.e. a higher level will not contain more atoms than a lower level).

It is possible to force an energy distribution out of equilibrium (fig. 6). If some of the atoms in the ground state (E^0) are forced to an upper level (E^1) before any of the existing upper level atoms can spontaneously decay back down, a *population inversion* is created in which there are more atoms in the upper level state than the lower. The population inversion is a non-equilibrium distribution and will not last very long. Ground state atoms must be continuously forced into the upper level to maintain the inversion. A sustained population inversion is crucial to maintaining stimulated emission.

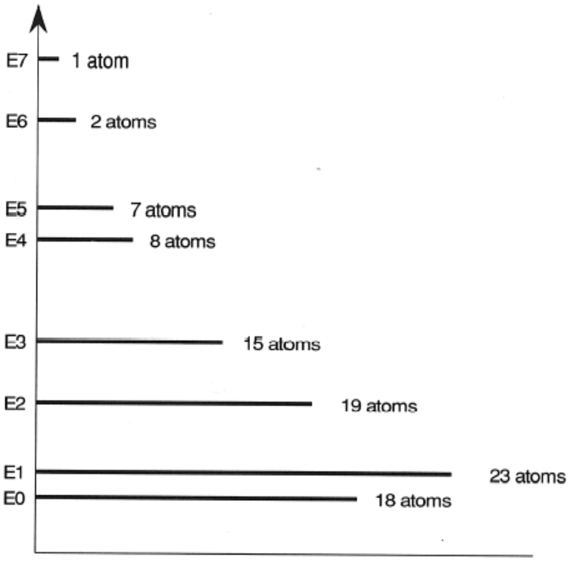


Fig.6. Population inversion between levels E0 and E1.

Light Amplification

So how does the laser amplify light? At the heart of all lasers is the *lasing medium*, which contains atoms that can be stimulated to spontaneously emit light. The medium may be a gas mixture (CO_2, helium-neon, etc.) a semiconductor substrate (laser diodes), a liquid (dye lasers), or a solid crystal (Nd:YAG, Nd:YLF, Ruby, etc.). The laser will also have an energy source to excite (pump) the atoms of the media. The pump source will usually be either an electric discharge, light from a hi-intensity light source, or another laser.

As the pump source excites the lasing media, sufficient energy is applied to create a population inversion and initiate spontaneous emission. The spontaneous light emitted by the media travels in random directions (fig. 7).

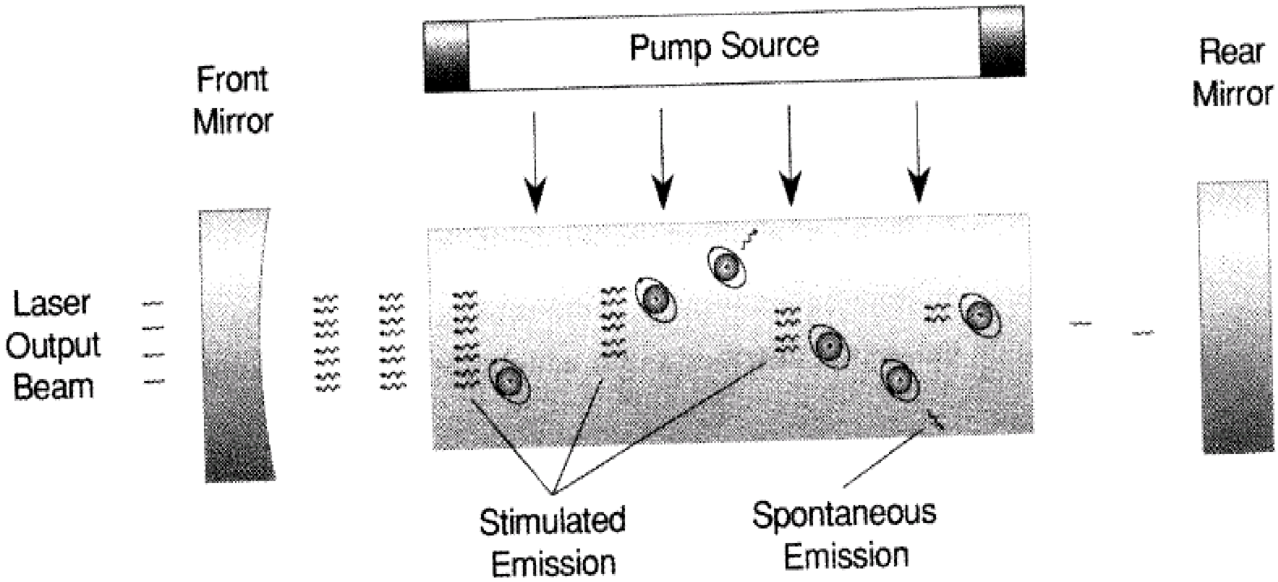
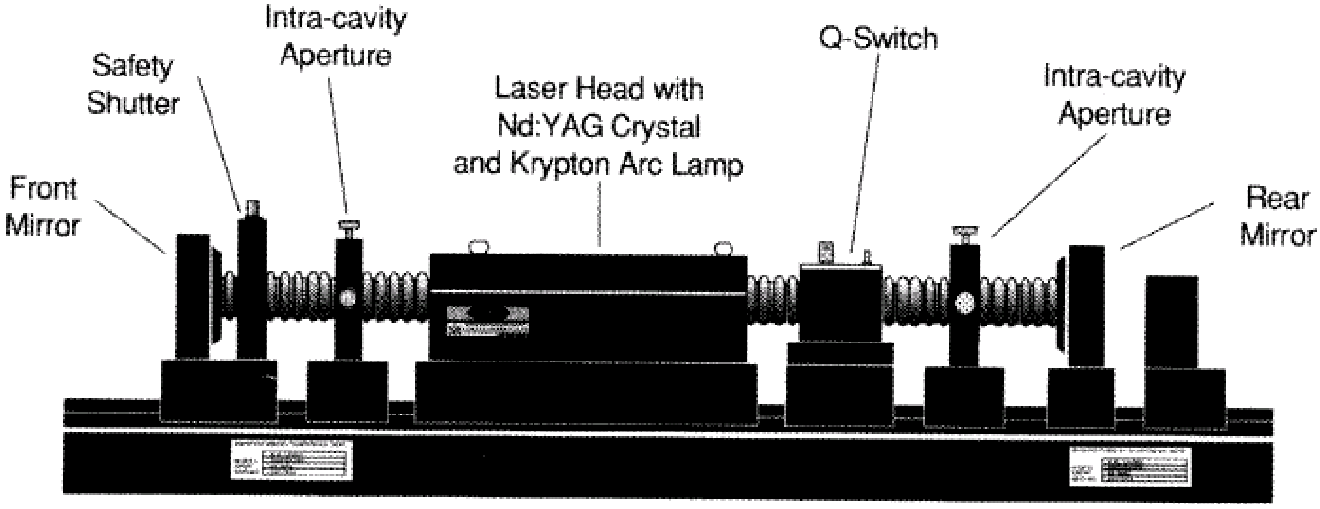


Fig. 7. Spontaneous emission, stimulated emission, and the optical feedback.

Optical feedback is created by placing a mirror at each end of the media to reflect those photons travelling along the longitudinal axis back into the media. The reflected photons cause other upper level atoms to emit their photons by stimulated emission. As this process continues, one photon becomes two, two become four, four become sixteen, etc. - LIGHT AMPLIFICATION!! All of the photons will be the same wavelength, will be in phase and will travel the same direction along the path of reflection. The population inversion assures that there is always a sufficient quantity of atoms in the upper level state to sustain the lasing process.

One of the mirrors of the optical feedback is coated to "leak" a small percentage (typically 10% or less) of the amplified light reflecting between the mirrors. This leakage is the laser output beam.

Chapter 2 – Nd:YAG Lasers



The basic process of laser amplification described in Chapter 1, though ignoring many of the subtleties of laser physics, applies to all lasers. Now we will look specifically at the solid-state Nd:YAG (Neodymium:Yttrium Aluminum Garnet) laser that is most frequently employed for beam-steered laser marking.

The lasing atoms in solid-state lasers are embedded in a solid piece of transparent material called the host. For Nd:YAG lasers, neodymium (Nd) atoms (the lasing media) are embedded in an yttrium aluminum garnet (YAG) crystal host. The YAG crystal is usually in the shape of a rod roughly the size of a pencil. The optimum neodymium concentration in the crystal is about 1% by weight. Its growth is best described as a black art.

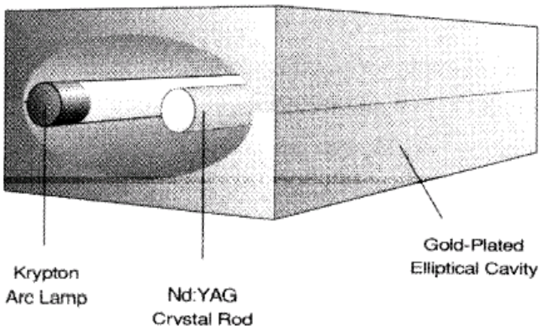


Fig. 8. Elliptical Cavity

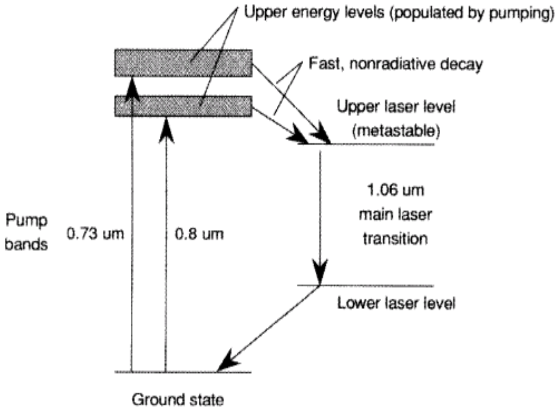


Fig. 9. Four-level energy schematic of Nd:YAG transitions.

Though difficult and expensive to produce, the Nd:YAG rod exhibits desirable optical, mechanical, and thermal properties which make it an excellent media for high power lasing operation.

The pump source is usually a krypton arc lamp positioned parallel to the Nd:YAG crystal (fig. 8). Both the Nd:YAG crystal and the krypton arc lamp are located inside a gold, elliptical shaped cavity. The cavity contours are carefully calculated to focus all of the pump light emitted by the krypton lamp to a focal region along the center axis of the Nd:YAG crystal. Gold is used for its high reflectivity to the wavelength of the pump light. The optical feedback is provided by a 100% reflective rear mirror and a partially transmitting front mirror.

A four-step process of energy transfer occurs in a Nd:YAG crystal (fig. 9). First, the neodymium atoms are elevated to one of two upper energy levels with the absorption if light emitted by the krypton arc lamp. Lamp light in pump bands near 0.73mm and 0.8mm is most efficient at exciting neodymium ions to the upper levels. The atoms then go through a rapid, nonradiative decay to a metastable upper laser level thereby creating a population inversion between the upper and lower laser level. When the atoms further decay to the lower laser level, energy is emitted as a photon of light with a wavelength of 1.06mm. This laser transition is the source of both the spontaneous and the stimulated emission which constitute the laser beam. Lastly, the atoms experience a nonradiative decay back to the ground state to repeat the process.

Multimode vs. TEM$_{00}$ Operation

At this point, the laser is operating in what is referred to as a *multimode* condition. Without delving deeply into laser optical modes, suffice it to say that a cross section of a multimode beam would show multiple "hot spots" or rings (fig. 10) and the diameter of the beam would be roughly determined by the diameter of the Nd:YAG crystal.

For marking very narrow line widths, the laser can be temporarily forced to operate in TEM_{00} (*transverse electromagnetic mode*) mode by dropping an electronically operated *intracavity* aperture between the optical feedback mirrors. The aperture restricts the paths of reflection between the mirrors thereby reducing the diameter of the laser beam and concentrating the amplified light to the center of the beam (fig. 11). A cross section of a TEM_{00} beam will show one central hot spot and a narrow beam diameter established by the diameter of the aperture. Because the reflected light-the cavity is partially blocked, TEM_{00} operation is achieved at the expense of lower overall output power although the quantum of light in the center of the beam may be higher.

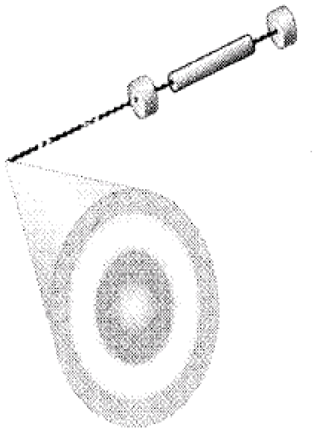


Fig. 10. Multimode Output.

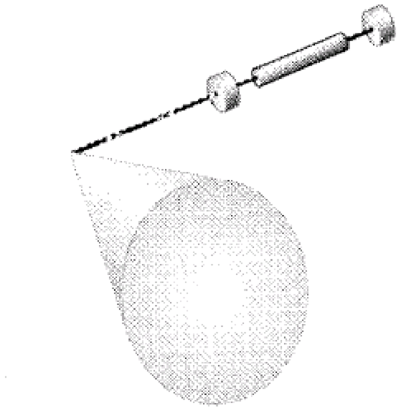


Fig. 11. TEMoo Output.

For special applications which require only narrow line widths (<0.005"), the laser can be permanently configured for TEM_{00} operation. By installing components desired specifically for TEM_{00} operation, the narrower line widths can be achieved with less power loss.

*** Tip:** The output mode of the laser beam is a crucial factor to the systems overall marking performance. Output power alone is not a good indicator of a systems ability to mark efficiently (see Chapter 3, Output Power vs. Energy Density)

The Acousto-Optic Q-Switch

For laser marking applications, an additional optical component is usually added to the optical cavity - *the acousto-optic Q-switch*. The Q-switch is a device that produces a pulsed laser output by alternately blocking and unblocking the path of reflection between the optical feedback mirrors. The "Q" stands for the quality of the optical feedback of the laser cavity.

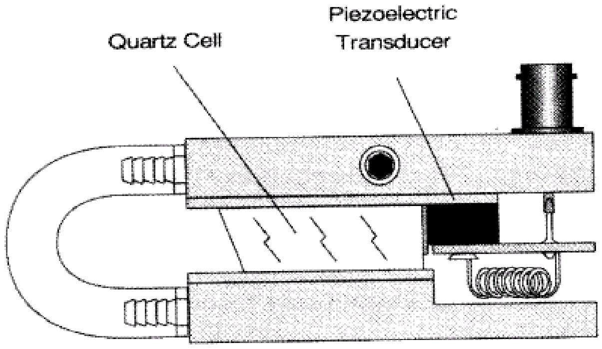


Fig.12. Acousto-Optic Q-Switch.

The acousto-optic Q-switch consists of a transparent material (usually quartz) with a piezoelectric acoustic transducer bonded to one side (fig. 12). In the static state, the light emitted from the Nd:YAG crystal passes through the Q-switch at an angle dictated by the materials normal index of refraction (fig. 13). The light then reflects off the rear mirror, passes back through the Q-switch, and returns to the crystal.

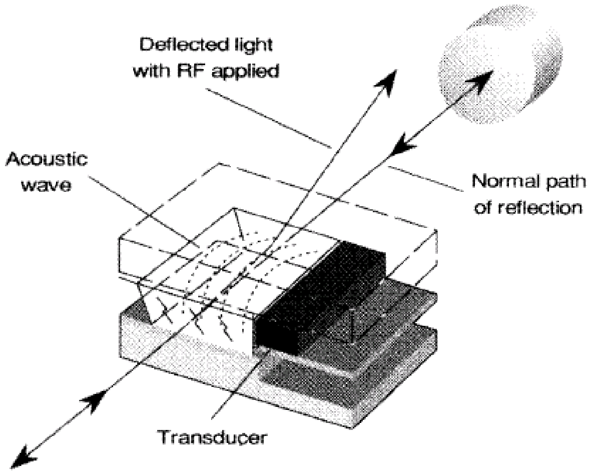


Fig.13. Deflected light with RF applied to transducer.

When an RF signal is applied to the transducer, an acoustic wave is projected through the quartz which momentarily compresses the material. This produces a periodic change in the index of refraction of the quartz. Some of the light passing through the Q-switch is diffracted to a small angle and misses the rear mirror. With this loss of the optical feedback which is necessary to stimulate emission, lasing action ceases.

Neodymium is a fairly unique lasing media in that it exhibits a comparatively long spontaneous or upper-level lifetime. During the period that the RF is applied to the Q-switch and stimulated emission is suspended, the population of the upper laser level will continue to grow as more atoms absorb lamp energy. Atoms already populating the upper level will not immediately decay to the lower level due to the long upper- level lifetime. During the non-lasing period, the upper level stores considerable amounts of energy. When the RF signal is removed and the optical feedback is restored, the resultant burst of laser light can be several kilowatts of peak power. Q-switching is an excellent method to produce very short pulse width and very high peak power pulses of light from a comparatively low power laser.

> *** Tip:** The long upper-level lifetime which results in high peak power pulses during Q-switched operation will detrimentally effect the marking operation during the much longer period which occurs while the steering mirrors are repositioning between characters or graphic images. All serious marking systems should include a *pulse suppression* circuit to suppress the "giant pulse" which occurs at the beginning of any new character or image.

Intra-Cavity Safety Shutter

The final component found in the laser cavity is the electrically activated safety shutter. The safety shutter also blocks the path of reflection between the optical feedback mirrors. Unlike the Q-switch, the safety shutter is a mechanical device designed to block the lasing action for long periods of time. All safety shutters are designed so that gravity will drop the shutter into the closed or non-lasing position, in the event of an electronic failure.

The following table summarizes typical performance specifications, including Q-switch pulse characteristics for the Nd:YAG lasers that are used for laser marking.

Nd:YAG Laser Typical Performance Specifications

CW Performance		15 watt TEM_{00}	50 watt Multimode	100 watt Multimode
CW Power (min.)	(watts)	8	50	100
Instability (max.)	(% RMS)	3	3	3
Beam Diameter @1/e2	(mm)	1	4	6.5
Beam Divergence @1/e2 (max.)	(mrad)	2.5	10	10
QS Performance @1 kHz				
Peak Power (min.)	(kW)	15	75	120
Energy / Pulse (min.)	(mJ)	1.9	12	20
Pulse Width (max.)	(nsec)	130	160	170
Peak Power Instability (max.)	(% p-p)	6	8	15
QS Performance @10 kHz				
Peak Power (min.)	(kW)	2.4	18	
Energy / Pulse (min.)	(mJ)	0.6	4	
Pulse Width (max.)	(nsec)	260	220	
Peak Power Instability (max.)	(% p-p)	15	15	

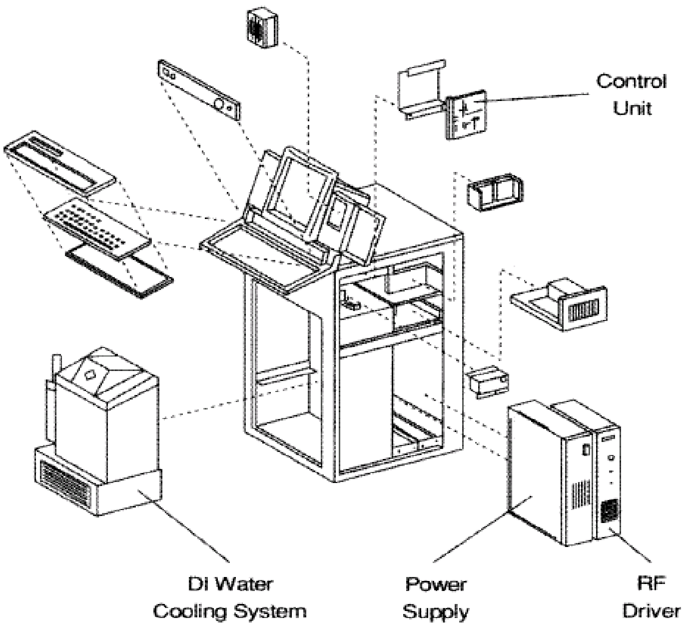


Fig. 14. Exploded view of InstalMark Signature Cabinet.

Support Electronics/ Cooling Systems

The Nd:YAG laser requires a variety of support elements to operate correctly (fig. 14).

The krypton arc lamp requires a stable DC power source delivering approximately 110 VDC at up to 35 amps. The power supply must also include a start circuit to apply a high-voltage ignition pulse across the lamp. The stability of the power source will directly effect the stability of the laser output.

The high-intensity krypton lamp generates a considerable amount of heat which must be removed. Excess heat can damage the expensive Nd:YAG crystal, damage the gold plating, or reduce the krypton lamps operating life. To remove the excess heat, Nd:YAG lasers are cooled by a closed-loop deionized (DI) water system. Deionized water is necessary for its high-optical transparency and 1ow electrica1 conductivity since both the Nd:YAG crystal and the krypton arc lamp are immersed in the water flow. The heat is subsequently removed from the DI water by a water-to-water heat exchanger connected to an outside water source.

For optimum performance, the DI water temperature is regulated by means of a solenoid which turns the outside water flow on and off as required. Regulation of the DI water temperature to within a few degrees further contributes to the stability of the laser output and the marking process.

The transducer in the acousto-optic Q-switch requires an RF power source. For operation of the Q-switch, the RF source is pulsed at frequencies from 1 to 50 kHz corresponding to the desired pulse rate of the lasers. The quartz cell inside the Q-switch is also water-cooled, but it is simply plumbed in parallel with the primary cooling lines to the laser head.

A control unit provides the operator and/or the computer with the means to adjust the laser output power, adjust the pulse rate of the Q-switch, set the position of the safety shutter, and monitor the lasers operation and performance.

Chapter 3 - Marking System Design

The beam-steered laser marking system deflects the laser beam across the surface much like a pencil on paper. Where the pencil deposits lead, the high intensity laser light alters the material to create a contrasting image. Simply stated but not so simply done.

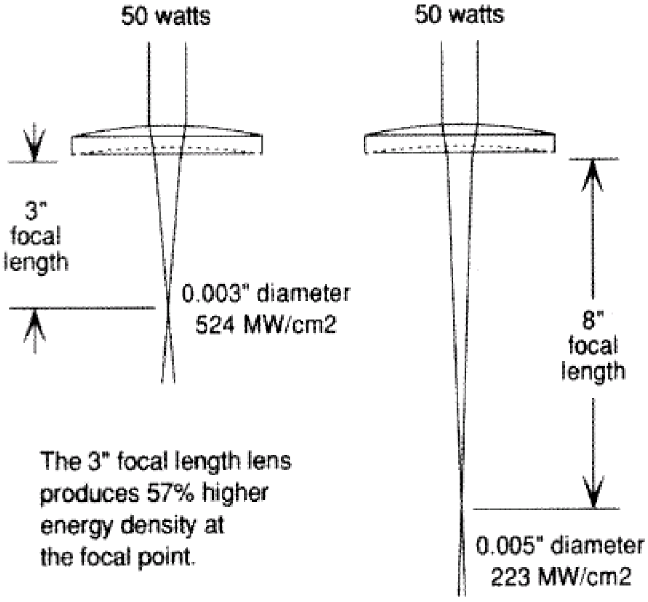


Fig.15. Shorter focal lengths produce higher energy density.

Output Power vs. Energy Density

When discussing beam-steering optics designs, it is important to understand the difference between the laser's output power and the *power density* or *"brightness"* of the laser beam at the work surface.

A continuous wave, 50-watt laser produces the same amount of light as a 50-watt light bulb. The light bulb, designed for general illumination, emits its light in all directions. Unlike the light bulb, the laser *"compacts"* all of its light into a narrow beam. The energy density, usually expressed as *watts per square centimeter,* is an expression not only of the amount of light emitted by the device but also how much light is present in a specific area. The light bulb produces very low energy density illumination with very little light per square centimeter while the laser emits a very high energy density beam of light.

The same principles apply to a focused laser beam. A laser producing 50 watts of light distributed over a 0.003" diameter spot will yield considerably higher energy density then a laser which distributes the 50 wafts over a larger 0.005" diameter spot (fig. 15). As you may have surmised, the true marking power of a system is the energy density produced at the marking surface, not simply the output power of the laser.

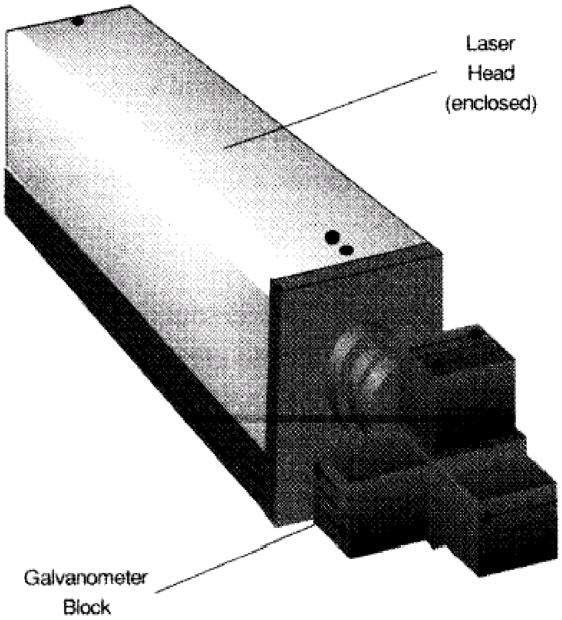


Fig. 16. The beam steering and focusing optics are located in the galvonometer block.

Delivery Optics Designs

The output beam of the Nd:YAG laser is directed and focused by optical components located in the *galvanometer* block (fig.16). Beam-steering is accomplished by two mirrors mounted on high-speed, high accuracy galvanometers. The galvanometers are mounted to provide independent beam motion on both the X and Y axes of the marking field and are crucial to producing a high quality marking image.

There are presently two designs for focusing the laser beam at the marking surface. Both designs utilize an optical telescope called an *upcollimator* to enlarge the beam and a focusing lens assembly to subsequently focus the beam on the marking surface.

The upcollimator increases the diameter of the laser beam prior to focusing. Although this may sound counter-productive, the diameter of the focused spot is determined by the diameter of the incoming beam and the focal length of the lens. As the diameter of the incoming beam increases with upcollimation, the focused spot will be correspondingly smaller and the energy density higher. As an added bonus, the larger beam diameter reduces the energy density at the surfaces of the steering mirrors to insure long term, reliable operation without thermal damage.

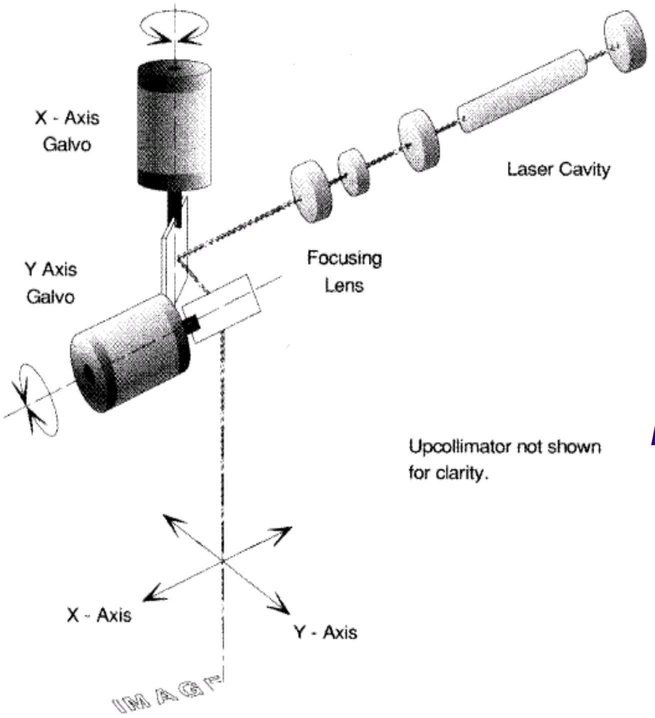


Fig. 17. Pre-focus beam-steering design.

The practical limitation to increasing the beam diameter is the size of the steering mirrors that are required to direct the beam without clipping or distortion. As the beam diameter increases, the increased mass of correspondingly larger mirrors reduces the maximum travel speed and detrimentally effects positioning accuracy. Each manufacturer optimizes the combination of upcollimation ratio and mirror size to achieve the best overall performance.

Pre-focus Delivery Optics

The two designs differ after upcollimation of the laser beam. The *pre-focus* design places a simple focusing lens after the upcollimator but before the beam-steering mirrors (fig. 17). This design requires a relatively inexpensive refocusing assembly and can provide large diameter marking fields.

One disadvantage of this design is a large focused spot size and corresponding reduced energy density. Both result from the long focal lengths that are required to accommodate the distance from the lens to the work surface (see lens performance specifications for relationship of spot size to focal length). Also, because the focal length of the lens is fixed, the focal point follows an arc as the marking beam sweeps across the marking field. As the beam travels from the center to the edge of the field, the focal point is elevated above the work surface due to the pendulum effect. The beam diameter and energy density will change dramatically across the field. Some systems attempt to compensate by mechanically adjusting the focal length to maintain the focal point on a flat plane.

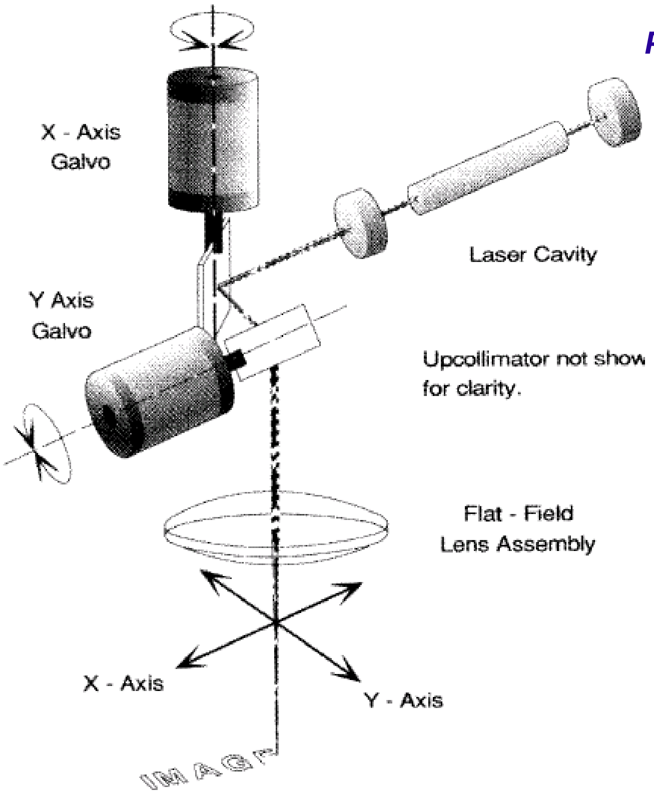


Fig. 18. Post-focus beam-steering design.

Post-focus Delivery Optics

The more common *post-focus* design places a multi-element, flat-field focusing assembly after the beam-steering mirrors (fig. 18). The multi-element lens is more costly than the simple lens used in pre-focus designs but provides the significant advantage of optically maintaining the focused spot on a flat plane throughout the marking field. The marking characteristics and image quality will remain consistent throughout the marking field without resorting to mechanical compensation.

Post-focus systems are available with a variety of lens options to tailor the systems performance to the application. The performance table on the following page characterizes the lenses available with the InstaMark Signature®. In general, longer focal lengths will provide larger marking fields at the expense of larger focused spot sizes and reduced energy density. The desired line width, marking depth, and marking speed must all be considered in selecting the correct lens for a specific job. Fortunately, all of the major manufacturers have applications laboratories which will assist potential users in making the correct lens selection.

Operating Software

The most significant advances to occur over the past ten years have been in the area of the operating software, primarily due to the rapid advances in personal computers. The first generation laser marking systems utilized bulky, slow mainframe computers with teletype keyboards for operator input and paper tape for program storage (and these were considered state-of-the-art at the time!). Later generations incorporated the then new PC with video monitors and floppy disk storage but controlled little more than the marking image and the beam marking velocity.

Today's marking systems feature *Graphical User Interface* (Windows) environments and can control all aspects of the marking process including the marking image, all of the laser operating parameters, and interactive communications with parts handling controllers and host computers. It is not unusual for today's markers to run in fully automated, unassisted manufacturing environments for 24 hours a day.

It is beyond the scope of this publication to detail all of the numerous features, benefits, and capabilities of the different software operating systems that are available. Any attempt would become a book in its own right when considering the software customization that the user or vendor can accomplish to tailor the systems operation to a specific application and manufacturing environment. Some examples of custom configurations are provided in the chapter on system integration. In addition, a demonstration disk of the InstalMark Signature® software is included with this manual.

> *** Tip:** The operating software must function in any number of capacities during normal operation. At one point it is a CAD system, at another, a drawing package, and at another a simple text editor. Do not be over-influenced by how "pretty" the screen is or by how many tools are available to draw a line.

How efficiently will it get the job done? Remember, for greater than 90% of the time the marking system is a machine tool. Programming, drawing, etc. will effect less than 10% of the systems productivity and resultant cost savings.

Flat-Field Lens Performance Specifications*

Focal Length		3"	5"	8"
Field Diameter	(in)	3	5	8
Distance	(in)	2.38	7.38	11.5
Depth of Field	(in)	0.059	0.133	0.200
Line Thickness	(in)	0.0025	0.004	0.008
Resolution	(in/step)	0.0002	0.0003	0.0005
Power Density	(Mwatts/cm^2)	524	223	102

**Measurements taken with 50-watt multimode laser output.*

Chapter 4 - Process Principles

Laser marking is a non-contact, thermal process relying on the heat generated by the laser beam to alter the surface of the workpiece. To achieve the desired results, the marking system provides the operator with several means of controlling the thermal reaction either manually and/or by computer control.

Lamp Current

The output power of the laser is adjusted by increasing or decreasing the electric current to the krypton arc lamp. As the current is changed, the light output from the lamp and the rate of laser amplification increases or decreases accordingly. Open-loop computer control of the lamp current was introduced about seven years ago and closed-loop current control based on the laser output power was introductory Control Laser approximately two years ago

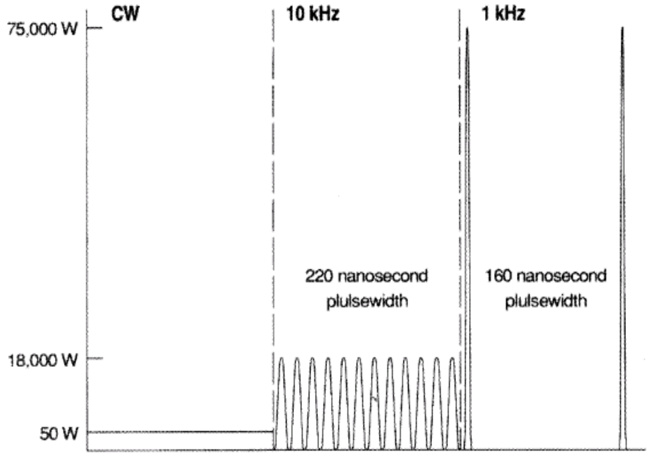
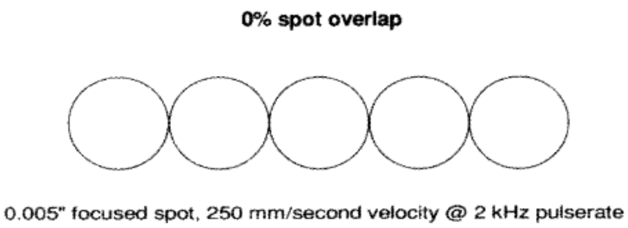


Fig. 19. The Q-switch separates the laser output into pulses of light.

Pulse Rate

After establishing the overall quantum of light amplification with the lamp current, the operator may adjust the Q-switch pulse rate (see Chapter 2, The Acousto-Optic Q-Switch). The Q-switch effectively divides the laser output-to pulses of light (fig. 19). To best understand the phenomena, visualize the Q-switched laser as an optical capacitor. Much like an electric capacitor, the laser stores energy (in the upper laser level) during the non-lasing periods between pulses. When the laser is pulsed by the Q-switch, the output is a burst of light containing most of the stored energy. If the pulse rate is set to a low frequency (1 kHz), the comparatively long duration between pulses will produce very high peak power pulses with very narrow pulse widths (app. 100 nanoseconds). If the pulse rate is increased to 10 kHz, the peak power will be much lower due to the shorter *''charge'' time* between pulses.

What does this mean to the target material? The high peak power pulses at low frequencies will increase the surface temperature very rapidly resulting in material vaporization and minimal heat conduction into the part. At higher rep rates, the lower peak power will produce much less, if any, vaporization but will result in significantly more heat conduction. The Q-switch pulse rate is probably the most important variable for control of the thermal process. As with the lamp current, the pulse rate can be controlled either manually or by the part program.



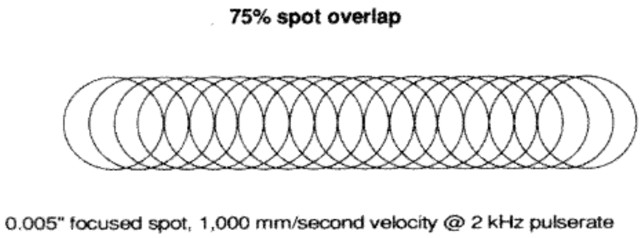


Fig. 20. The beam velosity determines the percentage of pulses overlap.

Beam Velocity (Marking Speed)

After the laser output has been configured with the lamp current and pulse rate, the operator must establish the beam velocity for marking.

In a perfect world, every application would run at the maximum speed for the highest system throughput. In laser marking however, the beam velocity is another important variable in the thermal process and must be set to achieve the desired process results. For deep marking (typically >0.002") each point on the engraved line will require exposure to several pulses to achieve depth. The beam velocity must be reduced until the desired depth is achieved (fig. 20). For shallow marking, the speed may be increased to the system's maximum velocity or until the separation between pulses is aesthetically unacceptable at the pulse rate setting. As a general rule, pulses should overlap at least 50% to give the appearance of a continuous engraved line.

> *** Tip:** Some of the more advanced systems reposition the beam between characters or graphic images independently of the marking speed. As example, the lnstaMark Signature repositions the beam at 32,000mm/sec regardless of the programmed marking speed for considerably faster cycle times.

Determining the best combination of lamp current, pulse rate, beam velocity and lens selection is an art developed after years of developing laser marking applications. The expertise to make this determination resides in the manufacturer's applications laboratory. The applications technicians are the only people fully qualified to determine the best hardware configuration and the optimum process parameters for a your application on their equipment. All serious laser marker manufacturers have this capability. AVAIL YOURSELF OF THIS SERVICE!

Suitable Materials

Nd:YAG lasers are compatible with a wide variety of materials for laser marking. Some of the material characteristics to be considered are:

Reflectivity to the 1.06mm wavelength -The laser light must be absorbed to generate heat. If the target material is highly reflective to the laser wavelength, it may require that the power be increased, the pulse rate decreased for higher peak power, or the beam velocity reduced. If the material is too reflective, it may not mark at all.

Most metallics are very absorptive to the Nd:YAG 1.06mm wavelength and can be readily marked. Gold is highly reflective and will require more power. Some organic materials such as wood and paper are almost 100% reflective and are subsequently unmarkable.

> *** Tip:** If reflectivity is a problem, it is possible to frequency double the laser to operate at the green, 532nm wavelength which may produce better results. A marking system utilizing a CO_2 laser with a wavelength of 10.6 microns (far-infrared) may also be investigated.

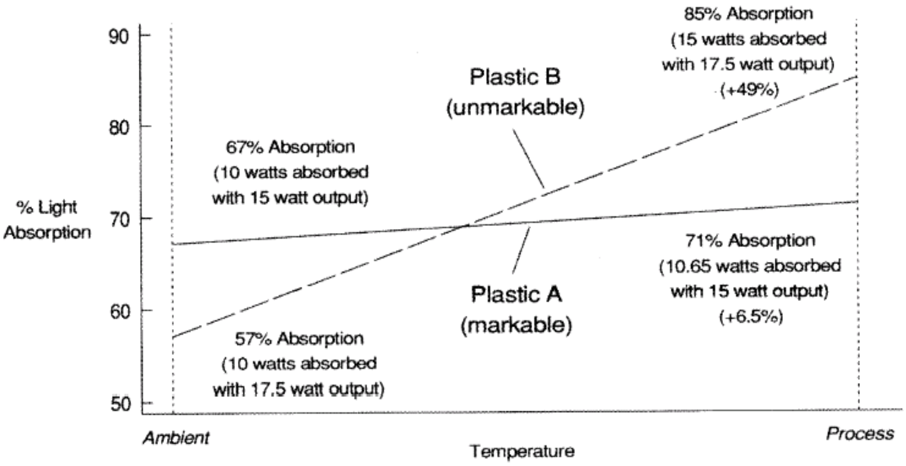


Fig. 21. The steep absorption/temperature curve of Plastic B will produce unacceptable results.

The absorption-temperature curve - The percent absorption of all materials will vary with changes in temperature (fig. 21). Because the laser marking process increases the surface temperature, materials which exhibit a significant increase in absorption may not be markable.

As an example, some plastics exhibit such steep absorption-to-temperature curves that it is almost impossible to achieve an aesthetically acceptable mark. The surface temperature and the percentage of absorption will begin to increase on initial exposure to the marking beam. Unfortunately, as a greater percentage of the laser output is absorbed, the rate of the temperature rise increases correspondingly causing the percentage of absorption to increase even further. The material reaction can runaway in a matter of milliseconds. If the laser power is reduced in an attempt to compensate and regain control of the process, there is insufficient absorption to achieve the initial temperature increase. The plastic will not respond to the laser at all. The alternate wavelengths of frequency-doubled Nd:YAG or CO_2 may effect a more controllable curve should this problem arise.

Thermal conductivity - Thermal conductivity will not completely inhibit laser marking but it may make it more difficult to achieve the desired results. Highly conductive materials will convey heat away from the point at which the laser is attempting to increase the temperature. The temperature rise will be much slower with the loss of heat to the surrounding area. The laser parameters will need to be adjusted to compensate for the material's attempt to *"heat sink"* itself.

Aluminum is a classic example of this characteristic. Compared to steel, aluminum will require somewhat more power and/or slower marking speed to achieve equivalent results.

Color - Dark colors absorb more light than lighter colors. This is equally true with the absorption of laser light, although the difference is usually marginal requiring a minor adjustment to the laser output power, the marking speed, or the lasers pulse rate. Painted colors have little effect since the laser usually vaporizes away the paint very quickly and exposes the color of the base material.

Surface finish - The surface finish of a target part is not a crucial factor in the thermal process itself but may be important for readability considerations. If the laser does not induce a color change, a rough surface will require deep engraving to achieve a readable contrast with the surrounding material. A smooth, machined surface will yield excellent readability with very shallow engraving.

Material hardness - For all practical purposes, material hardness is not a factor in laser marking. The laser can mark a hardened steel part just as readily as the untempered material.

Chapter 5 - Applications

Depending on the material, a contrasting mark can be created using any one of three different techniques. Each method is differentiated by the maximum temperature achieved on the material surface.

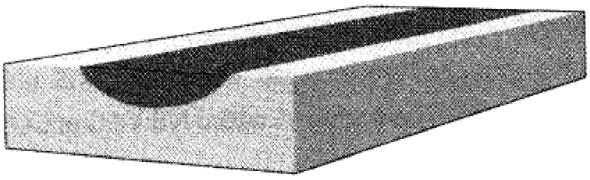


Fig. 22. Surface annealing of metallics.

Surface Annealing

Comparatively low temperatures can be applied to metallics to *anneal* the surface (fig. 22). The marking beam will produce a sharp, contrasting line to the surrounding material with very shallow material penetration. Marking by annealing has the advantage of not disrupting the surface which is important for some medical applications, specifically implantable devices. The disadvantage is that, because the process relies on heat conducting into the material, the beam velocity must be held comparatively slow.

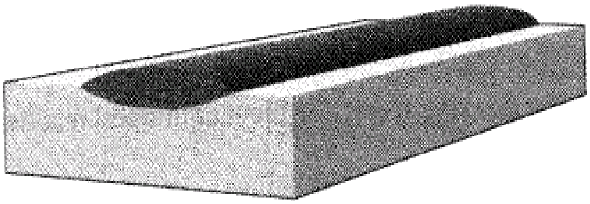


Fig. 23. Surface melting.

Surface Melting

As an alternative, the material can be brought to a *molten state* (fig. 23). This technique is seldom used with metallics as it offers no real advantages. It is frequently employed to induce a color change in plastics. A wide variety of commercial plastics yield excellent color contrast and high quality marking images.

Although the process also relies on conducted heat, the speeds can frequently be very reasonable since the process requires less depth than that required to anneal metallics. Excellent results are routinely obtained at penetration depths of less than 0.001".

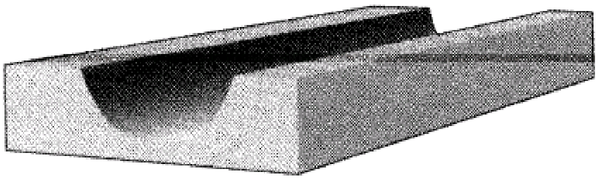


Fig. 24. Material vaporization.

Material Vaporization (Laser Engraving)

The third and most common method is the removal of material by *vaporization* (fig. 24). This technique has the considerable advantage of speed. Because the material is almost instantly vaporized with each pulse, the beam velocity can be set to the fastest speed possible which still achieves the desired depth and maintains acceptable pulse overlap.

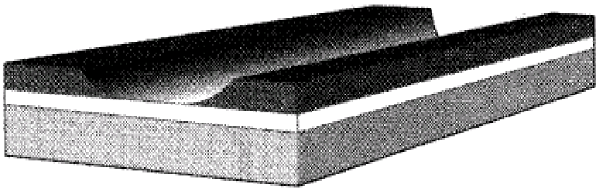


Fig. 25. Multiple color engraving.

Multiple Color Engraving

An interesting variation of this method has been developed for the automotive industry to produce multicolor engraving (fig. 25).

The dashboards of today's automobiles contain a wealth of button activated controls. Push buttons are employed to control driving lights, interior lights, air-conditioning and heating systems, stereo systems, windshield wipers, and even On-board Computers.

The button caps are molded from a colored, translucent plastic and are subsequently painted with a white base coat and a darker, contrasting top coat complementing the color scheme of the vehicle's interior. The laser marking system selectively removes the dark top coat to expose the white undercoat creating the desired text and/or graphic legend. The contrast between the two colors provides excellent daytime visibility. For night visibility, the button is backlit to project the color of the translucent plastic through the engraved legend.