INTRODUCTION TO LASER MATERIALS PROCESSING

COURSE NOTES

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2007

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INTRODUCTION

What is a **LASER**?

- A laser is a device which generates or amplifies light
- **LASER** is the acronym for **L**ight **A**mplified **S**timulated **E**mission of **R**adiation
- Essential Elements of a Laser
    - LASER **Medium** (gas, liquid, solid)
    - **Pumping** Process – must achieve a population inversion
    - Optical **Feedback** Elements – single or multiple pass
- Properties of LASER beams
    - **Monochromatic –** single wavelength
    - **Directional –** low divergence, beam spreads very little
    - **Intense –** high density of usable photons
    - **Coherent –** same phase relationship

Why Use Lasers For Materials Processing?

1. **Non-contact**
    - No tool wear as with traditional milling machines or EDM
    - Reduces chance of damage to process material due to handling
2. **No solvent chemicals**
    - Reduced waste handling costs – environmentally clean
    - Lasers can provide one-step alternative to chemical etching process
3. **Selective material removal**
    - Proper selection of laser wavelength and energy density on-target allows removal of one type of material without damage to underlayers
    - Examples: wire stripping, flex circuit contact exposure, thin film removal

4. Flexibility

- Laser material processing systems incorporate advanced computer control with programming interfaces that permit “soft retooling”
- Good for prototype work where high tool-up costs must be avoided

Heavy Manufacturing	Light Micromachining Applications	Electronics	Medical	General
Profile cutting in sheet and plate metals	Profile cutting in plastics and wood	Via formation in dielectric material: Tab, flex, MCM, PCB, PCW, BGA	Flow orifices <100µm diameter, catheters, angioplasty balloons	CVD diamond cutting, ink jet orifices
Seam and spot welding	Engraving	High accuracy wire stripping	Drilling and cutting delicate or thermally sensitive materials	Ceramic and glass micromachining
Drilling	Drilling	Contact exposure in flexible circuits	Micromachining applications where edge quality and cleanliness are critical	Thin film patterning; micro-lithography
		IC repair	Marking	

Table 1. Typical laser applications.

	Practical Resolution Limit	Attainable Aspect Ratio*	Taper	Undesirable Side Effects	Status of Technology Development
Excimer Laser	2 µm	>100:1	Yes	Recast layer	Moderate
CO_2 Laser	75 µm	100:1	Yes	Recast layer, Burring, Thermal	High
Nd:YAG	10 µm	100:1	Yes	Recast layer, Burring, Thermal	High
EDM	100 µm	20:1	No	Surface Finish	Moderate
Chemical Etch	200 µm	1:1.5	Yes	Undercutting	Moderate
Mechanical	Ø 100 µm	10:1	No	Burring	High

*Depth/hole diameter

Table 2. Comparison of machining methods

Laser Theory and Operation

Brief Review of Laser Physics

Quantum Theory of Light

The Quantum theory of light was developed by Planck & Einstein in the early 1900s. The theory states:

- Light is quantized in discrete bundles of energy called "photons"
- Photons are emitted when atoms or molecules drop from an excited energy state to a lower state
- Each light photon has an associated energy that depends on its frequency (Figure 1)

$$\mathbf{E_{photon} = h\nu_{photon} = E_2 - E_1}$$

Where E_2 and E_1 are upper and lower energy, **h** is Planck's constant (h = 6.626 x 10^{-34} J-s), and ν is the frequency of oscillation (s^{-1}).

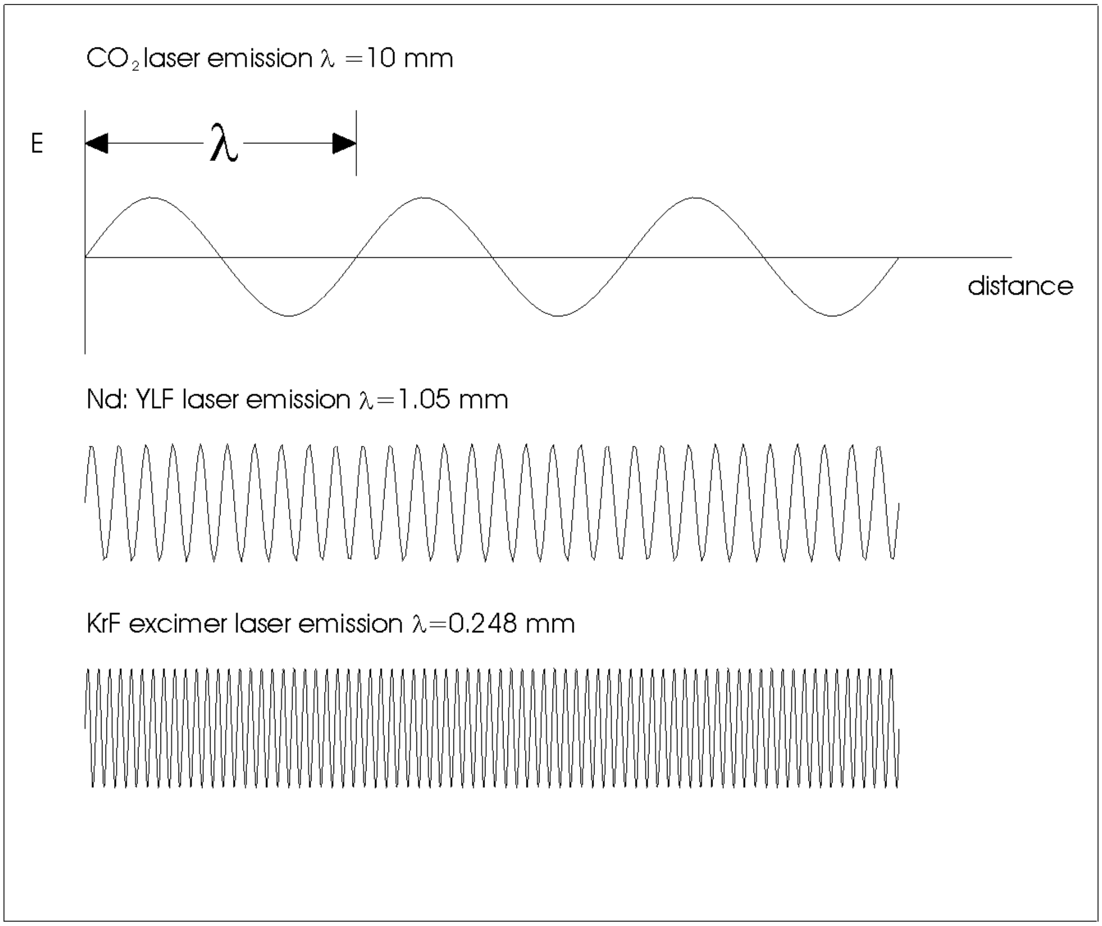


Figure 1- Comparison of Laser Wavelengths

- Although light is packaged in discrete photons (particle theory of light), light also is characterized by frequency and wavelength λ (wave theory of light):

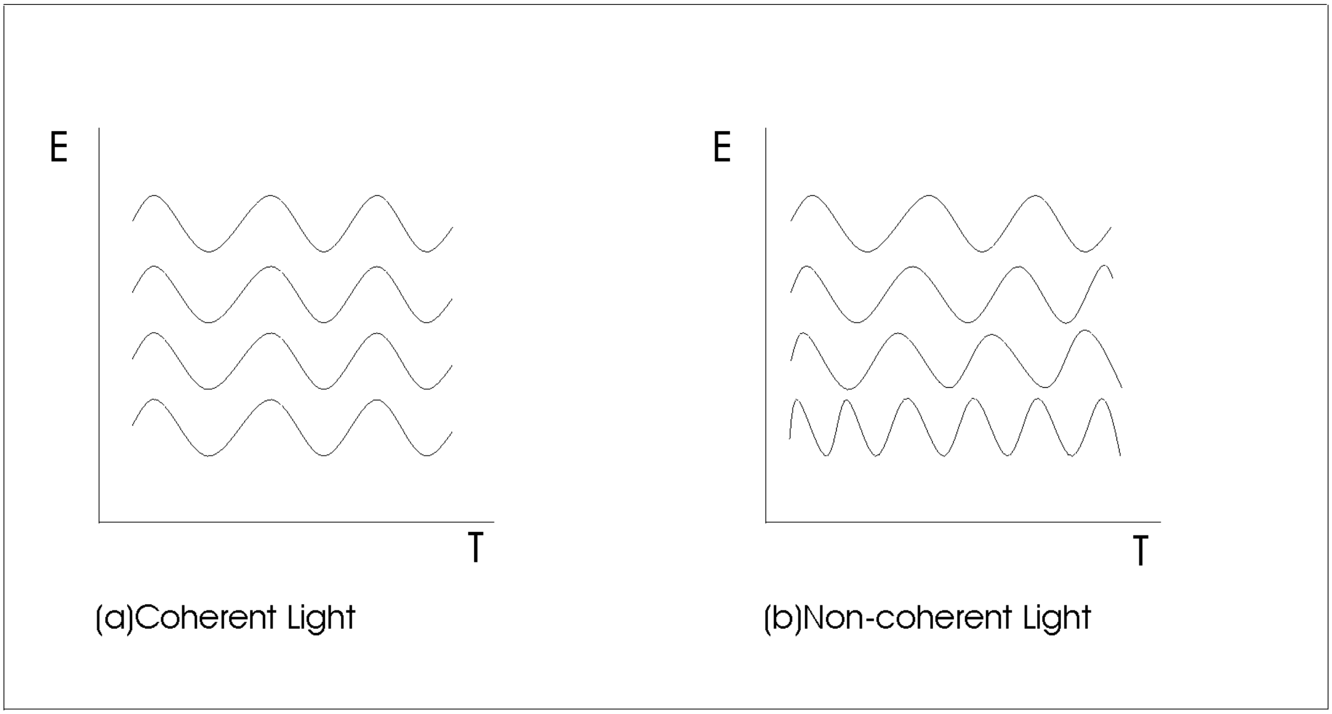
$$\boldsymbol{\lambda = c/\nu},$$

where **c** = speed of light = $\mathbf{3 \times 10^8}$ **m/s**.

- Consequently, photon energy is proportional to frequency but inversely proportional to wavelength.

Coherence and Divergence of a Beam

A laser beam is highly coherent and has small divergence. Coherence is where the phase relationship between any two points in the beam remains exactly the same (Figure 2). In other words, the amplitude of the oscillations and the wavelength of oscillations are identical and are exactly in phase.



(a)Coherent Light

(b)Non-coherent Light

Figure 2- Coherence Properties of Light

Any light that exits a confined space will undergo divergence. In laser physics divergence is the degree of spreading a laser beam exhibits after it exits the front aperture (Figure 3). In machining applications, divergence is undesirable because it leads to reduced energy and distorted images at the target surface.

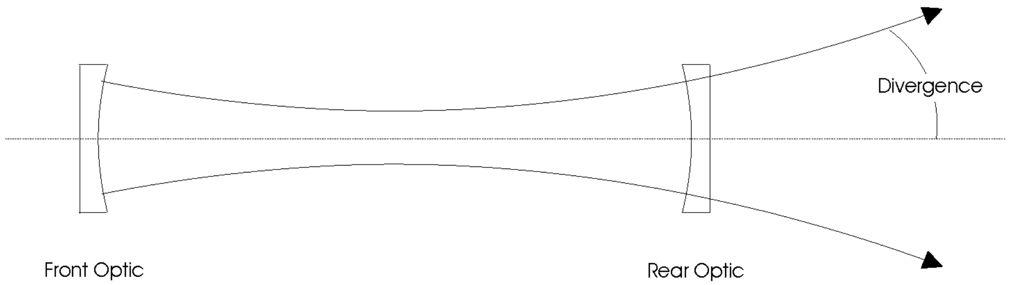


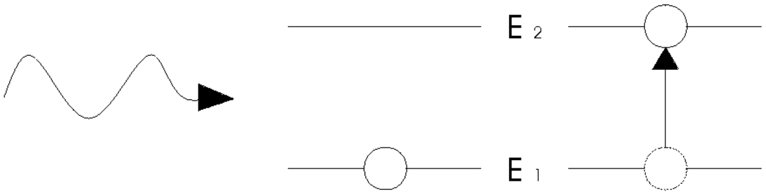
Figure 3- Divergence characteristics of a laser beam, normally given in units of milliradians.

Photon Interactions with Matter

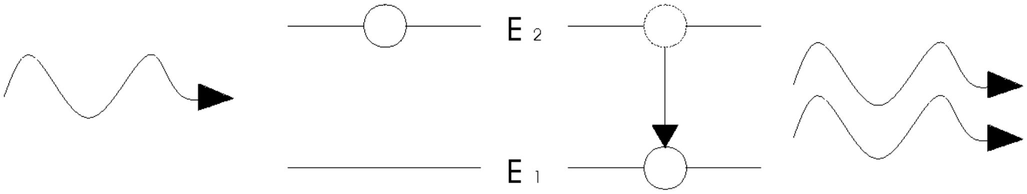
Possible photon interactions with matter include the following:

- **transmission** – Some photons go through some materials, perhaps associated with decrease in energy or change of direction
- **absorption** – the photon is absorbed by an atom or molecule
- **scattering** – the photon is scattered either elastically or inelastically
- **spontaneous emission** – the atom or molecule spontaneously drops to a lower energy state, giving off a photon
- **stimulated emission** – the photon stimulates the atom, causing it to emit an additional photon with identical characteristics to the stimulating photon

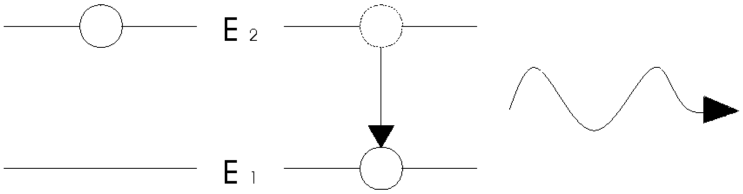
Figure 4 diagrams photon absorption and emission.



Resonant photon absorption.



Stimulated photon emission. Energy, wavelength, phase and direction of a stimulated photon are identical to the incident photon.



Spontaneous photon emission.

Figure 4- Photon Absorption and Stimulated Emission

Reaction cross-section is a measure of probability that a reaction will take place, assuming the basic constituents needed for the reaction are present. Therefore, stimulated emission cross-section $\sigma_{\text{stim emission}}$ is the probability that stimulated emission will occur between an excited atom or molecule and an incident photon.

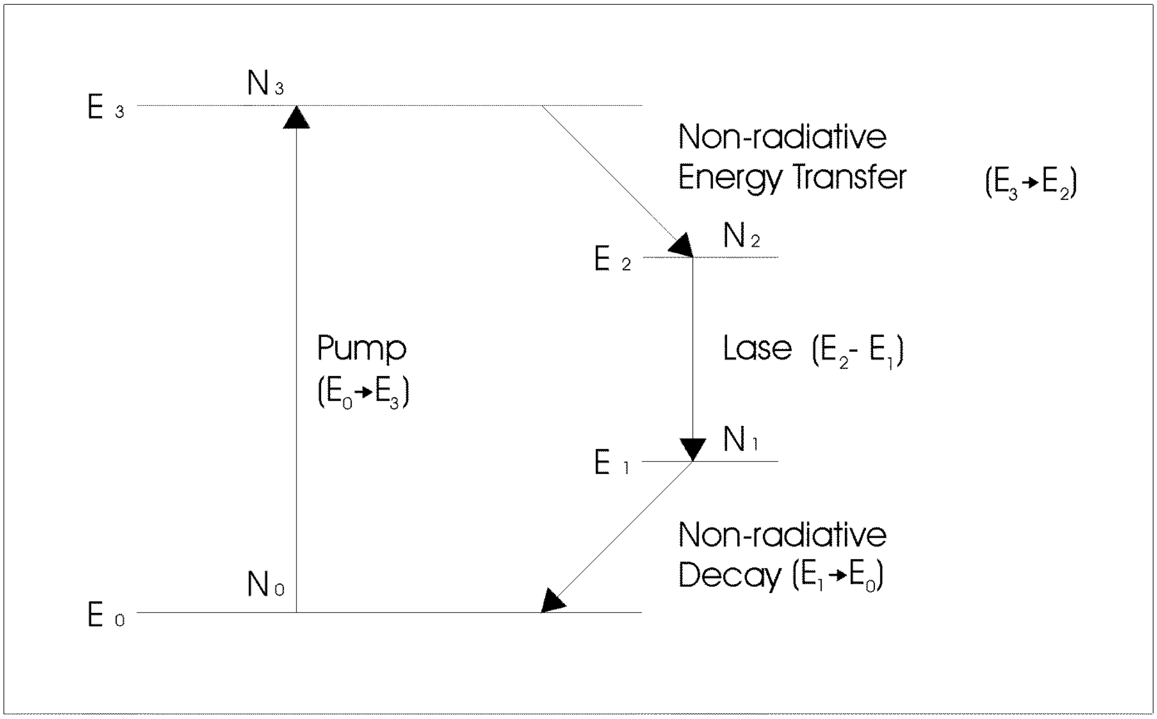
Population Inversion

A laser requires a "population inversion" to sustain an output. A population inversion exists between two lasing energy states when there are more species (N) occupying the upper state than the lower. The process used to excite lower energy atoms or molecules to their excited states is called "pumping".

Requirements for a population inversion in a 4-level system:

- Efficient pump mechanism and energy transfer to populate energy state E_3
- Short lifetime τ_3 for state E_3
- Short lifetime τ_1 for state E_1
- High probability of stimulated emission in the laser medium, i.e. high stimulated emission cross section $\sigma_{\text{stim emission}}$

A population inversion exists when $N_2>N_1$ in Figure 5. Consequently, the laser pumping mechanism must be sufficient to replace those excited atoms or molecules undergoing spontaneous emission from E_2, and those encountering photon absorption from state E_1 to E_2. Furthermore, if non-radiative decay lifetimes τ_1 or τ_2 are too long, an insufficient population in the upper energy state will result and will not support a laser pulse.



Essential Elements of a LASER Oscillator

A laser requires a lasing medium, pump process and a resonator cavity to sustain oscillation (Figure 6). The lasing medium can be a gas, solid, liquid, or semiconductor. The pump process excites the atoms or molecules of the lasing medium to an upper energy state by electronic means or kinetic energy transfer. Laser transmission is initiated by spontaneous emission and amplified by stimulated emission along the axis of the resonator cavity. The cavity mirrors reflect the photons back and forth through the laser medium for increased amplification.

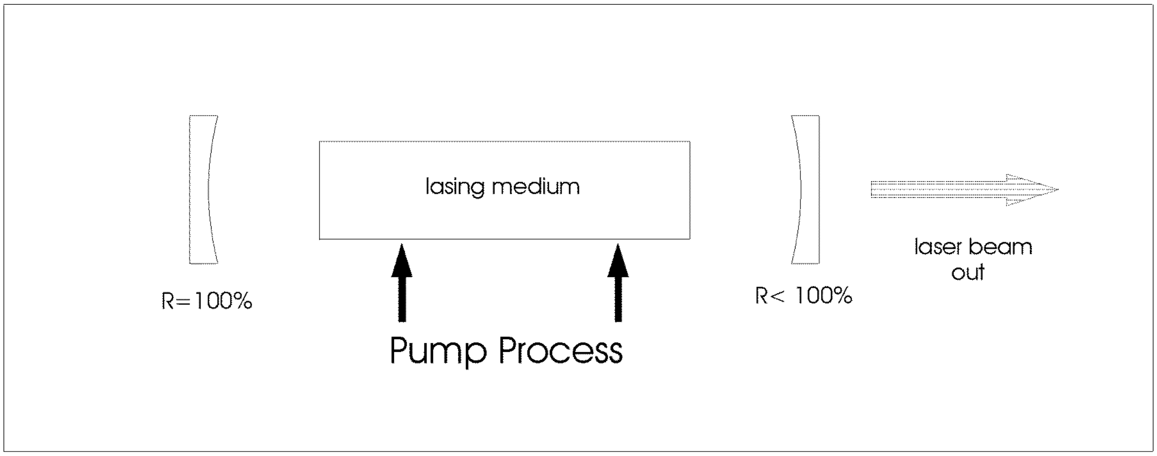


Figure 6- Essential Elements of a Laser

Characteristics of the laser cavity:

- Rear resonator mirror is fully reflective
- Front optic is partially reflective and partially transmissive – for a helium-neon laser, the front optic is about 98.5% reflective, for an excimer laser, the front optic is only 10% reflective because of the high gain in the laser medium
- Resonator optics can be concave, as in a helium-neon laser, or flat, as in an excimer laser
- Lasing medium must have high stimulated emission cross section so more photons are produced than absorbed
- Methods of laser pumping: gas discharge, optical (flashlamp), chemical pump, laser pump, electron beam excitation, diode laser pump

Energy is introduced into the laser through the pumping process, but only a fraction of the “wall plug” energy is present in the laser beam as it exits the front aperture. A typical laser might be less than 10% efficient. Most of the energy is lost in the form of heat.

Types of Industrial Lasers and Their Categorization

Lasers are categorized according to lasing medium. The four basic types of laser media are gas, solid state, semiconductor and liquid dye. Emission frequencies of industrial lasers vary from the IR into the UV (Figure 7). Only gas and solid state lasers are practical for most industrial machining applications, although new solid state devices show great promise. Dye lasers are generally not used in industrial settings primarily because of the highly carcinogenic nature of the dyes and solvents.

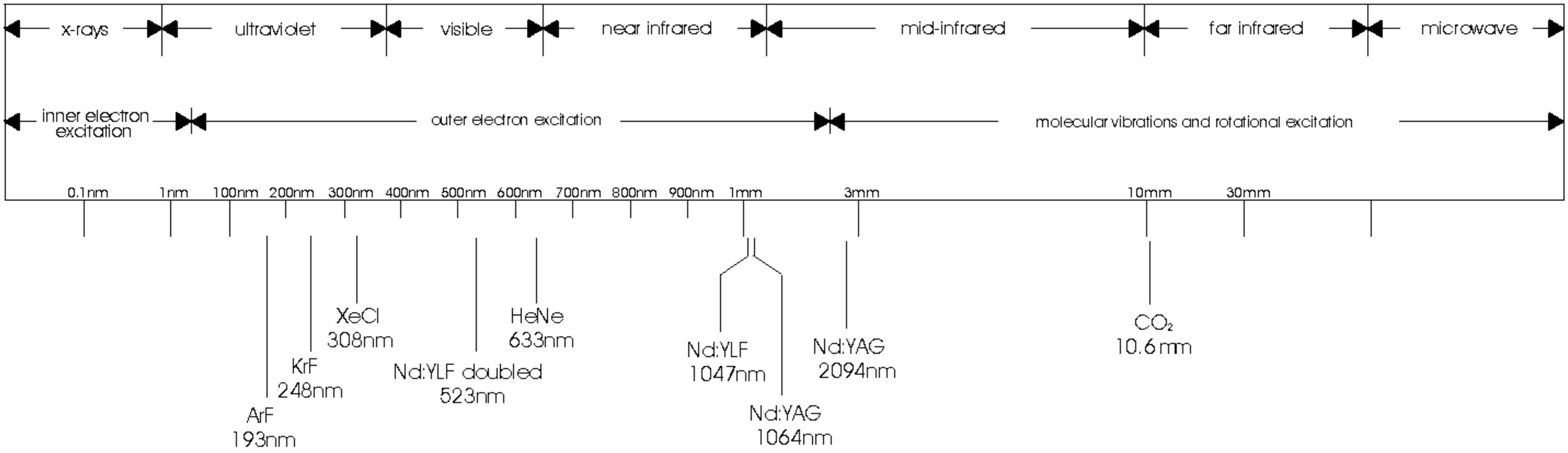


Figure 7- The Electromagnetic Spectrum

Type	Medium	Wavelength
Gas Lasers	Excimer	193-351 nm
Gas Lasers	CO_2	10 µm
Solid State Lasers	Nd:YAG (Fundamental)	1.064 µm
	Nd:YLF	1.047 µm
	Nd:YAG (2nd harmonic)	532 nm
	Nd:YAG (3rd harmonic)	355 nm
	Nd:YAG (4th harmonic)	266 nm

Table 3. Common lasers used in industry.

CO_2 Lasers

Characteristics of Carbon Dioxide Lasers

- most common laser in industry
- inexpensive
- wide range of power output capabilities
- high efficiency
- emission frequency of 9.4 - 11.0 um (infrared)
- high penetration depth (5 – 25 um or more)
- machining is a thermal process – material/photon interaction is primarily via vibrational excitation
- usually used in focal point machining mode except for CO_2-TEA lasers

CO_2 Laser Operational Theory

A carbon dioxide laser uses a gas mixture of CO_2:N_2:He. The CO_2 molecules constitute the active lasing medium, the N_2 gas serves in an energy transfer mechanism and the He atoms enhance the population inversion by depopulating the lower energy states. The population inversion and lasing transition in a CO_2 laser is established between vibrational and rotational energy states. Most CO_2 lasers are pumped by a high pressure electrical discharge (Figure 8).

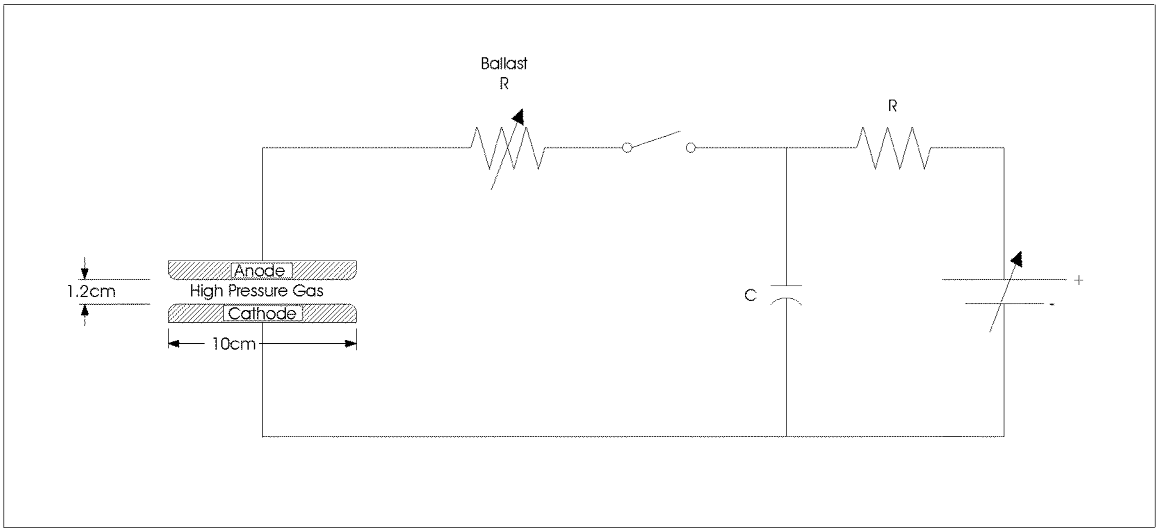


Figure 8- Simplified Electrical Discharge Circuit for a typical CO_2- TEA laser

Gas Discharge Circuit Operation

1. Storage capacitor is initially charged when switch is open
2. When switch is closed, the capacitor discharges through anode and cathode
3. Surrounding atoms in laser gas become excited due to current flow across electrodes
4. Capacitor C becomes drained of its initial charge as lasing transition in the gas occurs
5. Ballast resistor R used to stabilize voltage across electrodes
6. Switch opens, thereby initiating recharge of capacitor C

Molecular Degrees of Freedom – Energy Storage

Energy is stored in molecules according to their electronic configuration and degrees of freedom associated with their physical construction. Listed below are the degrees of freedom associated with simple molecules in order of increasing energy storage.

- translational motion – 3 degrees
- rotational motion – 3 degrees for all molecules except linear molecules (2 for linear molecules)
- vibrational motion – 3N – 6 degrees (3N - 5 for linear molecules), where N = # atoms in molecule
- outer electron excitation ~ 5 eV
- inner electron excitation ~ 5 keV
- nuclear excitation ~1 MeV

CO_2 is a linear molecule.

Energy Transfer

Excited CO_2(00l) molecules are formed by three methods (Figure 9):

- Inelastic collision between electrons and ground state CO_2 molecules

$$\mathbf{e^- + CO_2(000) \rightarrow Co_2(001)}$$

- Vibrational-vibrational excitation via N_2 molecules (laser gas mixture of CO_2:N_2:He)

    1. Electrons in the gas discharge current excite N_2 molecules vibrationally by inelastic collision

$$\mathbf{e^- + N_2(\nu=0) \rightarrow N_2(\nu=n),\ n = 1\ to\ 8}$$

    2. Excited N_2* molecules transfer energy to CO_2 molecules

$$\mathbf{N_2{}^*(\nu=n) + CO_2(000) \rightarrow N_2 + CO_2(001)}$$

- Electronic excitation and ionization – minor contributor
- Theory and experiment show that 60% of wall plug power can be channeled into pumping the upper CO_2 laser level, resulting in up to 27% wall plug efficiency. Intervibrational energy transfers from N_2 account for this efficiency.

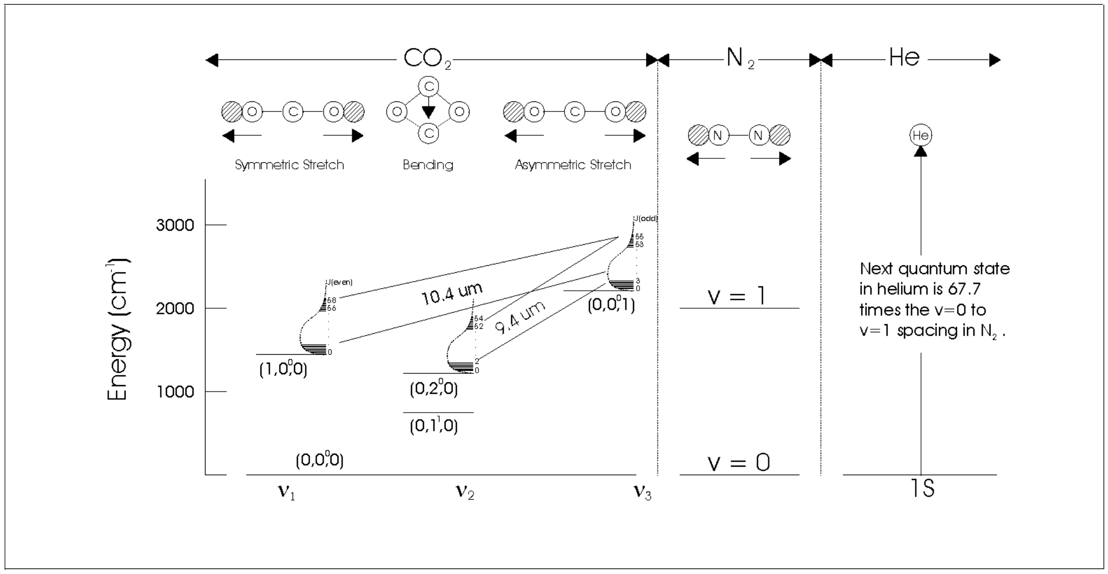


Figure 9- CO_2 laser pumping scheme and energy-level diagram. The quantum numbers ($\nu_1 \nu_2 \nu_3$) indicate the amount of energy in each of the vibrational energy modes illustrated at the top. The J quantum numbers indicate rotational energy states. The vertical axis is graduated in cm^{-1} which is another measurement of energy equivalent to $1/\lambda$.

Types of CO_2 Lasers

Type	Beam	Delivery Method	Applications
CW	Lower order mode Gaussian	Focal spot	High speed profile cutting; seam welding; cladding; engraving
Gate pulsed	Lower order mode Gaussian	Focal spot	Cutting and drilling in metals; spot welding
Enhanced pulsed	Lower order mode Gaussian	Focal spot	Cutting and drilling in IR reflective materials
TEA	High order multi-mode	Near-field imaging	Marking in thermally insensitive materials; wire stripping; flex circuits; via drilling

Table 4. Types of CO_2 lasers.

Important CO_2 Machining Characteristics

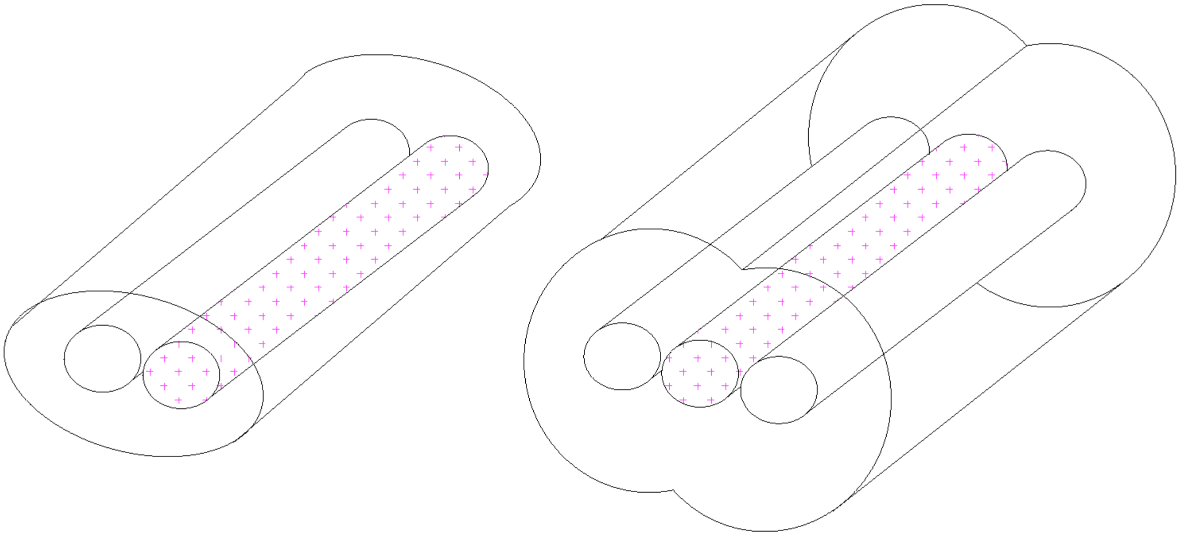
- Material interaction via thermal overload and vaporization
- Penetration depth is 5 to 10 µm
- Ultimate feature resolution ~ 10 µm
- Practical feature resolution ~ 50 µm
- Inert gas used to limit oxidation in process area

Solid State Nd^{3+} Lasers

Solid state lasers are constructed by doping a rare earth element or metallic element into a variety of host materials. The most common host materials are $Y_3A_{15}O_{12}$ (YAG), $LiYF_4$ (YLF) and amorphous glass. The Nd:YAG laser is discussed because it is the most common solid state laser in industry.

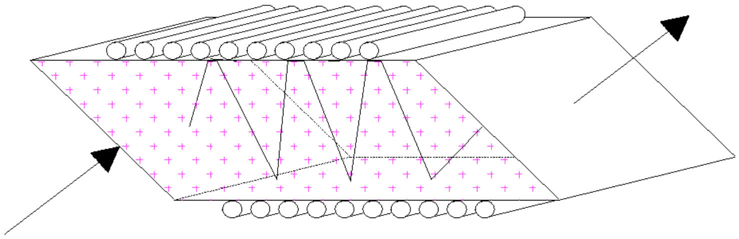
Characteristics of Nd Lasers

- Typical solid state lasers are pumped optically by arc lamps or flashlamps (Figure 10). Arc lamps typically are used for continuous wave (cw) pumping; flashlamps are used with pulsed lasers. Diode laser pumping is becoming increasingly popular and will open doors to new industrial applications.
- Solid state lasers are electronically excited. The atoms of the active medium become excited when an electron jumps to a different orbit around the nucleus. In Nd:YAG and Nd:YLF lasers, the neodymium ions (3^+) constitute the active medium.
- Nd lasers are easy to pump. All Nd lasers (Nd:YAG, Nd:YLF, Nd:glass) are four-level laser systems with numerous absorption bands above the upper lasing energy state $^4F_{3/2}$. Atoms at these states readily decay to $^4F_{3/2}$ making it easy to establish the required population inversion (Figure 11).
- Emission wavelength of Nd doped lasers varies somewhat with different host materials. Some host materials have a less defined lattice structure than others. The energy linewidths in these materials are "broadened" such that the transition wavelengths are different.
- Nd laser outputs can be frequency doubled, tripled or quadrupled through harmonic generation
- Nd lasers respond well to Q-switching



(a) single flashlamp

(b) double flashlamp



(c) multi-flashlamp with complete internal reflection

Figure 10- Typical solid state pumping schemes.

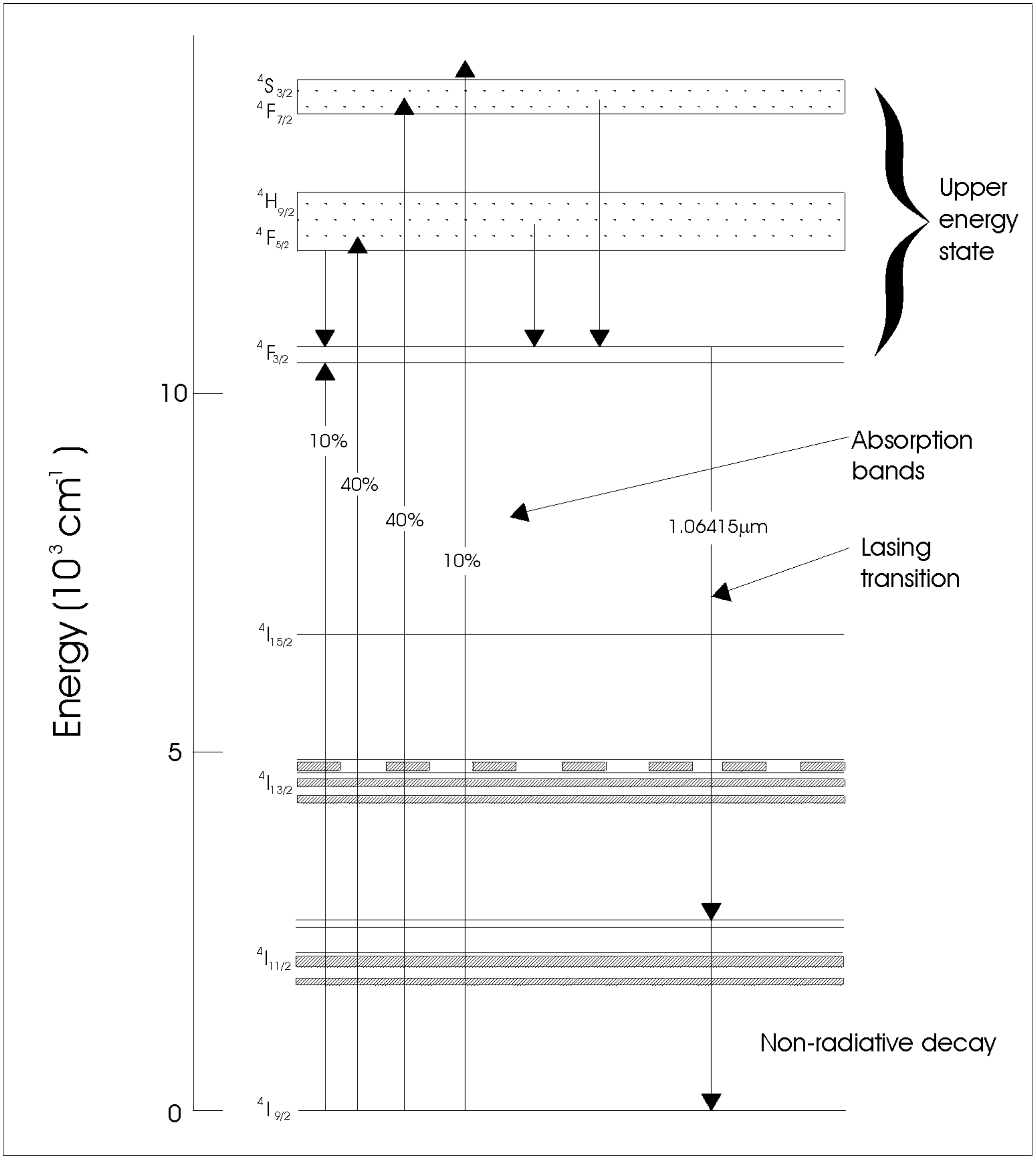


Figure 11- Energy-level diagram and pump scheme for the Nd: YAG laser.

Characteristics of YAG Lasers

Type	Beam	Delivery Method	Applications
CW	Lower order mode Gaussian	Focal spot	Profile cutting; seam welding; cladding; engraving
CW pumped; Q switched	Lower order mode Gaussian	Focal spot	Cutting and drilling in metals; spot welding
Flashlamp pumped, pulsed	Lower order mode Gaussian	Focal spot	Cutting and drilling in metals; spot welding

Table 5. Characteristics and applications of YAG lasers.

Q Switching

Photons that evolve from spontaneous emission in directions other than along the laser axis are amplified like those along the axis. These photons, however, are not reflected back into the cavity and are lost in the environment. The combined loss of photons travelling off-axis is called amplified spontaneous emission (ASE).

A pulse energy enhancement technique called “Q switching” is used in many solid state lasers to minimize the negative effects of ASE. There are several switching devices in use, both optical and electrical. One such Q switch device is an electronic shutter, sometimes called a Pockels cell, that is triggered open and shut by an electrical signal (Figures 12 and 13).

Q-switch technique, step by step:

1. Laser is pumped with Pockels cell shut, cavity loss is high because the shutter prevents oscillation

2. Population inversion (gain) grows because pumping continues but there are few photons to invoke stimulated emission

3. Pockels cell opens

4. Cavity loss is greatly reduced now that oscillation is permitted

5. Optical output is produced causing population inversion to diminish and gain to reduce

6. Sequence is repeated for each laser pulse

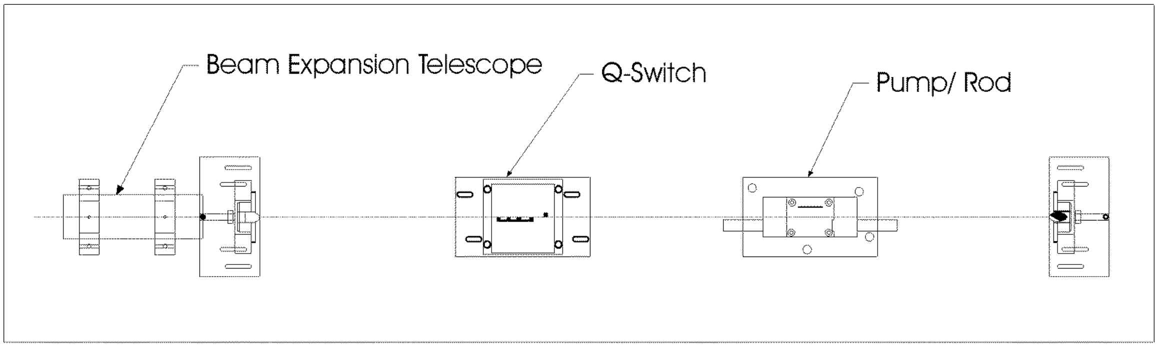


Figure 12- Typical optical layout of a YAG laser.

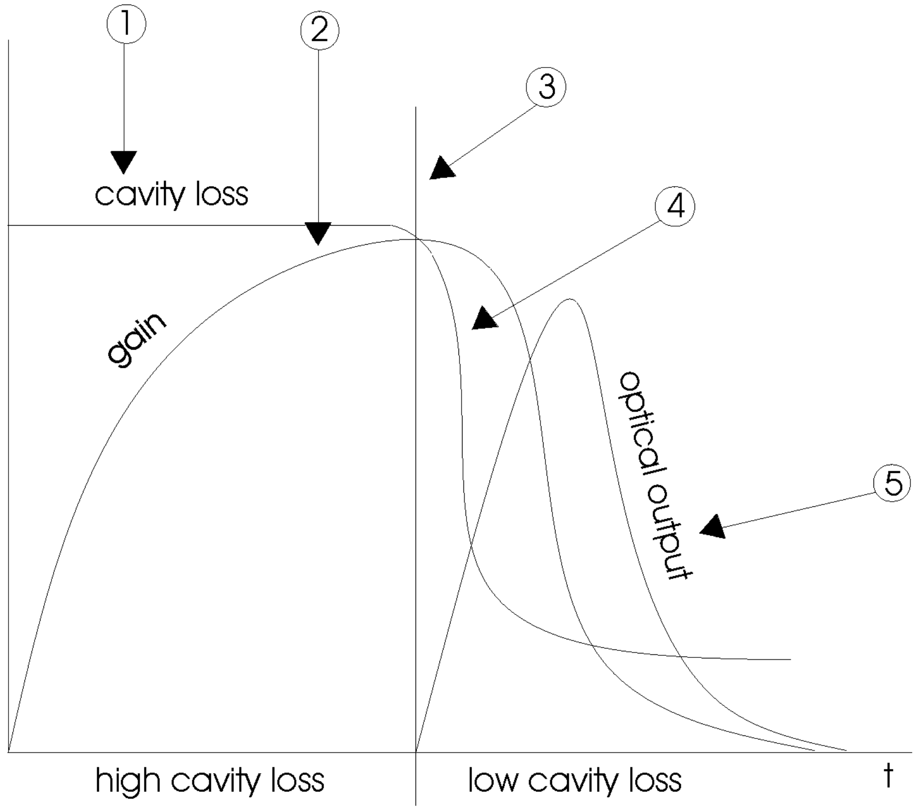


Figure 13- Q-Switching, step by step

Nd:YLF vs. Nd:YAG

- Not all Nd^{3+} lasers have identical characteristics
- For instance, the Nd:YAG fundamental wavelength is 1.064 μm, the Nd:YLF fundamental wavelength is 1.047 μm
- Nd:YLF pulse energy is greater than that for a similarly constructed Nd:YAG laser at low pulse rates as more energy can be stored per Q-switched pulse because the Nd:YLF upper state energy level lifetime, τ_{YLF}, is about three times longer than τ_{YAG}.
- The YAG host material has better thermal conductivity and more stable refractive index than YLF. The resulting parabolic temperature profile within the YLF laser rod produces a thermal lensing phenomenon that focuses the beam just outside the laser rod.
- Other solid state lasers are currently being investigated (Ruby, Alexandrite, etc.) for materials processing applications

Harmonic Generation

As a result of the proliferation of laser experimentation in the 1960's, it was discovered that some materials exhibit a nonlinear optical effect when irradiated with high energy laser emissions. More specifically, the electric dipoles established by the electrons and the nuclei in these materials oscillate in response to incident radiation such that two separate wavelengths of light exit the material. The output of these emissions include the original wavelength and a component half the wavelength of the incident beam. This phenomenon is called harmonic generation. Other techniques also allow sum and difference frequency light generation (Figure 14).

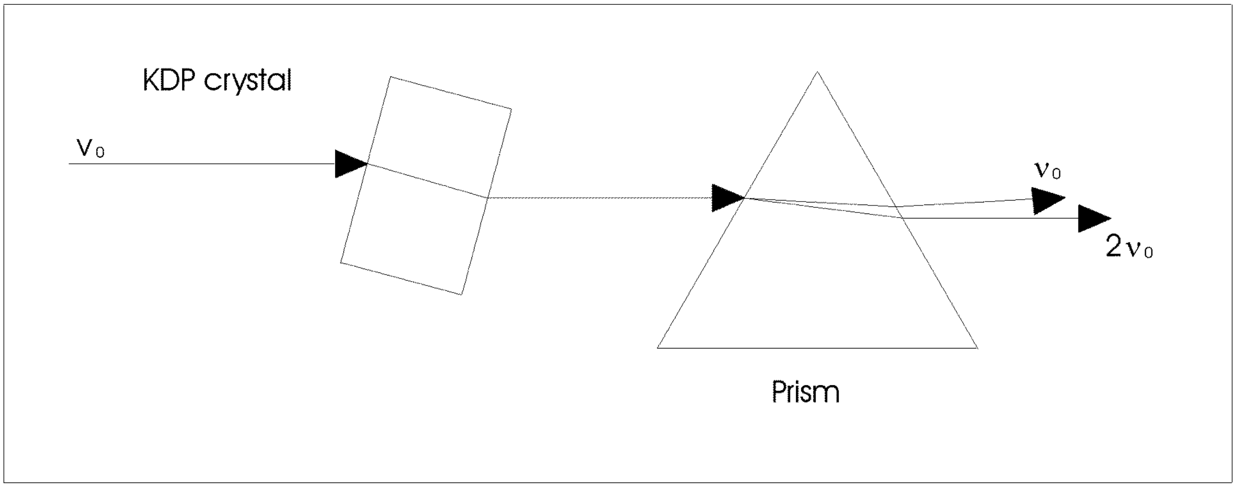


Figure 14- Harmonic generation of a laser beam through an anisotropic medium.

Harmonic generation is useful in creating different wavelengths, however, total output energy of the shorter wavelength component is typically reduced to one-half the energy of the incident radiation or less.

	Fundamental	**Doubled**	**Tripled**	**Quadrupled**
YAG	1064 nm	532 nm	355 nm	266 nm
YLF	1047 nm	524 nm	349 nm	262 nm

Table 6. Harmonic frequencies of Nd:YAG and Nd:YLF lasers.

Excimer Lasers

Brief History of the Excimer Laser

- **Late 1970's – Lasing first demonstrated**
- **Early 1980's – First commercial devices appear (Lambda Physik EMG series, Tachisto)**
    - Short gas lifetime (minutes/thousands of pulses)
    - Short Mean Time Between Failures (MTBF)
    - High operating costs
    - Not "User-friendly"
    - No history of applications development
- **Mid 1980's – Significant engineering advances (Lambda "MSC" series, Questek, computer control)**
    - Electronics upgraded (preionization and circuit protection)
    - First attempts at computer control
    - Materials compatibility investigated
    - Increased gas lifetime
    - Applications development progressing – mostly "scientific"
    - Very first industrial installation (IBM, Siemens)
- **Late 1980's – More engineering advances – "Industrialized" lasers appear (LPXi series, Cymer)**

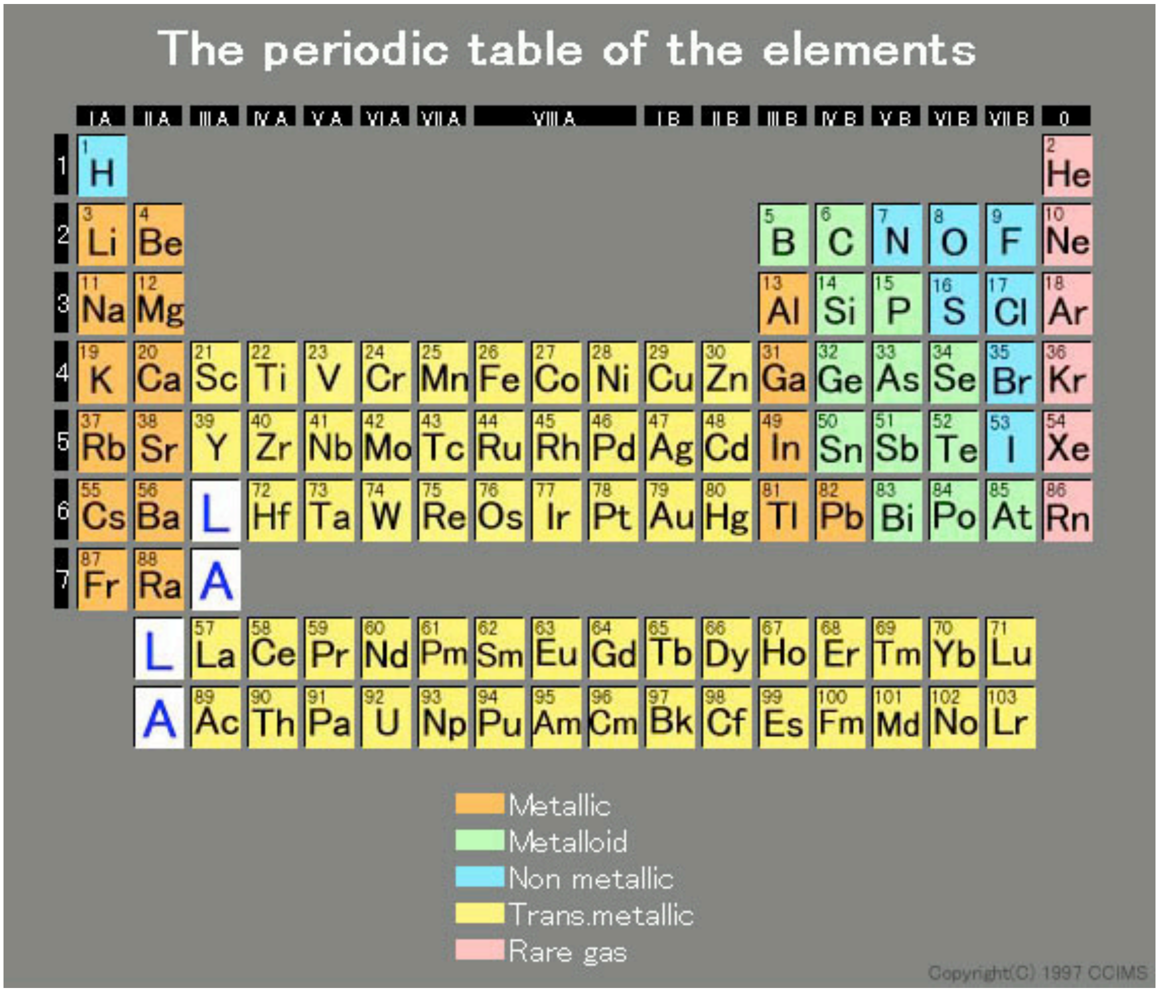
  - Lasers fully computer controlled
  - Longer gas lifetime (days/millions of shots)
  - Increased industrial applications development due to improved lasers, miniaturization trends, unique capabilities
  - Increasing installed industrial base
- **1990's – Materials compatibility issues drive costs down, gas lifetimes up (weeks/tens of millions of shots per fill)**
  - Large installed industrial base (Lambda 1000, 2000, 3000 series, Cymer lithographic lasers, Lumonics Index and PM848)
  - Continued applications development in many new, unique and exciting fields
  - Excimer lasers become increasingly visible in industrial settings: 24 hours/day, 7 days/week operation
  - Excimer lasers become known as the "third" industrial laser alongside CO_2 and solid state lasers

Most excimer lasers are capable of using any of the six gas mixtures available, but it is usually not advisable to mix fluorine and chlorine in the same laser in industrial situations.

Mixture	Wavelength	Gas Lifetime	Average Power	Comments
F_2	157 nm	~10^5 pulses	< 5 Watts	Absorbed by optics and air; requires vacuum beam delivery
ArF	193 nm	~10^6 pulses	30 Watts	Good for low power, high resolution industrial applications
KrCl	222 nm	2 x 10^6 pulses	30 Watts	Lower power, short gas life, not very useful
KrF	248 nm	10^7 pulses	50 – 200 Watts	Good industrial wavelength and power
XeCl	308 nm	2 x 10^7	50 – 200 Watts	Good industrial wavelength, particularly on glass products
XeF	351 nm	10^6	< 50 Watts	Not absorbed by some materials

Table 7. Excimer gas mixtures.

A unique characteristic of the rare or Noble gases is that these gas molecules will not normally form compounds with other elements in their ground energy state. The rare gases will combine with certain elements, however, in their excited state (Figure 15). Such a compound is called a "dimer" molecule and can be used as the active medium in an excimer laser.



The periodic table of the elements

	IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA			IB	IIB	IIIB	IVB	VB	VIB	VIIB	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	L	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	A															
		L	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		A	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

🟧 Metallic
🟩 Metalloid
🟦 Non metallic
🟨 Trans.metallic
🟥 Rare gas

Excimer Laser Energy Transitions and Pump Scheme

The pump scheme for the KrF excimer laser shown in Figure 16 is electronic. The lower Kr + F state is unbound or repulsive; the Kr and F atoms cannot move close to each other because of the lower state energy barrier at the far left. When pumped by the gas discharge, the Kr and F atoms are ionized and form the excited dimer molecule at the upper energy state labeled $Kr^+ + F^-$. The atoms can approach closer, now that the previous energy barrier no longer exists. The lifetime for the KrF^* molecule in this state is less than 5 ns during which stimulated emission must occur, or the atoms will fall to their ground state spontaneously or through collisions.

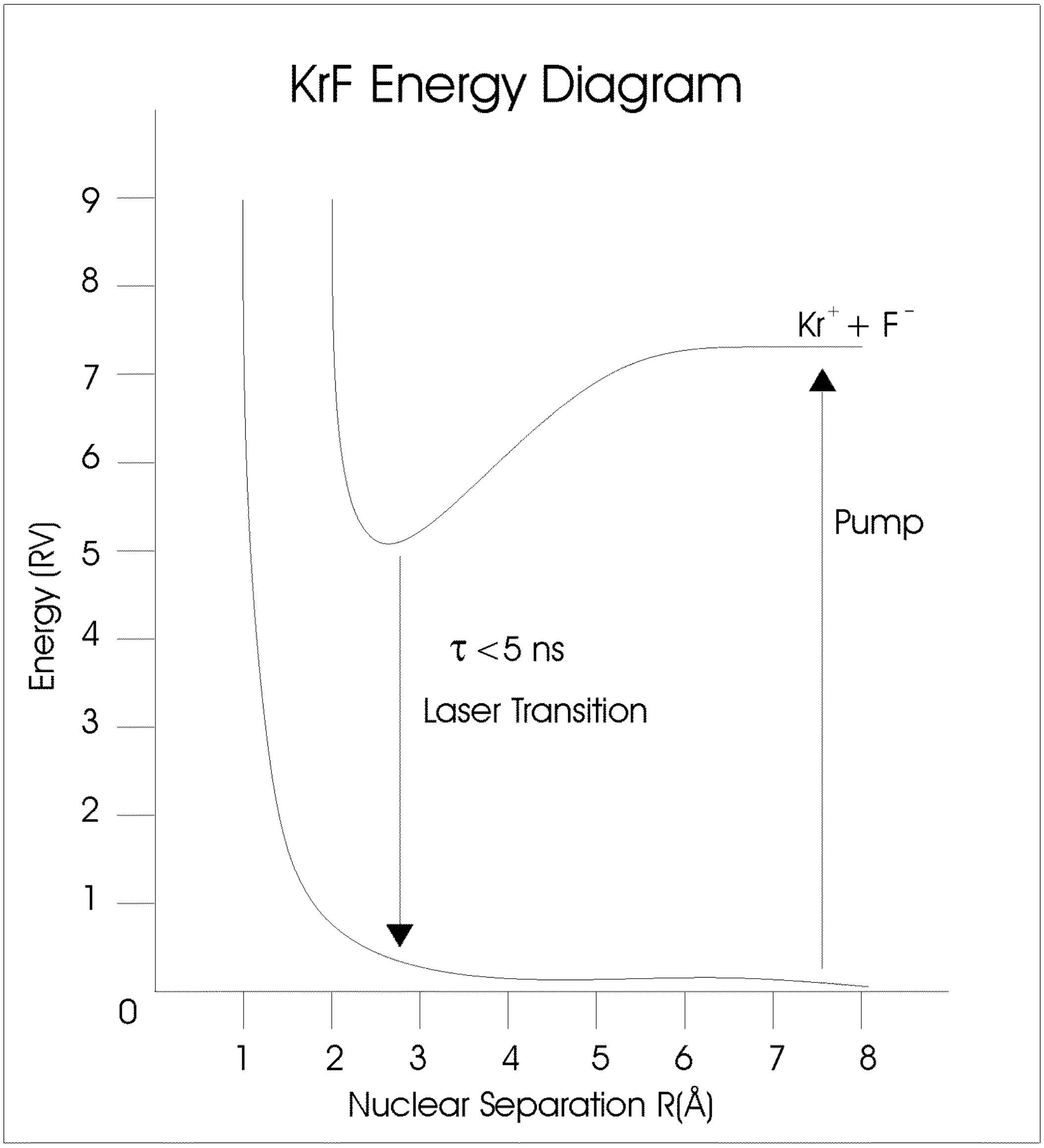


Figure 16- Energy Diagram and pumping scheme for KrF excimer laser.

Important Properties of KrF and Other Excimer Lasers

- Since the lower state does not exist in the bound condition, it is easy to populate the upper, bound state. This condition and the high stimulated emission cross-section for KrF make a population inversion easy to establish and the laser medium gain very high.
- The frequency of the excimer UV transmission is sufficiently energetic to break the chemical bonds of most materials. For many materials machining is accomplished through ablation instead of thermal overload.
- The pumping mechanism for excimer lasers is a gas discharge with up to 45 kV peak excitation voltage. High voltages and currents of this magnitude test the limits of electronic technology. High voltage power supply failures in excimer lasers are an issue to address in proper laser design.
- The partial reflectance of the front resonator mirror is only 10% because of the high gain.

A typical excimer laser gas mixture is a $Kr:F_2:Ne$ blend with neon constituting most of the volume. The neon acts as a third body collision partner in the formation of the excited KrF^* molecule (Figure 17). The voltages and currents required for excimer laser operation test the limits of high voltage electronic technology. Consequently, excimer lasers are more complex than other types of lasers, require more maintenance and are more expensive to maintain.

The laser medium in an excimer laser is pumped by a high speed transverse electrical discharge. DC high voltage is supplied to the pulse forming network that consists of a thyratron switch, magnetic pulse compression circuit and storage capacitors. When the thyratron switch is closed, a high voltage spike is impressed across the preionization pins and electrodes, ionizing the gas and pumping the excimer atoms to their excited state.

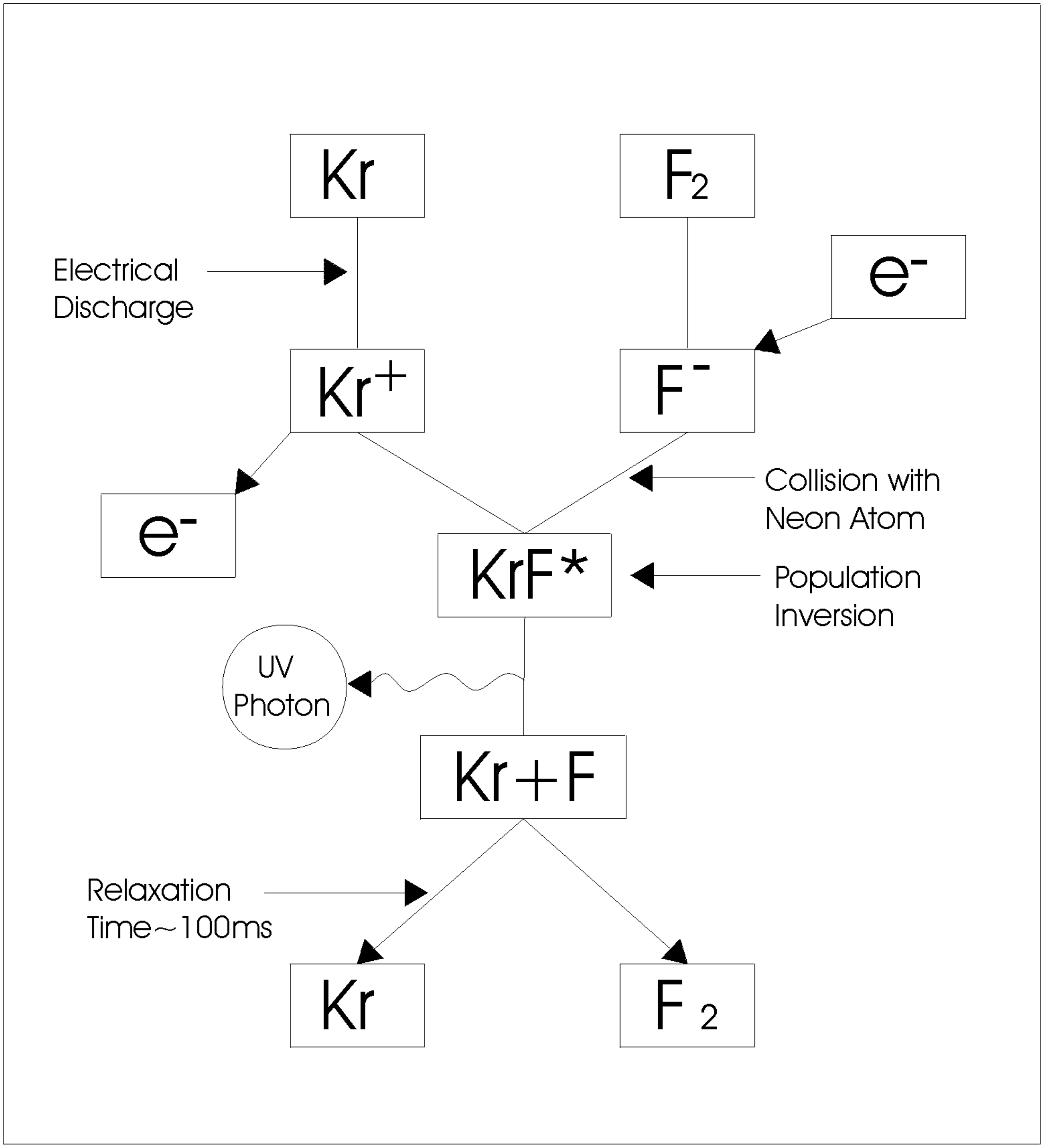


Figure 17- Simplified diagram of molecular transitions in the KrF excimer laser.

Gas Discharge

The actual gas discharge excitation process takes place in four steps: preionization, kinetic transfer, formation of excited dimers and laser transition.

An initial electron density of $10^7 - 10^8$ electrons/cm^3 is required to produce a sufficient population inversion between the upper and lower energy states. Typical industrial excimer lasers employ spark preionization to achieve this. The preionization pins are timed to fire just prior to when full high voltage reaches the electrodes, thereby providing the electron density required.

Step 1: The thyratron actuates and places 45 kv across preionization pins and electrodes, creating a gas plasma.

Step 2: The electrons in the gas plasma are accelerated by the electric field between the electrodes as they transfer their kinetic energy to the surrounding atoms.

Step 3: Excited KrF^* molecules are created by inelastic collision with the electrons. These molecules have an approximate lifetime of >5 ns in their excited state and will decay spontaneously if not stimulated by an additional photon.

Step 4: The laser transition step is initiated by those photons produced by stimulated emission along the laser axis. These photons are reflected back along the axis by the resonator optics at each end of the laser so that they may subsequently produce stimulated emission with other excited molecules. The laser emission occurs in about a 20 ns pulse because the electronic circuitry can not sustain a constant high voltage and the gas discharge is short-lived.

After the pulse is completed, the gas constituents require a 100 ms relaxation period before they can participate in the next discharge cycle.

The relaxation time requirement of the excimer gas mixture places a significant constraint on the pulse rate capability of the laser. The laser is limited to a pulse rate compatible with the 100 ms relaxation time unless the gas between the electrodes is replenished. A typical excimer laser overcomes this constraint by recirculating the laser gas so the volume of the gas is completely refreshed and exchanged several times between laser pulses. At the same time, the gas is cooled and filtered during the circulation process such that repetition rates of 400 pulses per second or higher are achievable.

Major Components of an Excimer Laser

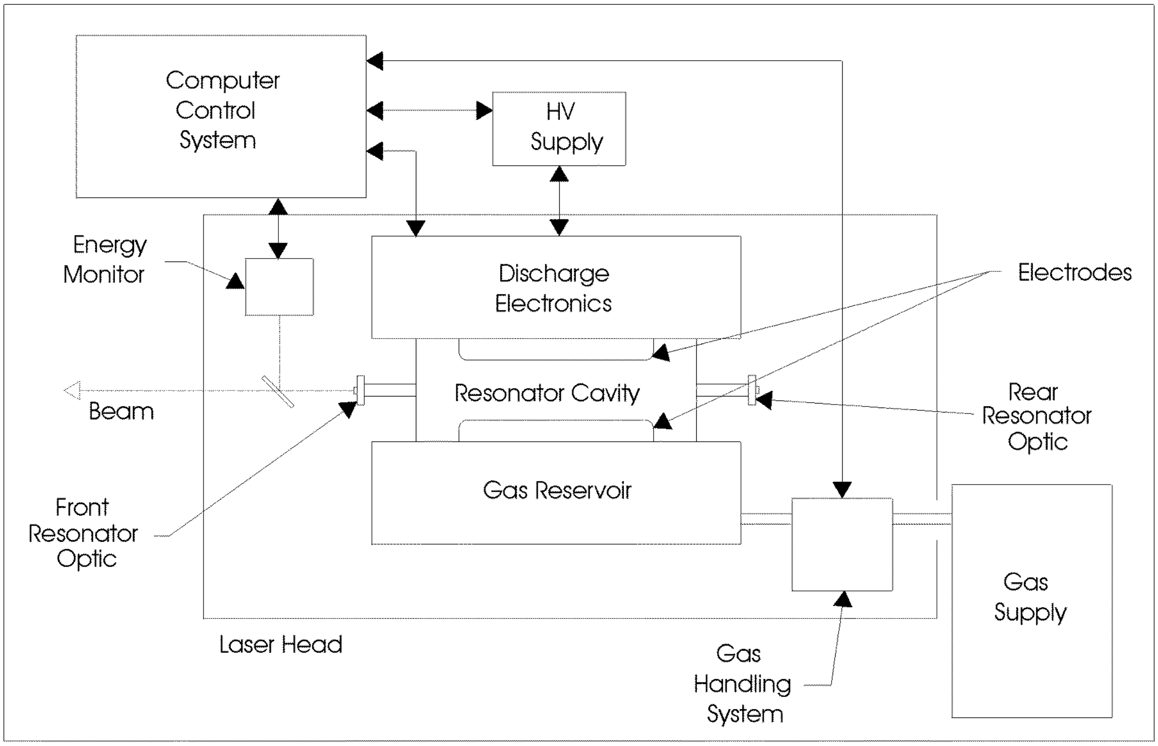


Figure 18- Basic Components of an Excimer Laser

List of components:

Laser head

- Electrodes, preionization pins, rails
- Electrostatic particle precipitators
- Cooling fins
- Blower assembly

Pulse forming network

- Thyratron switch
- Magnetic pulse compression
- Storage capacitors

HV power supply

- Switched mode type
- Delivers stabilized DC high voltage
- At 15-25 kV

Energy monitor

- Beam sampling optics
- Photodiode detector
- A/D circuitry

Gas handling system

- Gas manifold
- Solenoid valves
- Interlock control

Computer control system

- Automated energy stabilization
- Noise immune communications with other subsystems (fiber optics)
- Automated gas adjustments and refills

Excimer Laser Energy Monitoring

During normal operation, laser output energy depends on the high voltage setpoint. Raising the high voltage setpoint increases the energy of the laser beam. Therefore, the output energy of the excimer laser must be monitored to ensure uniform machining. The energy monitor mounted at the front aperture provides pulse energy information to the laser control computer. If the energy varies, the computer increases or decreases the high voltage setpoint to compensate.

As the laser gas ages, high voltage excitation must be increased periodically to maintain laser energy at a constant level. This voltage adjustment can be accomplished by computer or manually. Eventually, the high voltage power supply limit will be reached and separate measures must be undertaken. Three adjustments to the gas mixture are possible:

1. **Halogen injection** – a spurt of fluorine gas injected into the laser reservoir can extend gas lifetime significantly. This method can be repeated several times until further injections are ineffective.
2. **Partial gas replenishment** – a significant portion of the laser gas is removed and replaced with fresh volume in the correct component gas ratios. At some point, even this method becomes ineffective.
3. **New fill** – the entire reservoir is evacuated and replaced with fresh gas. A new fill is necessary when other methods fail.

Beam profile

After a new gas fill, the excimer laser beam profile is Gaussian on the short axis and flat-topped along the long axis (Figure 19).

As the gas fill ages, changes in chemistry alter the electrical properties of the gas. These changes result in beam growth along the short axis. The beam changes to a flat-topped profile on both axes, beam divergence increases and peak pulse energy is reduced in the far field. A halogen injection or partial gas replenishment will counteract these changes temporarily, but full beam profile will not be restored completely without a new gas fill.

Sputtering electrode and preionization pin material over the life of the laser generates minute particles of dust within the resonator cavity. The dust plates out on the resonator window as well as on other internal components. Dust on the windows absorb UV emission, particularly in the central portion of the optics, and damages the optic over a period of time. Therefore, regular window cleaning is critical to proper laser operation.

Resonator optics must be aligned perpendicular to the beam axis for efficient laser oscillation. Misalignment of the windows causes the optical feedback to be skewed with respect to the gain medium, resulting in lower overall gain. Misalignment in the long axis results in hot spots in the beam profile; misalignment along the short axis causes a dramatic drop in total power, often without discernible hot spots.

As the preionization pins wear, the spark gap increases, adversely affecting gas preionization. As the cathode wears and becomes more flat, the discharge becomes non-uniform. Worn electrodes or preionization pins can cause a trapezoidal or split beam, as shown in Figure 19e. This effect cannot be corrected by resonator alignment and becomes more pronounced as the gas fill ages. The resulting non-uniform power density of the beam is unacceptable for critical applications. Laser refurbishment is the only remedy.

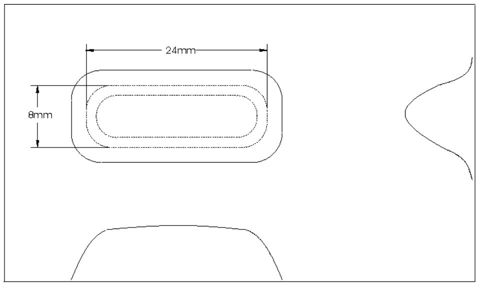


Figure 19a- Normal beam profile with new gas fill.

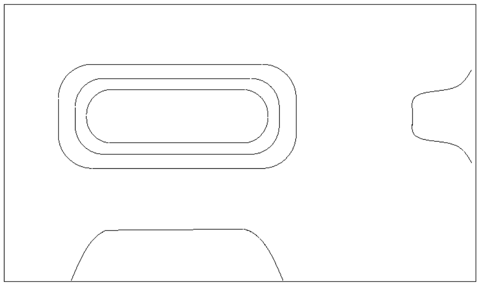


Figure 19b- Beam profile of an old gas fill.

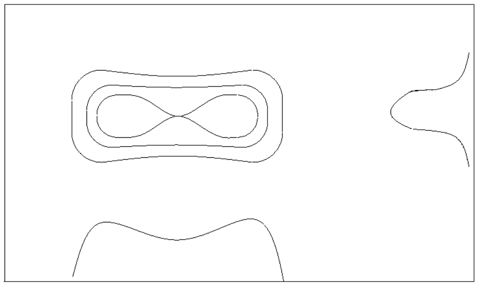


Figure 19c- Beam Profile of a laser with dirty optics.

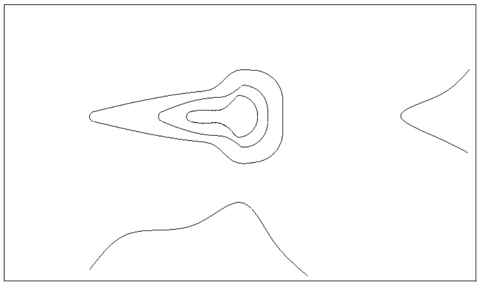


Figure 19d- Beam profile of a laser with misaligned resonator optics.

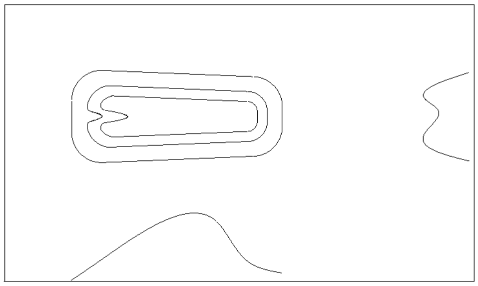


Figure 19e- Beam profile of a laser with worn electrodes or preionization pins.

Beam Profilometry

A typical beam profilometer employs a photoluminescent crystal as the detector (Figure 20). A small fraction of the laser beam is deflected into the crystal for measurement by a beam splitter. The intensity of fluorescent emissions by the crystal is proportional to the intensity of the incident UV light. Hence, a visible image is created analog as to the spatial intensity profile of the beam. This image is relayed to a CCD camera where it is digitized, processed and analyzed by a video image processor. The processed image consists of a false color intensity map or 3-D histogram.

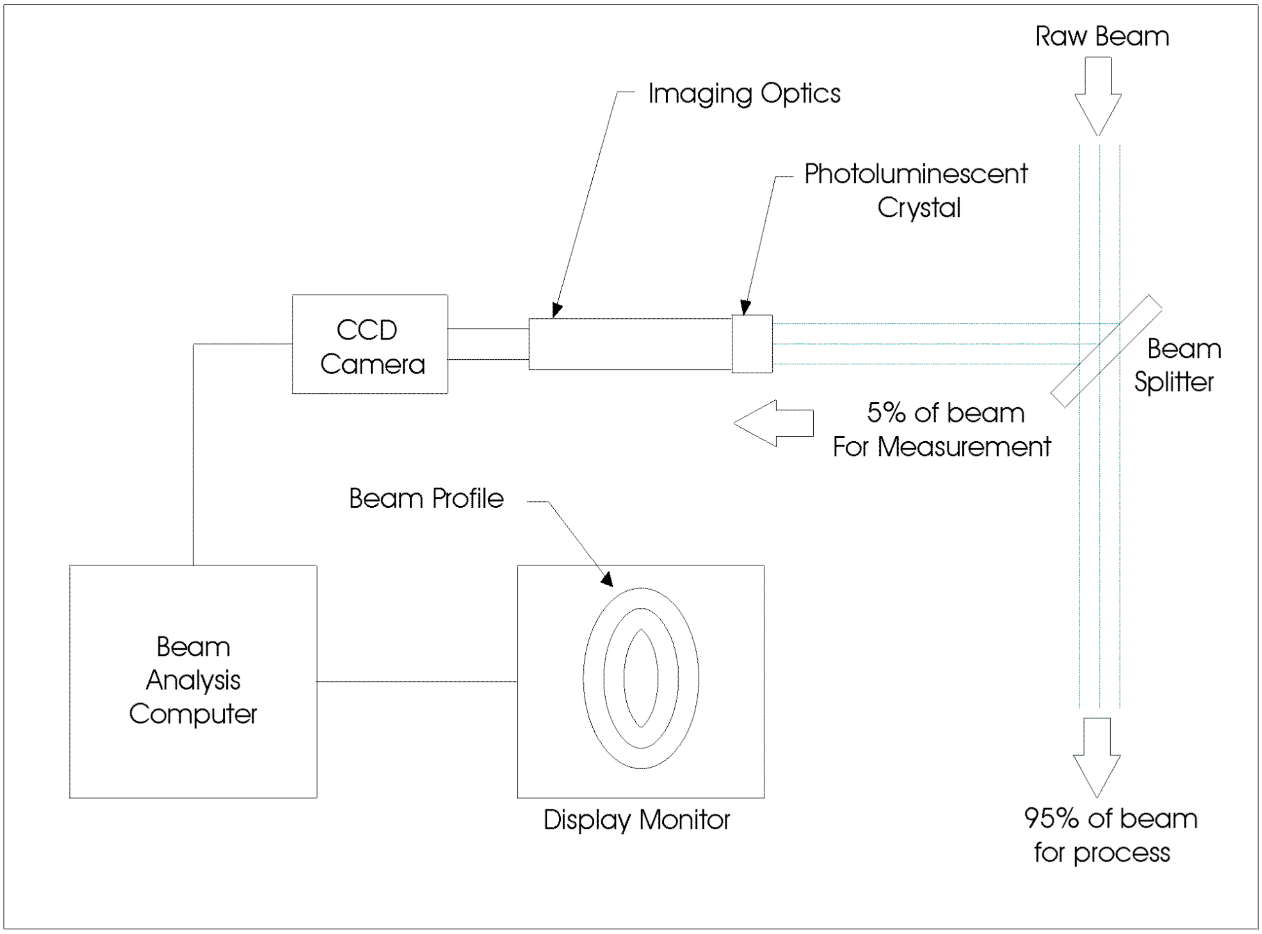


Figure 20- Beam Profilometry

Beam profilometry has the following applications:

- Real-time viewing of the laser output while the system is enclosed
- Diagnosis of laser or resonator optics problems
- Helpful during resonator optics alignment after maintenance
- Long term laser performance monitoring
- Process monitoring for applications sensitive to beam profile (on target or mask plane diagnostics)

Two types of beam profile viewing are possible:

1. Raw beam viewing directly from the laser
    - Good for diagnosing laser problems
    - Assists during laser alignment
2. Mask viewing
    - Permits on-target energy distribution analysis
    - Provides process control information
    - Verifies proper alignment of mask

Types of Excimer Lasers

Some well-known manufacturers of industrial excimer lasers are Lambda Physik (Goettingen, Germany) and Lumonics, Inc. (Kanata, Canada). Performance characteristics for several excimer lasers manufactured by these companies are provided below.

Parameter (KrF)	Lambda 1000	LPX220i	Lumonics PM-848	Lumonics Index 886
Max pulse energy	300 mJ	450 mJ	450 mJ	600 mJ
Max average power output	60 W	80 W	80 W	30 W
Beam size	8 x 24 mm	8 x 23 mm	10 x 25 mm	14 x 30 mm
Beam divergence (mrad)	4.5 x 1.5	1 x 3	1 x 3	1 x 3
Pulse repetition rate (pulses/sec)	0-200	0-200	0-200	0-50

Table 8. Laser parameters for several industrial excimer lasers.

Unique Characteristics of Excimer Lasers

- Resonator cavity configuration produces a beam ideal for near-field imaging

- High peak power of the laser beam permits ablation of the target material with little or no heat affected zone
- The 193-351 nm optical wavelength permits generation of high resolution (~1 μm) features on the target surface
- The shallow absorption depth permits tight control of feature depth by controlling the number of pulses applied
- Large beam cross-section accommodates a large imaging mask for near-field imaging

Disadvantages of Excimer Lasers

- High performance electronic components require frequent and costly maintenance
- Laser gas is toxic and corrosive
- Laser gas consumption is high and expensive
- Changes in gas chemistry affect beam shape and quality
- Components inside laser require routine replacement and cleaning due to corrosiveness of the laser gas
- Resonator optics and beam delivery optics degrade with the exposure to UV light and require replacement
- Optics need routine cleaning

Operation and Maintenance Costs

Operation and maintenance of an excimer laser materials processing system typically requires the attention of one full time operator and a part-time maintenance technician (3-5 hour/week).

Routine Operational and Maintenance Expenses (based on 8 hrs/day, 100 Hz operation):

Expense	**Estimated Yearly Cost**
Electric Power @ 3 kW	$600
Gas Consumption	$12,000
Routine parts (optics, filters)	$400
Total Routine Operating Expenses	**$13,000**

Laser Refurbishment

Excimer lasers are designed to operate over a range of different pulse rates. Lasers at high pulse rates typically have lower output power. Therefore, a laser runing at 200 pulses per second would still require refurbishment after one billion pulses, which would occur after six months.

Laser Refurb (every 1 billion pulses or approximately every year at 100 Hz)	**<u>$17,000</u>**
Total Laser Operation And Maintenance	**$30,000**

Laser refurb is required approximately every year for a laser operating 8 hours/day. A refurb normally includes the following:

- Clean and acid etch all internal surfaces of laser
- Electrode replacement
- Complete preionization pin replacement
- Fan assembly and precipitator replacement

The refurb does not include the replacement cost of the thyratron, heat exchangers, capacitors, halogen filter or resonator optics. If these items require replacement, additional charges are levied.

Principles of Laser Materials Processing

Review of Optical Physics

The part of a laser processing system that directs the beam to the target, once the beam leaves the laser head, is the beam delivery system. Components of the beam delivery system include the masks, turning mirrors, attenuators, field lenses and imaging lenses that manipulate and shape the beam, and the optical chamber that holds these devices.

The Law of Refraction (Snell's law) (See Figure 21)

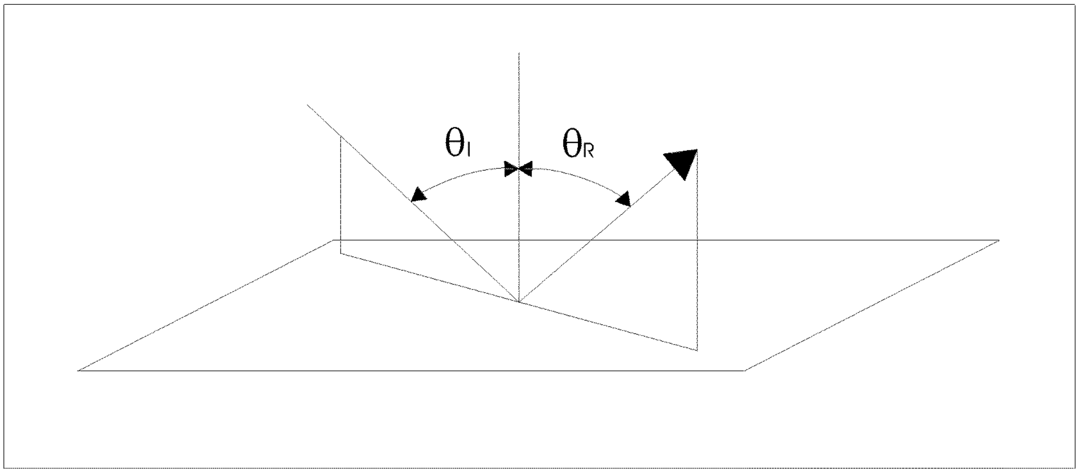


Figure 21- Snell's Law

1. The incident, reflected and refracted rays, and the normal to the surface, lie in the same plane.

2. The angle of reflection is equal to the angle of incidence.

3. For a light ray traveling through two media *1* and *2*, the ratio

$$\frac{\sin\theta_1}{\sin\theta_2} = \text{constant}$$

If material *1* is a vacuum, then the constant is specific to material *2* and is called the index of refraction. The index of refraction of a material is an indicator of the speed of light traveling in the medium (Figure 22).

A more familiar way of writing Snell's law for two materials is:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2.$$

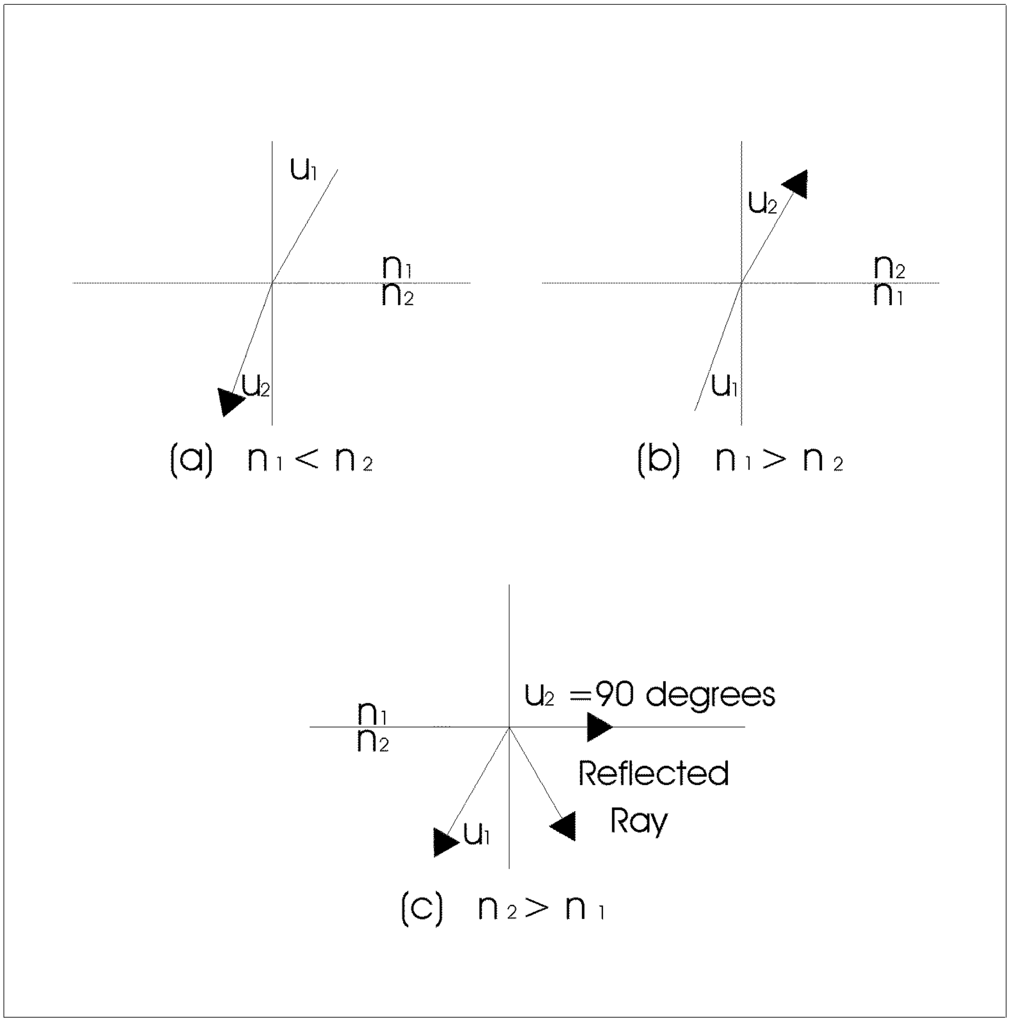


Figure 22- Snell's Law

Optical Components

Optical components in the beam delivery system shape and guide the laser beam to the target surface. The optical properties of these components vary significantly and so do the prices.

Ultraviolet optical materials:

- Magnesium fluoride (MgF_2) – best resistance to radiation damage but most expensive
- Fused silica (SiO_2) – medium cost; reduced transmission at shorter wavelengths
- Calcium Fluoride (CaF_2) – degrades slowly with exposure to electromagnetic radiation; least expensive

Infrared optical materials:

- Germanium (Ge) – high refractive index $n = 4.0$; exhibits poor transmission qualities at high temperatures > 200ºC
- Zinc Selenide (ZnSe) – refractive index $n = 2.4$; scratches easily; requires AR coating
- Sodium Chloride (NaCl) – low refractive index; water soluble, good transmission

Nd:YAG optical components are usually fused silica.

The price of optical components depends on the substrate material, coating, diameter and focal length, if applicable. The table below lists some typical prices for UV optics.

Plano-Convex Lens	CaF_2	Fused Silica	MgF_2
1.5-inch, 75mm	$325.00	$400.00	$500.00
1.5-inch, 100 mm	$200.00	$200.00	$325.00
1.5 inch, 200mm	$140.00	$180.00	$250.00

Table 9. Estimated relative prices for UV lenses. In general, the shorter the focal length, the more expensive the lens.

Considerations in choosing optics:

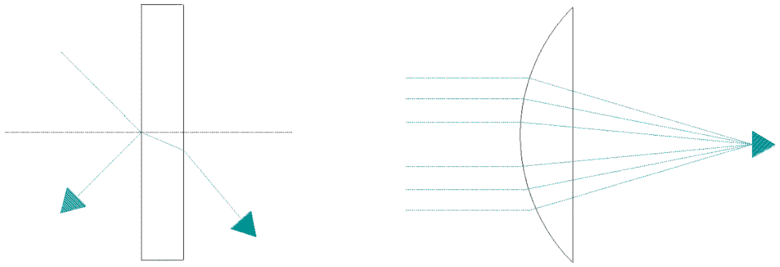
- Proper wavelength
- Compatibility with the surrounding environment, i.e. moisture, temperature
- Resistance to irradiation
- Beam size

- Demagnification and fluence requirements
- Cost

Many optics, mostly those with high index of refraction, come with an anti-reflection (AR) or interference filter coating. Coated optics cost more but may improve machining quality, depending on the application. Consistency of the coatings depends on the manufacturer. (Figure 23)

(a) Coating applied to front optic surface as in a turning mirror

(b) Coating on back surface of optic as on a rear resonator optic

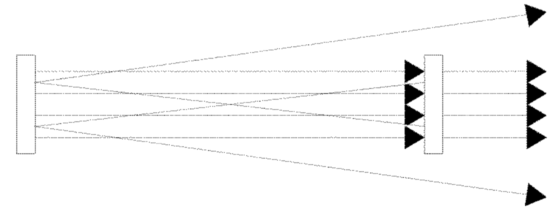


(c) Beamsplitter

(d) Simple plano-convex lens

Figure 23- Simple Laser Optics

The high divergence of excimer lasers leads to unacceptable optical losses where long beam delivery systems are used. The employment of unstable resonator optics can remedy this problem in some instances. An excimer laser with unstable optics is difficult to align and emits a reduced energy output. A stable, flat/flat resonator cavity like that shown in Figure 24(a) delivers a low divergence of about 1 x 3 mrad. Resonator optics in this configuration as in an excimer laser, cost nearly $900.00 a set. The unstable resonator cavity shown in Figure 24(b) produces a divergence near 0.1 x 0.3 mrad but at only one-half the output as in 24(a). Typical price for unstable resonator optics is $3,000.00 per set.

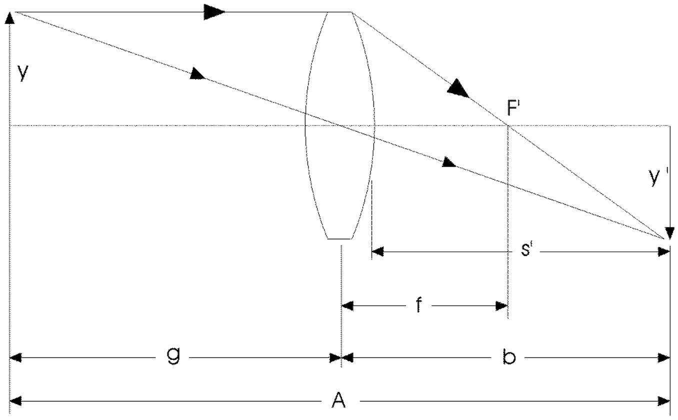


Stable Resonator Optics

Unstable Resonator Optics

Figure 24- Excimer Laser Resonator Optics

Figure 25 shows some important relationships for a thin lens. Figure 26 shows other simple optical parameters.



A =distance object-image
b =image distance
f =focal length (normally for d-line, l =587,6nm)
F' =focal point in image space
g =object distance
h =incident height
m' =image magnification
s' =back focal length in image space
y =object size
y' =image size

Figure 25- Important parameters for a thin singlet lens

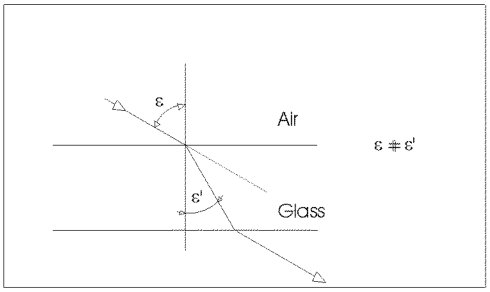


Figure 26a- Refraction

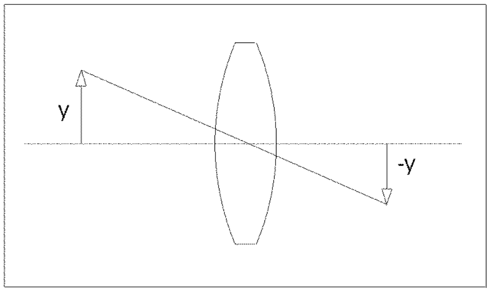


Figure 26b- Orientation through a Singlet

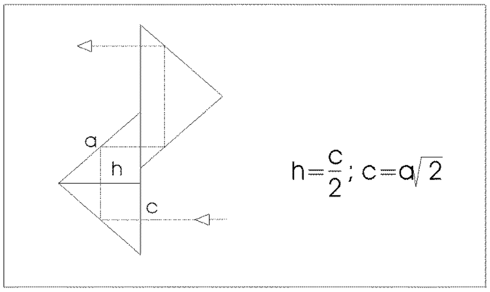


Figure 26c- Beam Steering in Prism

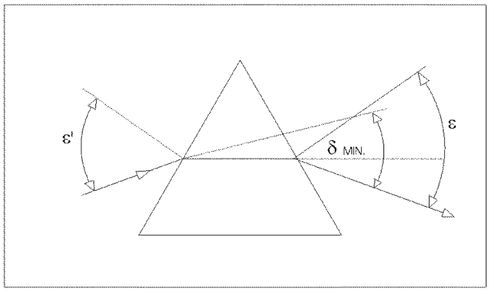


Figure 26d- Prism Beam Steering

Beam Splitters

Two main methods are used to split an incident beam into two or more components. The first is by using a dielectric coated optic. Depending on the coating, a portion of the beam will be transmitted and a portion will be reflective. In many cases, a beam will be split in equal halves using a 50%, 45° to incidence beam splitter. This transfers the original beam size to both resulting beamlets, but reduces energy density and peak power by half, so in many cases the technique is not useful – especially when the beam is to be split into many components (Fig. 27).

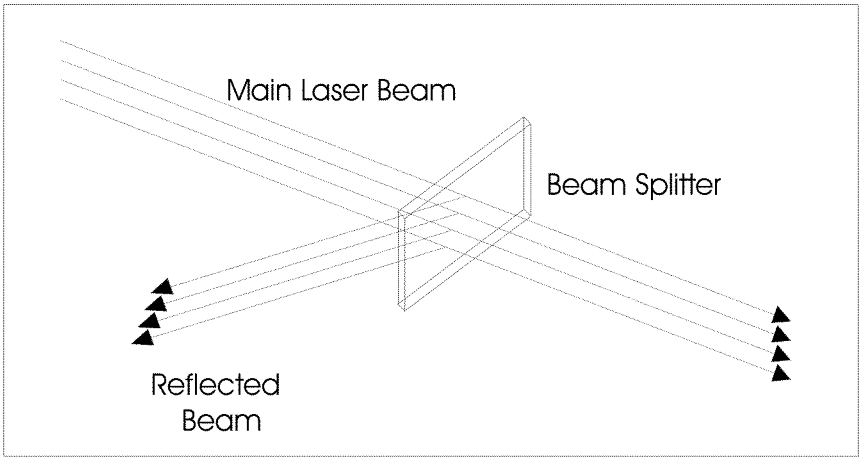


Figure 27- Dielectric Beam Splitter

Frequently a better way to split the beam is by using a physical divider and “scraping” off portions of the beam (Fig. 28). We have successfully employed this technique to split an incident excimer laser beam into 12 equal components.

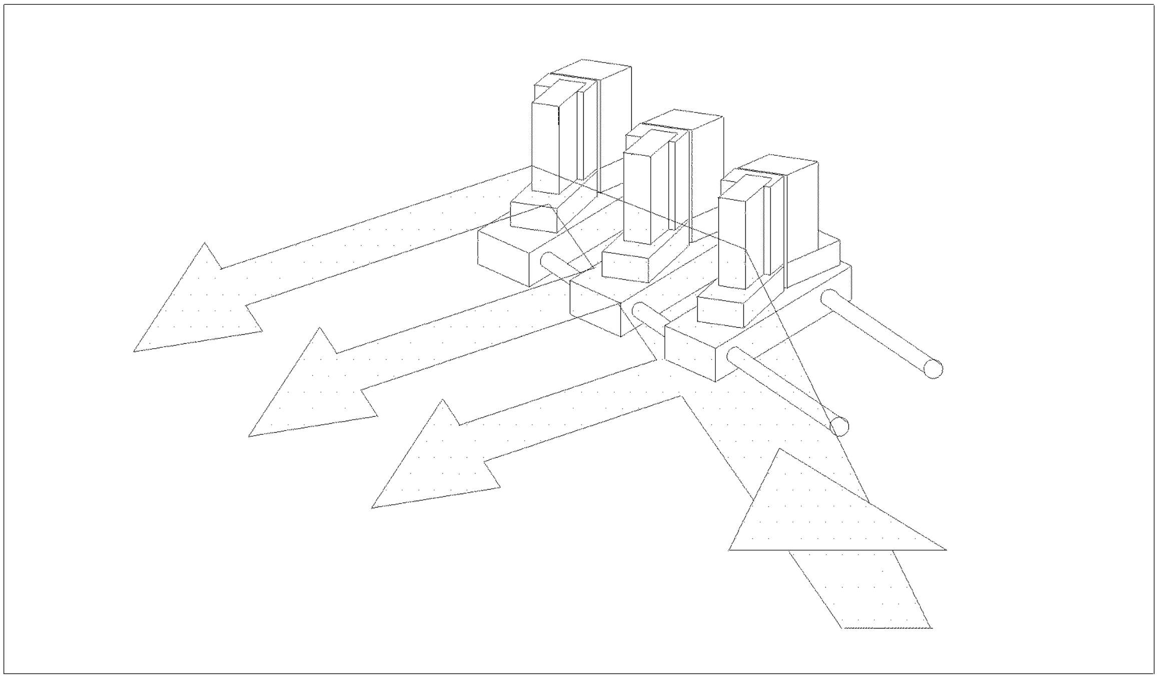


Figure 28- Physical beam splitter giving three resultant beamlets.

Telescopes

Normally, laser beams have very small beam diameters. If larger objects are to be illuminated, or if one wishes to fill an imaging lens to get the smallest spot size, the system must be expanded. Expansion can be achieved two ways (Figure 29) as illustrated by the following:

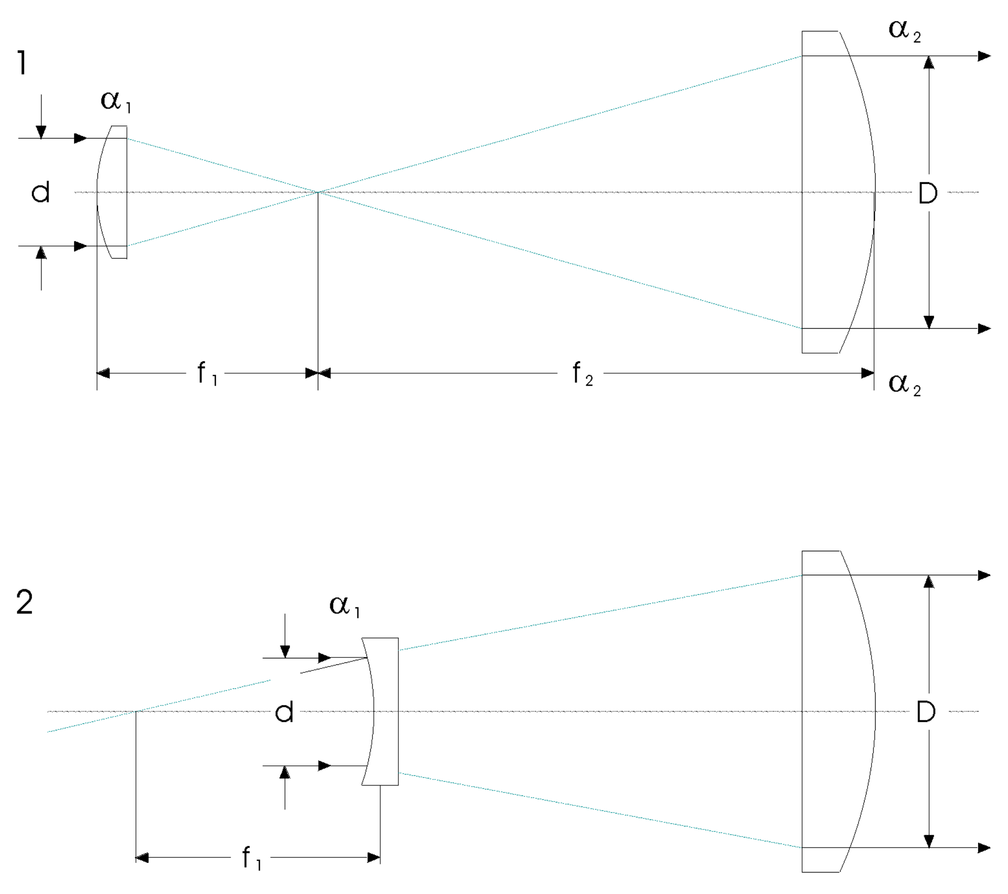


Figure 29- Physical Parameters of Telescope Optics

The first method uses two positive imaging lenses of the Kepler telescope type (Figure 30). It offers the advantage of having a real focus at which a spatial filter can be easily inserted. The disadvantage, however, is that for powerful lasers, the extremely high beam intensity at the focus can cause breakdowns in air.

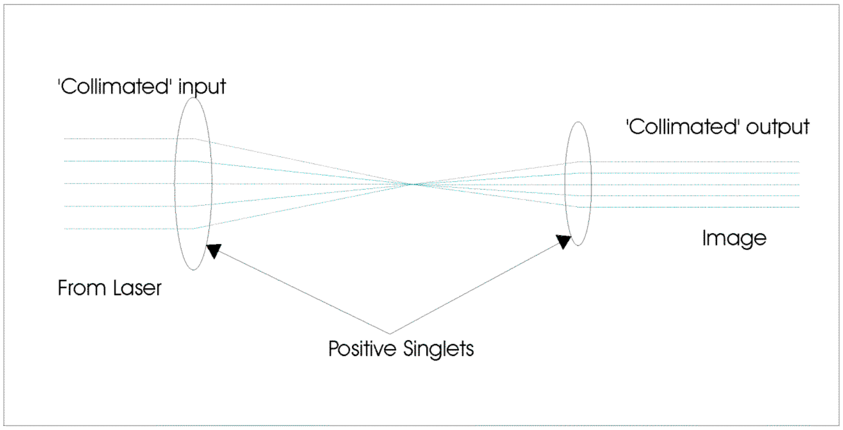


Figure 30- Keplerian Telescope

The second method uses a negative entrance lens and a positive collimator lens of the reversed Galilean type (Figure 31). It offers the advantage of being shorter than the Kepler type and has a virtual focus which prevents air breakdown. On the other hand, a spatial filter cannot be inserted.

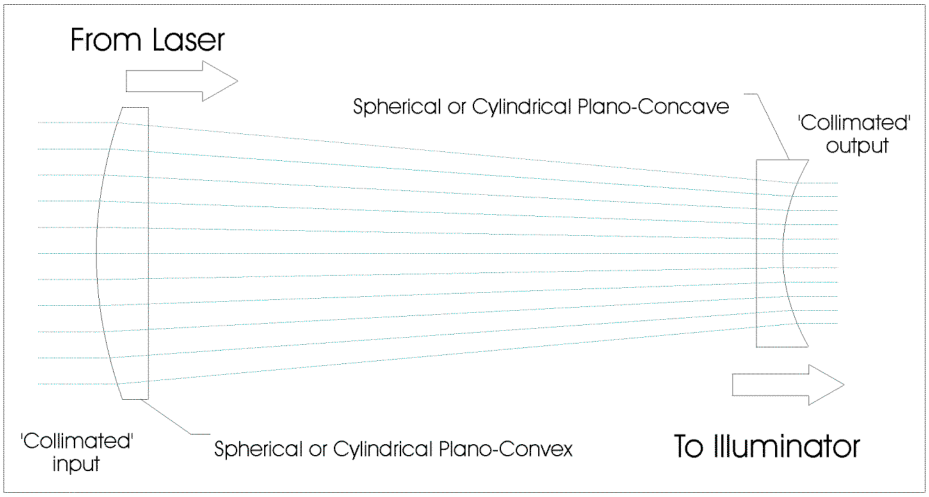


Figure 31 - Galilean Telescope

The expansion ratio in each case is characterized by the focal length ratio and the divergence of the laser beam is reduced by the absolute value of the ratio of the two focal lengths.

If we wish to reduce the beam diameter by reversing the lens arrangement, the divergence will increase by the absolute value of the focal length ratio. i.e. we can no longer expect “parallel” laser light. Nonetheless, this technique can be used to get higher throughput for a simple mask or to achieve a higher energy density in a “collimated” beam.

Homogenizers

The purpose of a beam homogenizer is to break up the beam into small sections and recombine them in a pattern that increases the overall fluence over a smaller cross-section. The following considerations must be taken into account:

1. Loss of power density in one part of the raw beam must not affect uniformity of the beam at the mask exposure plane

2. Significant optical losses are present in any homogenizer configuration

3. Homogenizers are expensive and AR coated – the coatings are susceptible to overheating by hotspots within the raw beam

Figures 32, 33 and 34 show three different types of homogenizers used with excimer lasers.

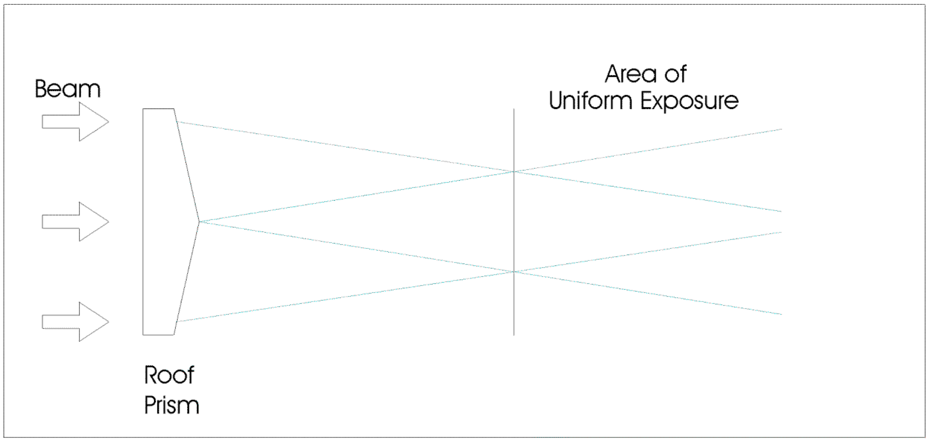


Figure 32- Simple roof prism homogenizer.

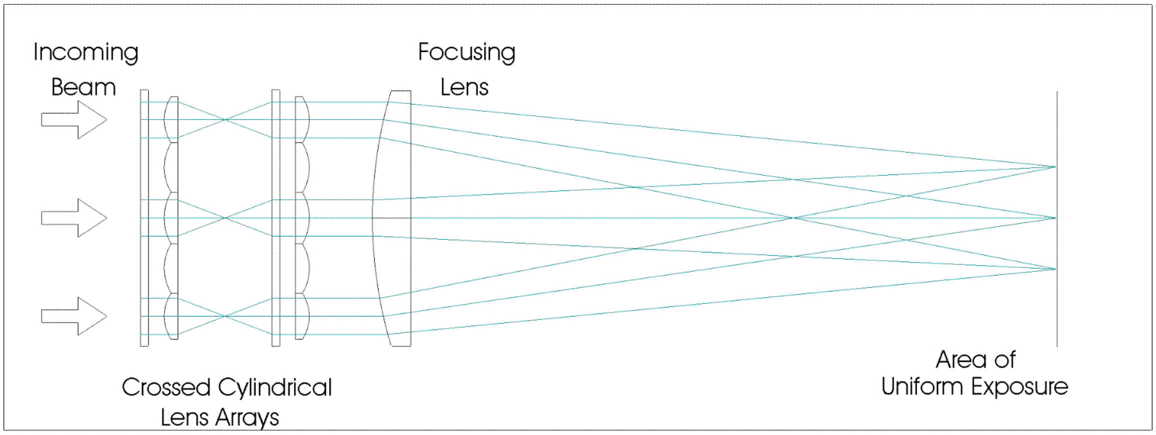


Figure 33- Crossed Cylinder Lens Homogenizer

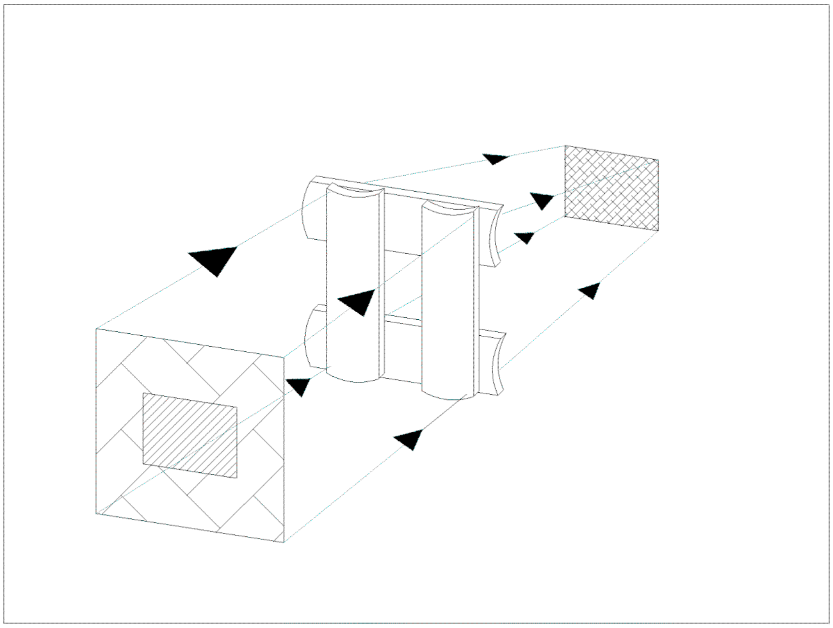


Figure 34- A homogenizer for use with excimers. Each cylinder lens is independently adjustable.

Photo-Ablation and Material Interaction with UV Light

Photo-Chemical Color Change

- Occurs in plastic and ceramics at raw beam fluences
- Excimer UV light alters the surface molecular structure resulting in change of light absorbing properties
- Color change results

Photo-Ablation

- At higher fluences, the energy from excimer UV light breaks molecular bonds in the target material surface (Figure 35). Each material has its own photo-ablation threshold, below which photo-ablation does not occur (Figure 36).
- Small interaction volume due to shallow absorption depth limits heat conduction and concentrates the energy in the top exposed surface
- Ablation by-products and excess heat are carried away by expansion of the plasma plume

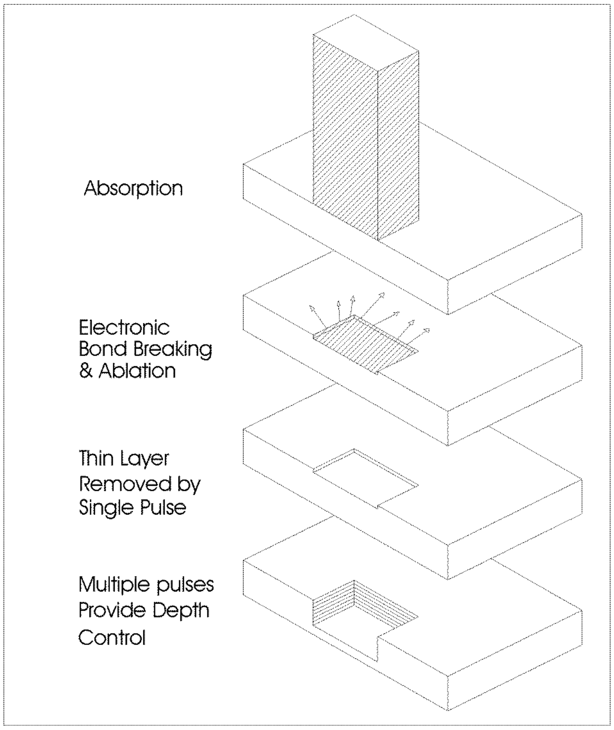


Figure 35- Photo-ablation process by exposure to uv light. A single ablation layer is typically <1.0mm thick, due to the short uv wavelength.

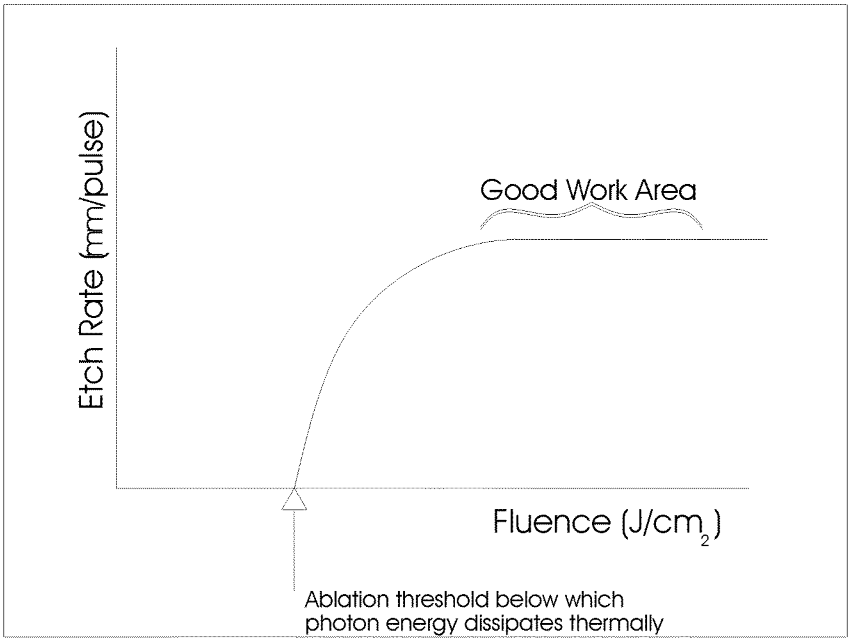


Figure 36- Etch Rate vs. Fluence

Thermal effects

- As fluence increases, absorption depth increases resulting in larger interaction volume; greater volume results in increased heat conduction to the surrounding material
- As pulse repetition rate increases, residual heat cannot escape, resulting in thermal effects
- Laser light absorbed by materials below ablation threshold can impart significant heat to the material
- Certain materials such as metals are removed by thermal input at high fluences; however, small interaction volume helps control thermal damage

Taper Effects

Although the shape of the image at the target surface resembles the true shape of the mask, during near field imaging, the perimeter of the image tends to collapse inward as the photo-ablation depth penetrates into the material (Figure 37).

Characteristics of taper:

- Taper angle is approximately 7° - 10° as the cutting depth penetrates into the processed material. This can be increased by using low fluence or other beam motion techniques. It can be reduced to approximately 2° in low aspect ratio applications by the use of high fluence and low divergence resonator optics. It is also possible to use double sided drilling (simultaneous or serial processing) to reduce taper. This sometimes leaves an "hourglass" shaped feature.

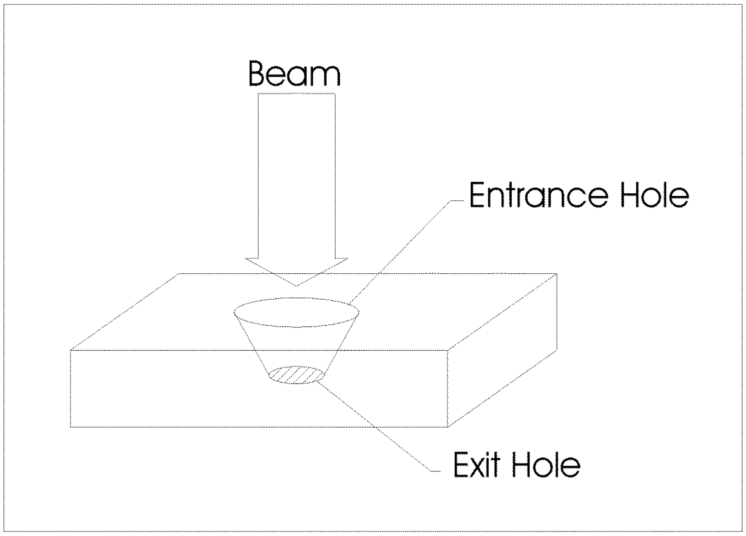


Figure 37- Taper effect in laser hole drilling.

- The consequence of the taper phenomenon is that the exit hole on one side of the processed part will be smaller than the entrance hole – the size difference depends on the thickness of the material
- Taper effects must be considered when choosing mask sizes and demagnification parameters

Ablation Parameters

Achievable Exposure Area: Excimer Raw Beam Energy vs. Fluence					
Raw Beam Energy	0.5 J/cm^2	1 J/cm^2	5 J/cm^2	10 J/cm^2	25 J/cm^2
100 mJ	0.2 cm^2	0.1 cm^2	0.02 cm^2	0.01 cm^2	0.004 cm^2
200 mJ	0.4 cm^2	0.2 cm^2	0.04 cm^2	0.02 cm^2	0.008 cm^2
400 mJ	0.8 cm^2	0.4 cm^2	0.08 cm^2	0.04 cm^2	0.016 cm^2
600 mJ	1.2 cm^2	0.6 cm^2	0.12 cm^2	0.06 cm^2	0.024 cm^2

Table 10. This table displays the maximum surface area a raw beam energy can deliver at the fluence levels listed across the top. The data is based on a 2 cm^2 raw beam size.

For any fluence ρ and area a, the product ρ x a will be a constant; that is:

$$\rho_L a_L = \rho_T a_T.$$

For example, the area illuminated by a 100 mJ beam and fluence 5 J/cm^2 can be calculated:

$$a_T = \frac{\rho_L a_L}{\rho_T} = \frac{(0.1/2)(2)}{5.0} = 0.02cm^2$$

Process	Material Type	Laser Wavelength (nm)	Fluence (J.cm^2)	Power Density (MW/cm^2)	Etch Depth/Pulse (microns)	Comments
Etching	Plastics	193 248 308	0.5 to 2	50 to 200	0.1 to 1	Imaging patterns, arrays
Etching	Ceramics and hard dielectrics	193 248 308	5 to 15	500 to 1500	0.1 to 0.3	Imaging patterns, arrays
Etching	Metal foils	193 248 308 351	5 to >20	500 to >2000	0.1 to >0.25	Imaging patterns, arrays
Drilling	Plastics > 1mm	193 248 308	3 to 10	300 to 5000	0.2 to 5	Spot imaging
Drilling	Ceramics and hard dielectrics	193 248 308	10 to >50	2000 to >5000	0.2 to 2	Spot imaging
Drilling	Metals	193 248 308 351	20 to >50	2000 to >5000	0.2 to 2	Imaging patterns, arrays
Marking	Plastics	308 351	0.5 to 2	50 to 200	0.1 to 1	Imaging patterns, arrays
Marking	Ceramics and hard dielectrics	308 351	1 to 15	100 to 500	0.1 to 0.3	

Table 11. Processing parameters for different excimer wavelengths and materials.

Beam Imaging and Focusing

Two methods of laser machining are used in industry. Focal point machining typically is used with solid state lasers and CO_2 lasers that do not have longitudinal electrodes. Near-field imaging is possible with excimer lasers and TEA CO_2 lasers because the multimode emissions offer a uniform cross-sectional energy density.

Characteristics of Near-field Imaging

- Fluence and spatial distribution controlled by optical magnification
- Image quality is independent of beam divergence, diffraction, and incoherence
- Fairly simple optical setup
- High tolerances achievable – imperfections in mask demagnified
- Theoretically, imaging resolution is on the order of emission wavelength
    - Excimer laser 0.2 – 0.4 µm
    - Nd:YAG laser (Fundamental) 2 µm
    - CO_2 laser 20 µm
- In reality, practical imaging resolution is dependent on optics:
    - Excimer laser 1-5 µm
    - Nd:YAG laser (Fundamental) 5 µm
    - CO_2 laser 75 µm

Advantages of Near-Field Imaging	Disadvantages of Near-Field Imaging
Very flexible for a wide range of shapes	Mask must fit into usable portion of the beam
Fairly simple optical setup	Focus is critical to feature quality
High tolerances can be met	Spherical aberration can distort image shape
Choice of different masks for different applications (metal, chrome on quartz, dielectric)	Energy density non-uniformity across the mask is duplicated on the part
Very wide range of demagnification possible	Work area on process material limited by demagnification

Table 12. Advantages and disadvantages of near-field imaging.

Near-field imaging involves use of a mask to project a pattern of light onto a part. The features of the mask are etched into the target material at a magnification determined by the relative positioning of the optical elements.

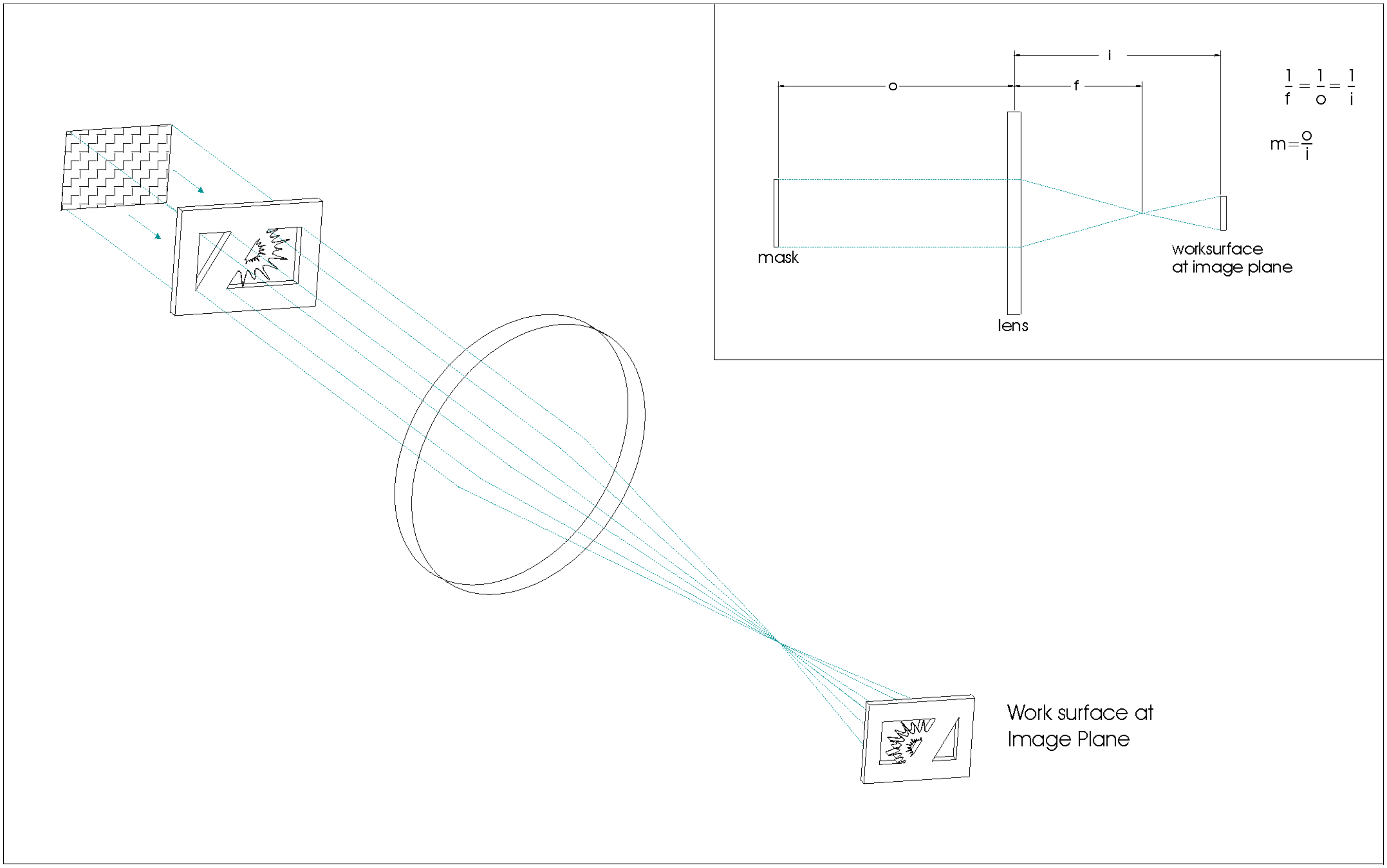


Figure 38- Simple Near Field Imaging

Thin Lens Equation and Demagnification

The relationship between the mask, imaging lens and image on the target material is described by the *thin lens equation*:

$$\frac{1}{O}+\frac{1}{I}=\frac{1}{f}$$

O = object distance
I = image distance
f = focal length (normally expressed in millimeters)

(See Figure 38)

The term magnification in optics is normally used to describe the ratio of the image size to the size of the object. Magnification implies that the image size is greater than the size of the object. The term demagnification implies that the image is smaller than the object and is described by the equation:

$$d=\frac{O}{I},$$

where d is the demagnification.

Beam Compression

Fluence

The term fluence describes the amount of energy per area deposited on the target surface by a single laser pulse. Fluence should not be confused with pulse energy, because the amount of fluence that strikes the target depends on transmission losses in beam delivery components as well as spatial compression of the beam. Fluence is important in laser machining because specific materials require minimum fluence levels to produce thermal ablation or photo-ablation in the case of excimer lasers. This is shown by the following equation:

$$\rho=\frac{E}{A},$$

where ρ is the fluence (J/cm^2), E is the energy measure on-target in Joules, and A is the area of the image. Fluence can be determined for focal point applications as well, where A is the area cross-section of the beam at the focal point.

Cylindrical Compression

A cylindrical lens is normally used for scanning a large area with a relative low fluence and for planarization. If a cylindrical optic is used to compress the beam, then the dimension of the beam changes only in one direction. The fluence after compression, ρ_1, is given by:

$$\boldsymbol{\rho_1 = \rho_0 d(1-L_f),}$$

where ρ_0 is the initial fluence before the lens, and d is the demagnification factor, and L_f is the percent loss through the optic. Optical losses typically run about 5% per optical element, so it is important to minimize the number of optical elements in the design of the optical system.

Spherical Compression

If a spherical optic is used to compress the beam, then the dimension of the beam changes in both directions. The fluence after compression ρ_1 in this case, is given by:

$$\boldsymbol{\rho_1 = \rho_0 d^2(1-L_f),}$$

where ρ_0 is the initial fluence, d is the demagnification factor, and L_f is the percent loss through the optic. Size constraints placed upon the optical systems limit the achievable demagnification factor and fluence for a given lens focal length. Substituting the demagnification equation into the thin lens equation to obtain:

$$O = (d + 1)f$$

$$I = \frac{(d+1)}{d} f.$$

Size and Energy Constraints in Near-Field Imaging

- The optical chamber can be insufficient in length to accommodate a specific demagnification for a given lens (either too long or too small).
- Laser energy can be insufficient to photo-ablate certain materials for a specific demagnification
- The vertical (short) beam width may be too small to accommodate a mask required for a specific demagnification or image size.
- The required image and mask size (<0.004 inch) can be small enough to create undesirable diffraction interference at the image plane. This condition is a particularly serious limitation if the image is a repeated pattern of holes or shapes.

Beam Utilization Factor (BUF)

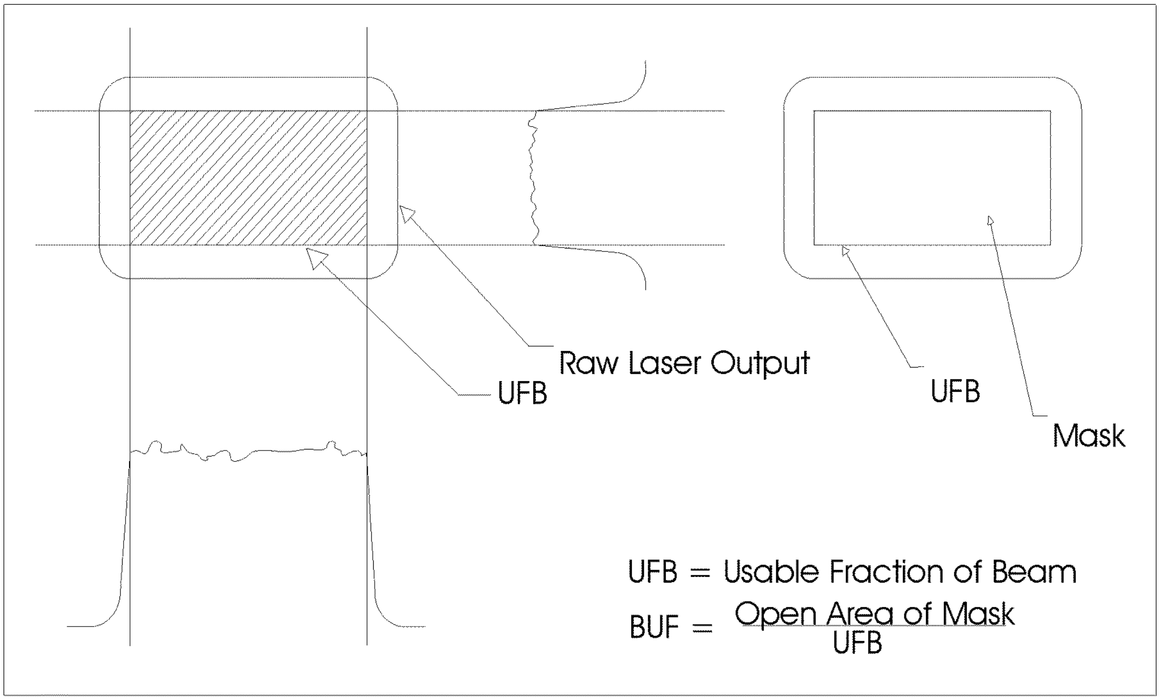


Figure 39- Beam Utilization Factor

Beam Optimizing Considerations

- Optimum beam utilization is essential to quality part manufacturing at affordable costs.
- Techniques for optimizing BUF include parallel processing schemes in which on laser beam illuminates multiple imaging systems to process many parts simultaneously.
- Size of usable fraction of the beam is highly dependent on resonator optical alignment.
- Definition of useable fraction of the beam is application dependent. One process may require tighter fluence control than another.
- Refractive optical materials absorb a small fraction of the beam. This absorption depends on optic thickness.
- Reflection from surfaces of refractive optics contributes to losses.
- Reflective optical components have losses of 1-2%.
- Absorption losses can be minimized by proper choice of optical materials and high quality optics workmanship.

- Reflective losses with refractive elements can be minimized with angle and wavelength dependent high-reflection dielectric coatings.
- Losses are best controlled by limiting the number of optical elements. Refractive optics should be as thin as possible.
- Sometimes more elements are acceptable if the process requires high precision and beam utilization is a secondary consideration.

Motion control of beam delivery components provides a powerful method of automating part processing with laser systems. The following list describes just a few of the motion control alternatives involving beam delivery optical setups:

Autofocus – the lens is focused automatically by a stepper motor controlled by the system computer at the touch of a key or through a process program.

Automagnification – the mask and lens are slewed according to algorithms derived from the thin lens equation.

Rotary or linear mask control – a rotary mask or linear mask assembly is actuated by a computer controlled stepper motor or pneumatic device. Mask alignment permits high precision overlays, such as counterbored holes. Mask aligners with letter stencils can produce custom serialization marks under computer control.

Galvanometer Beam Steering – in many applications, the processing time would be too slow if the beam remained still and the part moved, for instance using an X/Y table (Figure 40). A preferable method in many cases, especially for well collimated beams of low divergence, is to hold the part still and move the beam with mirrors mounted on opposing orthogonalized galvanometers (Figure 41). Areas up to 4” in diameter can be exposed on target at extremely high speeds, depending on the sensitivity of the application to angular distortions. Area galvo scanning can be combined with table stepping to provide a high speed method of processing larger parts.

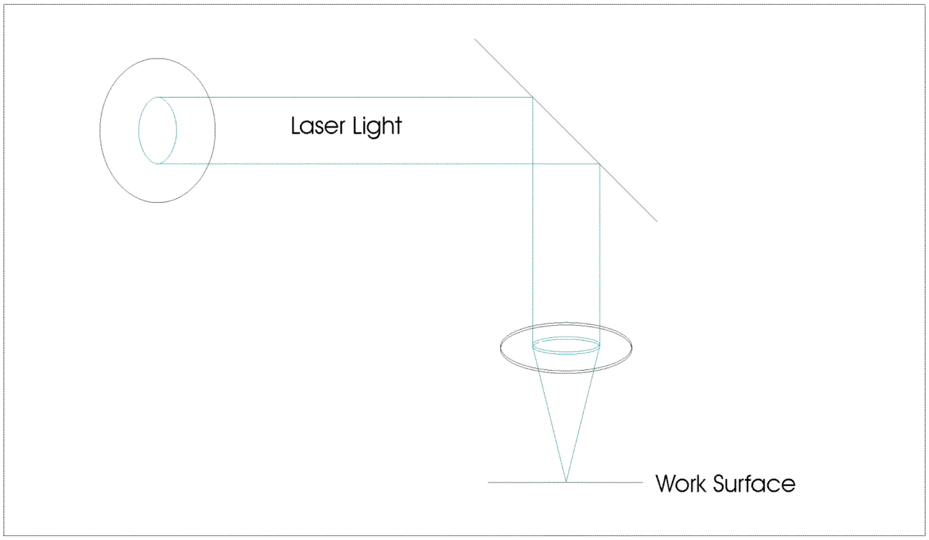


Figure 40- Simple fixed, Focused beam at work surface.

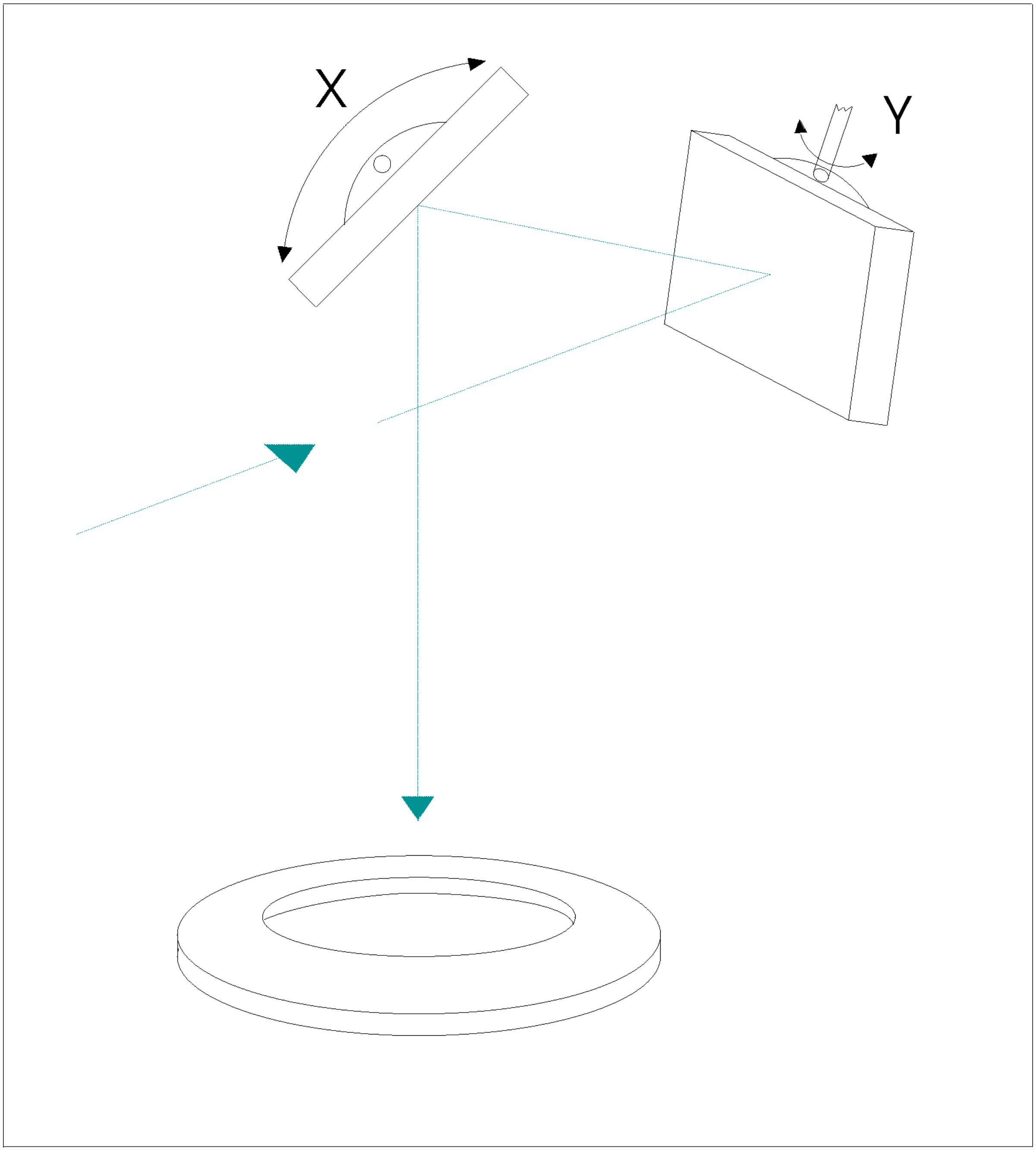


Figure 41- Galvo Scanning Beam Delivery

Special Beam Delivery Techniques

Scanned Illumination Imaging

Scanned illumination imaging is a powerful technique for increasing the image surface area on the target material without the reduction of fluence (Figure 42). Using a properly designed lens system, 3 µm feature resolutions at 20 J/cm^2 fluence with feature areas of 2 mm^2 have been achieved. Important considerations when implementing this technique are:

1. Imaging lens must have sufficient aperture to accommodate the entire image
2. Laser pulsing must be interpolated accurately with the scanning mirror feedrate
3. Optical setup must be configured to accept the scanning mirror and fixed mask

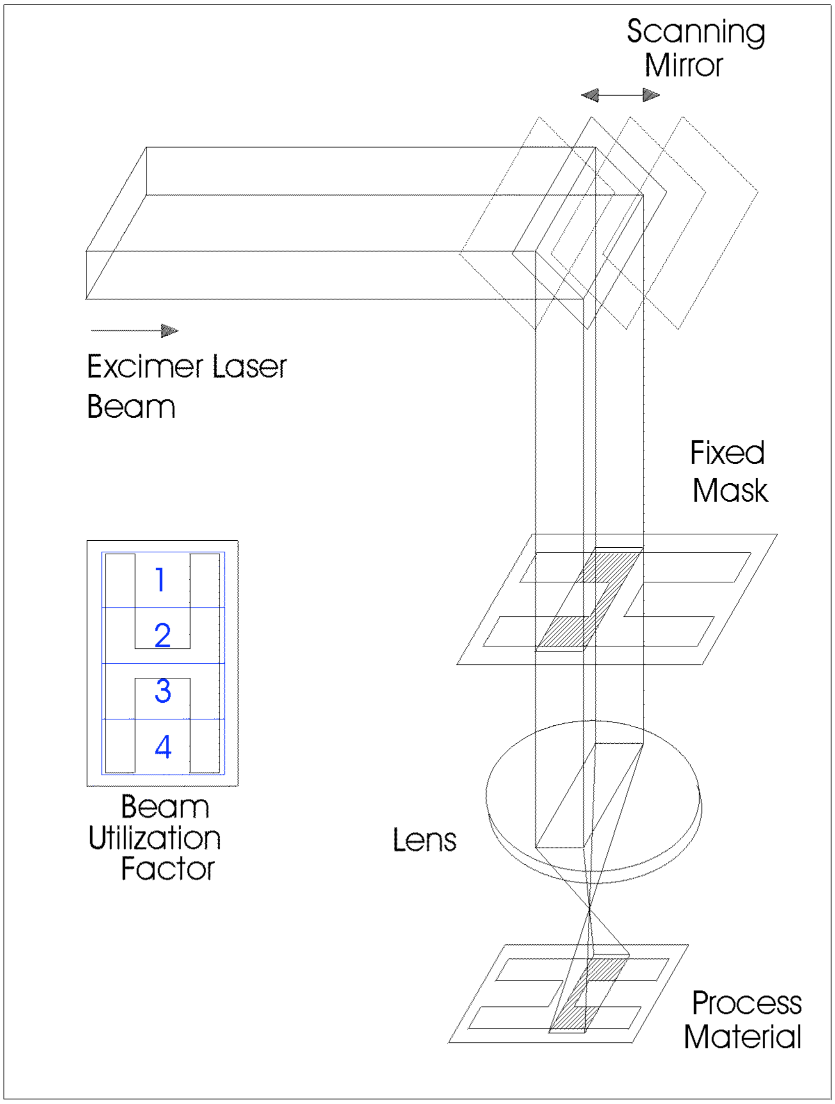


Figure 42- Scanned illumination imaging.

Coordinated Opposing Motion Imaging

In coordinated opposing motion imaging (Figure 43), both the mask and part are mounted to computer controlled X-Y stages. During processing, the mask and stages perform interpolated moves in opposing directions, the magnitude of mask movement being larger by a factor equal to the image system demagnification. This opposing motion causes the laser image to precisely track the position of the moving part, remaining at the same position relative to the part as different areas of the mask are exposed. The lens is always used in the paraxial, on-axis condition.

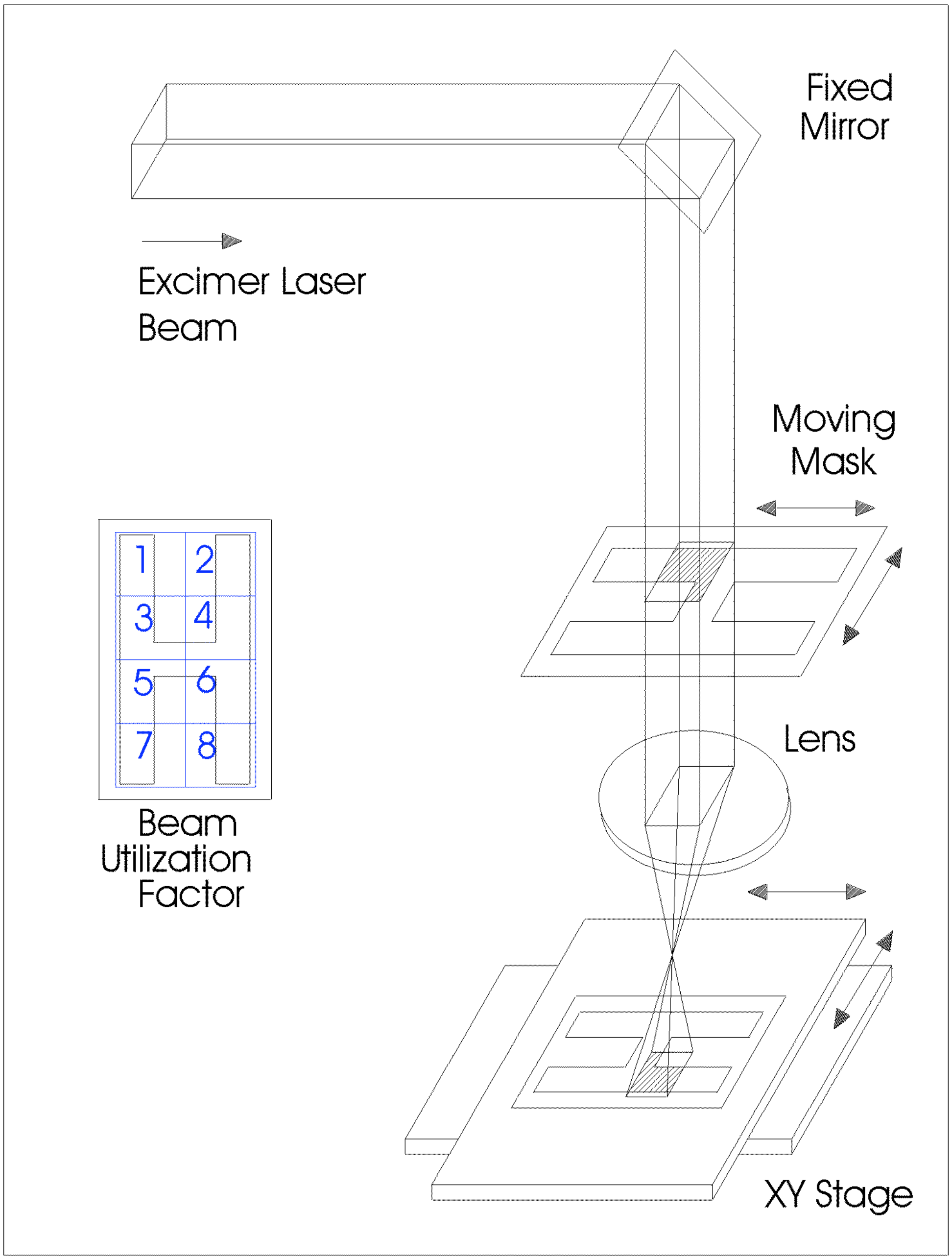


Figure 43- Coordinated Opposing Motion Imaging

Direct Write Machining

Direct write machining provides a useful technique of generating large cutout features and performing high volume hole drilling in materials where fluence requirements limit spot size. The required features can be drawn in CAD and then directly translated to motion control code utilizing a CAD/CAM programming interface (Figure 44). Specific functions possible using this technique include:

1. Features on the CAD drawing can exist on different layers that correspond to automatic mask changes or changes in laser pulse spacing within a single process program
2. Points can be placed in the CAD drawing to trigger step and repeat drilling operations
3. Drill marker points can be drawn on different layers within the CAD file to control drilling depth

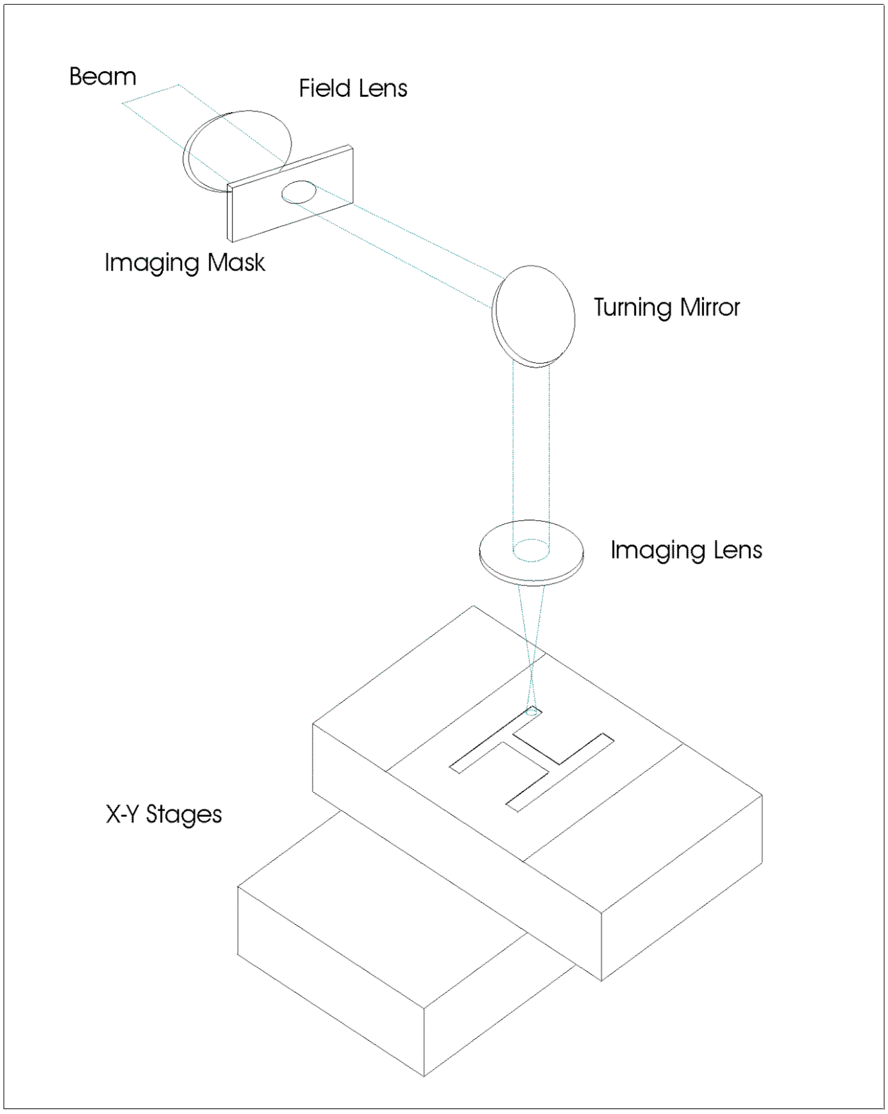


Figure 44- Direct write machining.

Contact Mask Processing

Contact mask processing is a technique by which fluence on-target is controlled by simple beam shaping optics and feature shape is determined by a blocker mask in contact with the workpiece (Figure 45). The exposure of the contact mask may be performed with the part stationary or scanned under the beam. If scanning is used, laser firing must be interpolated with the table feedrate to ensure uniform exposure. Contact mask scanning allows very large areas of material to be processed. Characteristics and considerations in contact mask processing:

1. The blocker mask material must be selected so the beam does not damage the mask as it ablates the material below:
    - Aluminum
    - Copper
    - Molybdenum
2. If the mask is not expendable, select the minimum fluence required to minimize the damage.
3. Periodic cleaning of the mask edges is required for maintaining sidewall quality.
    - Feature resolution is limited by the limits of the size of the feature that can be put into the mask. Features down to 25 µm have been achieved.
    - A conformal mask can be laminated to the workpiece as an integral component of the final product – good approach for via formation in microelectronics packaging.

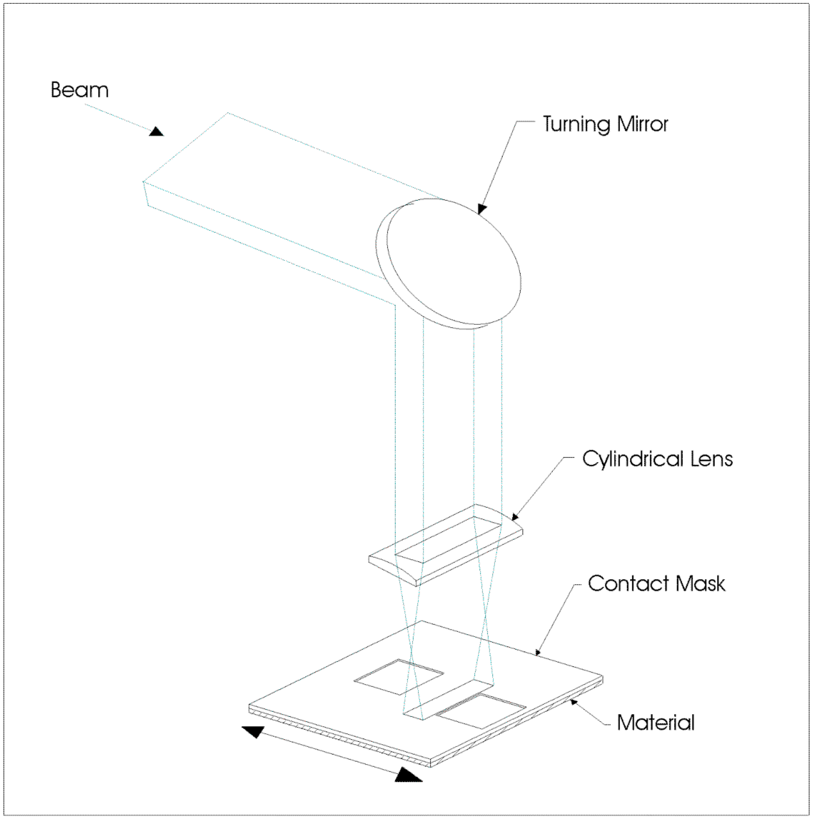


Figure 45- Contact mask processing.

Beam Dividing

Beam dividing can be used to increase the BUF as illustrated in Figure 46. Figure 47 shows a technique used to split the beam from a CO_2 laser into seven components and shutter each beamlet to produce continuous marks on a moving production line. Alternatively, many small lasers can be used and fired only on demand.

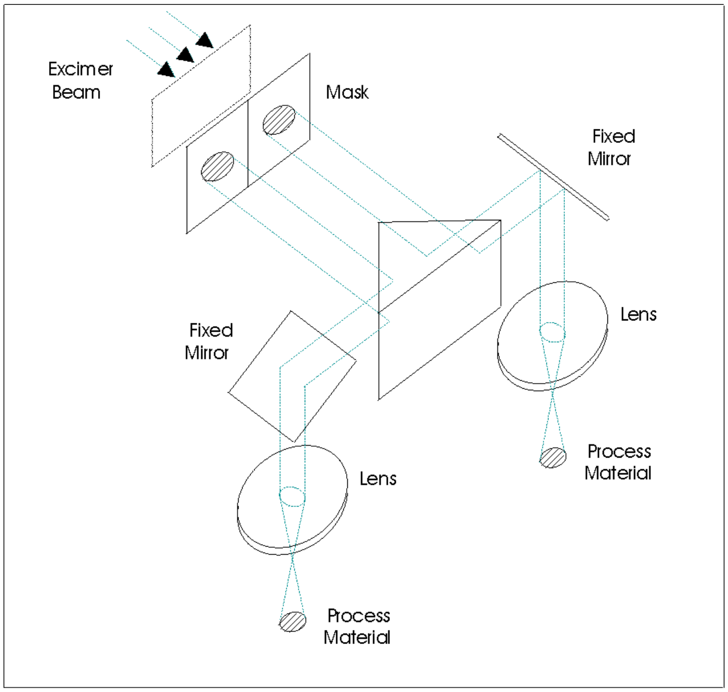


Figure 46- Parallel Processing with an Excimer Laser

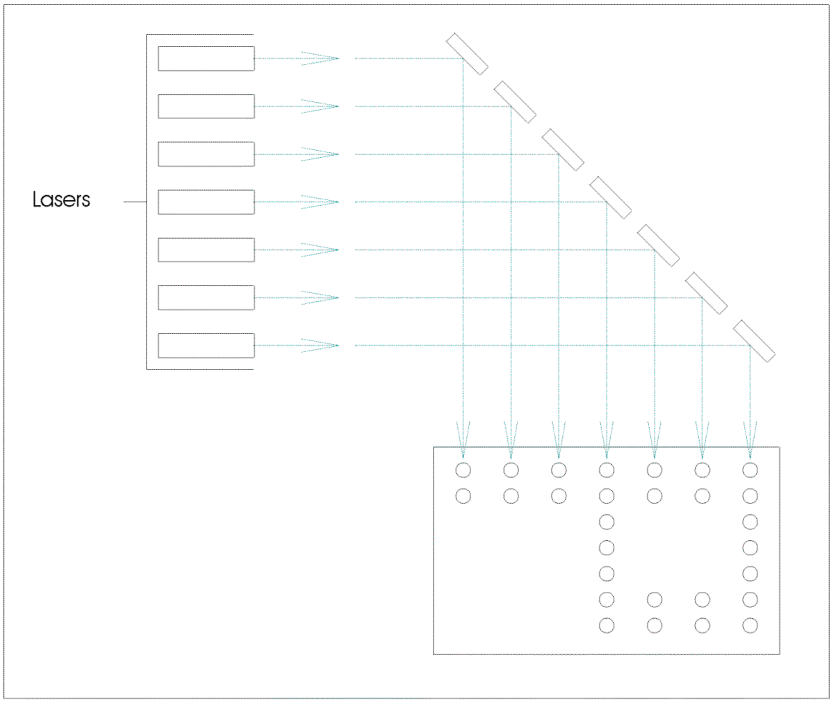


Figure 47- On-line marking with seven beamlets.

Steps to an Effective Optical Setup

1. Determine which laser is best.
    - Are machining quality and tolerances tight enough to warrant UV laser use or can CO_2 or Nd:YAG do the job?
    - Is the target material thin enough for excimer laser machining, or is a CO_2 wavelength required?
    - What is the best wavelength, and should more than one laser be used?
    - How much fluence is required?
2. If excimer laser imaging is chosen, determine the wavelength and energy required.
    - Is 193 nm, 248 nm, or 308 nm best absorbed?
    - What is the ablation threshold of the material?
    - Experiment to determine optimum fluence and wavelength, if possible.
3. Determine required exposure area.
    - What are the required feature sizes?
    - Can feature be broken into smaller portions?
    - How long will it take to accomplish the job?
4. Determine resolution and optical setup type.
    - Contact mask or imaging system (LWD or microscope system?)
    - Which objective is best?
    - Select an objective that minimizes optical losses
5. Determine pulse energy required
    - Required pulse energy on-target = required fluence x feature area
    - Don’t forget to factor in optical losses
6. Determine optical parameters
    - Select demagnification
    - Maximize BUF, use beam shaping/splitting as required
    - Determine optical path, use readily available optics
    - Consider size of beam delivery system and support structure
    - How critical is beam uniformity? Homogenizer? Consider losses
    - Don’t forget to factor in taper effect

7. Select laser and illumination scheme
    - Laser energy required = required pulse energy on target x BUF
    - Select lowest pulse energy laser to do the job
    - What if required pulse energy is greater than maximum output of available lasers?
        - Reconsider optics scheme to reduce losses
        - Consider scanned illumination technique

System Integration

Processing System Considerations

1. General Requirements
    - Choose the correct laser
    - On-line or off-line
    - Clean room requirements?
    - Available utilities – electrical, cooling, venting, gases
2. Beam Delivery System (BDS)
    - Gets photons from laser to workpiece
    - Shapes and conditions beam for efficiency (including automated BDS)
    - Protects operators
3. Motion Control/Parts Handling
    - X, Y, Z, θ stages
    - Galvos?
    - Robotic or conveyor required to move parts?
    - Tooling or part pallets; roll-to-roll?
    - Vacuum chucks, assist gas?
    - Camera system? Simple or machine vision? Color or black & white?
    - Computer control
    - Safety – Class I operation – gases, optics, stray light, mechanical, electrical

Laser Packaging

- Industrial laser packages are available from many laser vendors
- System houses often repackage non-industrial packaged lasers into turnkey systems
- Industrial packaging must incorporate laser safety features as mandated by U.S. Federal law (beam stop)
- Maintenance access features:
    - Quarter turn latches on exterior panels
    - Quick-change resonator windows

- HeNe laser resonator optics alignment system
- Modular subassemblies
- Quick-change laser or laser vessel

Part Viewing Systems

Choice of an imaging system depends on the dimensions of required optical parameters and practicality. Two types of imaging systems are available:

1. Long working distance (LWD) setup
    - Objective focal lengths greater than 50 mm
    - Object distances up to 2 meters
    - Working distances to 250 mm
    - Depth of field up to 100 µm
    - Demagnifications less than 15X
    - Potential for high beam utilization
    - Part viewing can be problematic
2. Microscope imaging setup
    - Objective focal lengths 10 to 30mm
    - Object distances ~500 mm
    - Working distances 5 to 10 mm
    - Depth of field 1 to 5 µm
    - Demagnifications 10X to 60X
    - Low beam utilization
    - Through the lens part viewing
    - Complex mask illumination required for reflective objective

Long Working Distance Optical Systems

Characteristics of LWD Objective Lenses

	Plano-Convex Singlet	Corrected Doublet	Four Element Corrected	Multi-element Telecentric
Resolution	>10 µm	~5 µm	~2 µm	~2 µm
Field size (mm)	~10 mm	~10 mm	~5 mm	Up to 25 mm
Complexity	Very low	Low	Moderate	High
Cost	Very low	Moderate	Moderate	High
Losses	2 to 5%	5 to 10%	5 to 10%	>20%
Notes	Very inexpensive Barrel distortion	Dual wavelength operation Moderate distortion	Low distortion	Very large field of view Good depth of field

Table 13. Characteristics of LWD lenses.

Advantages of LWD Systems	Disadvantages of LWD Systems
Small numerical apertures with large field sizes	Small demagnification factors
Large depth of field	Long optical path lengths
Resolution to 2 µm	On-target viewing problematic
Low optic losses	Large support structure required

Table 14. Advantages and disadvantages of LWD systems.

Part viewing

In LWD laser imaging systems, the laser objective lens cannot be incorporated as an optical element of the part viewing optics because LWD objectives are typically not chromatically corrected for the visible spectrum. In addition, LWD objectives do not produce high magnification. The general approach in this case is to employ a completely separate camera part viewing system.

One alternative is to position the viewing system slightly off-axis to avoid obstruction of the laser beam (Figure 48). This permits high contrast viewing with a camera and zoom lens assembly. The main disadvantage to this setup is the parallax inherent to off-axis viewing.

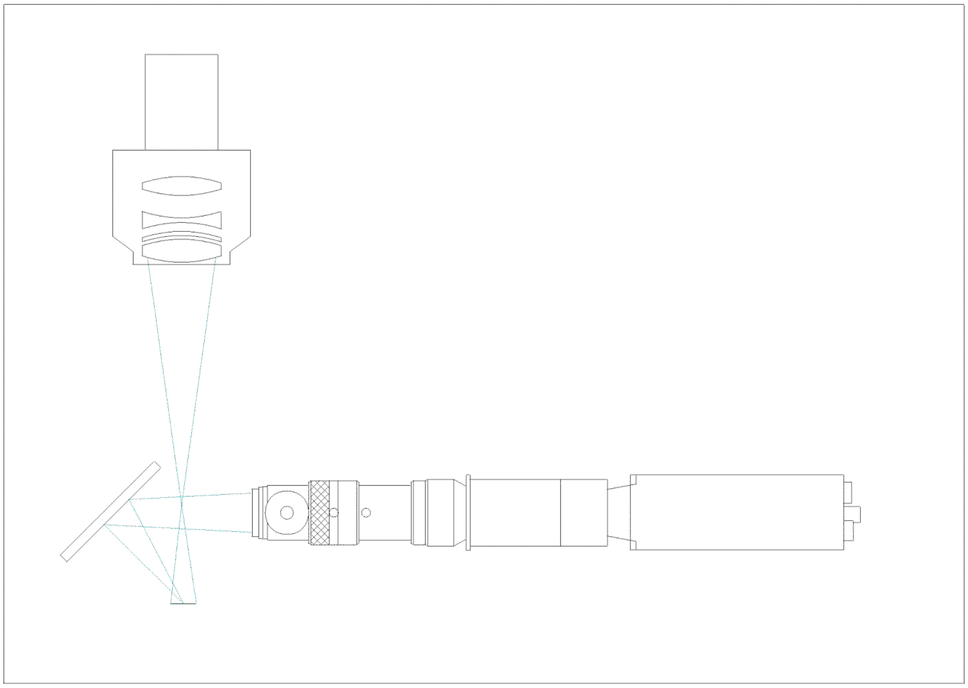


Figure 48- Off-axis viewing.

Another approach to part viewing is a mirror with a central opening to permit on-axis viewing (Figure 49). The laser beam is aligned to pass through this opening without hitting the mirror and parallax errors are eliminated. A disadvantage to this setup is a loss of contrast in the part image due to the central obscuration in the viewing mirror. Furthermore, the laser beam must be confined to the opening in the mirror.

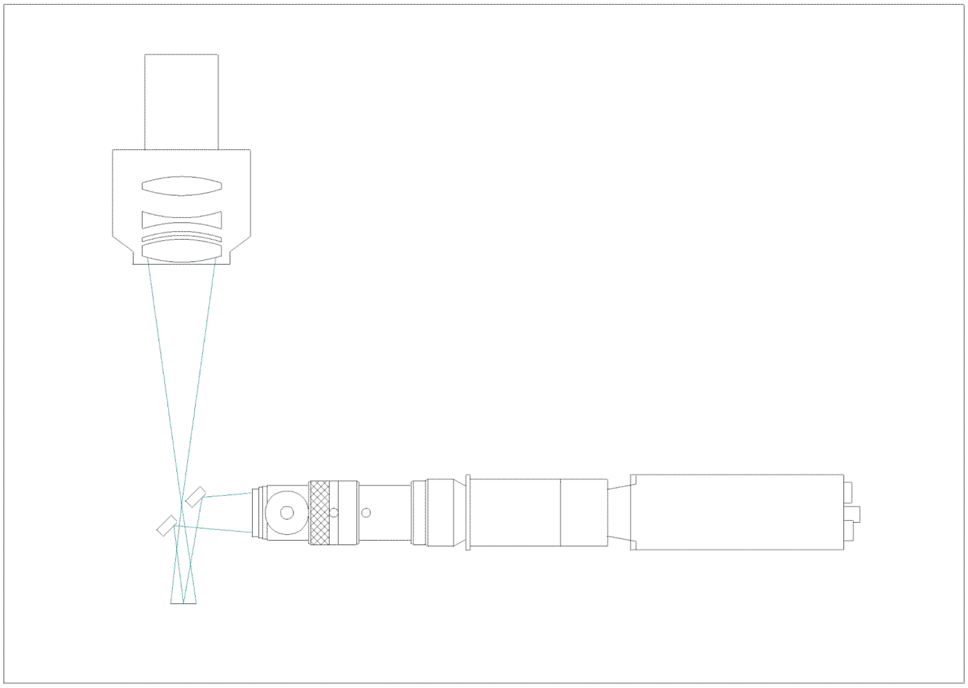


Figure 49- On-axis viewing.

A third option in part viewing is the on-axis, off-line viewing setup illustrated in Figure 50. In this case, the workpiece must be slewed a known distance from the on-line beam axis to the viewing axis to be observed. The best way to accommodate this type of viewing is to include the table motion immediately before and at the end of the process program.

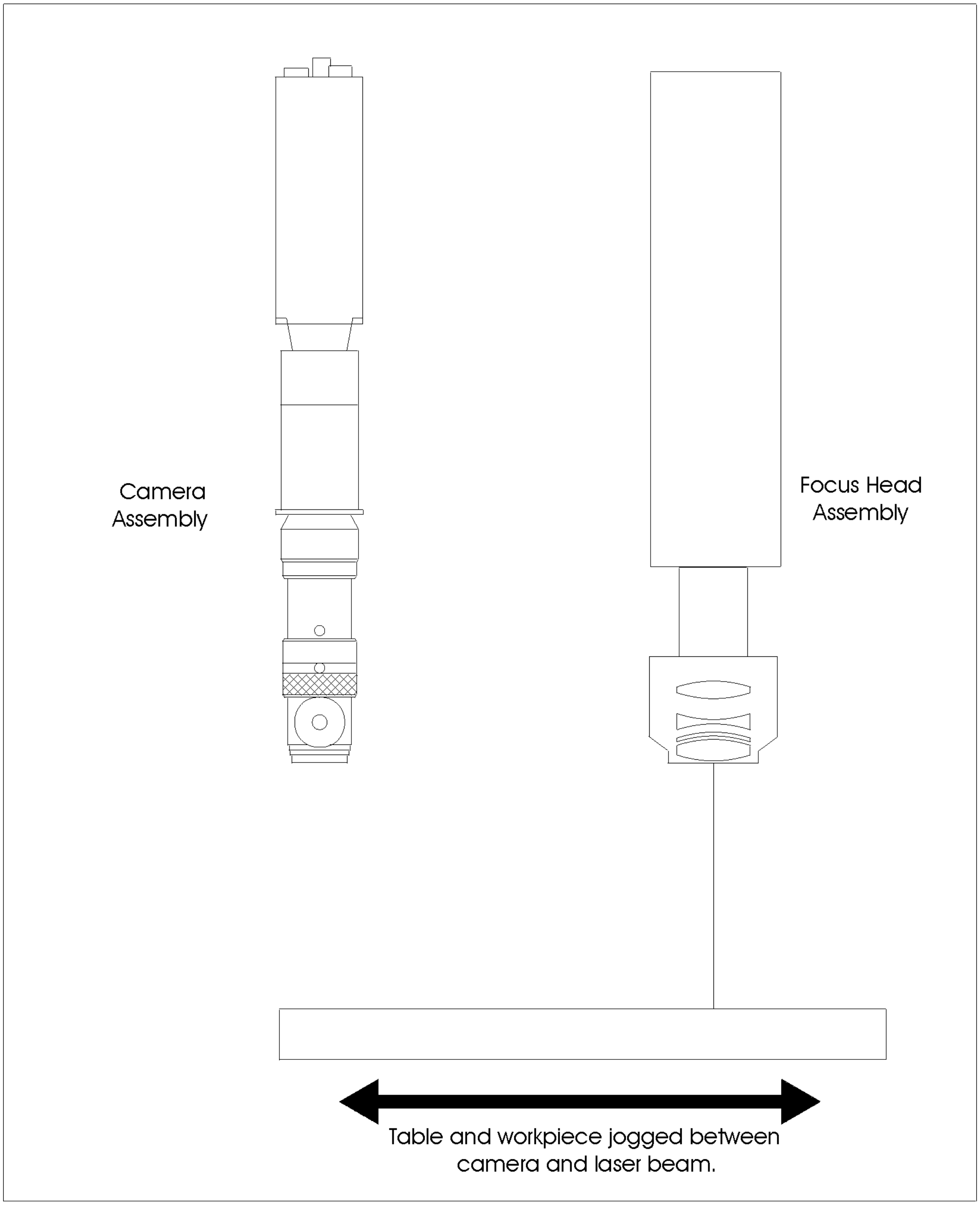


Figure 50- On-axis, off-line viewing setup.

Still another part viewing approach is the on-axis, on-line viewing setup shown in Figure 51. This setup is the most costly. The dielectric optic in the center is UV coated for reflection on the bottom side and visual coated for transmission on the top. This viewing setup is particularly useful for microscope viewing.

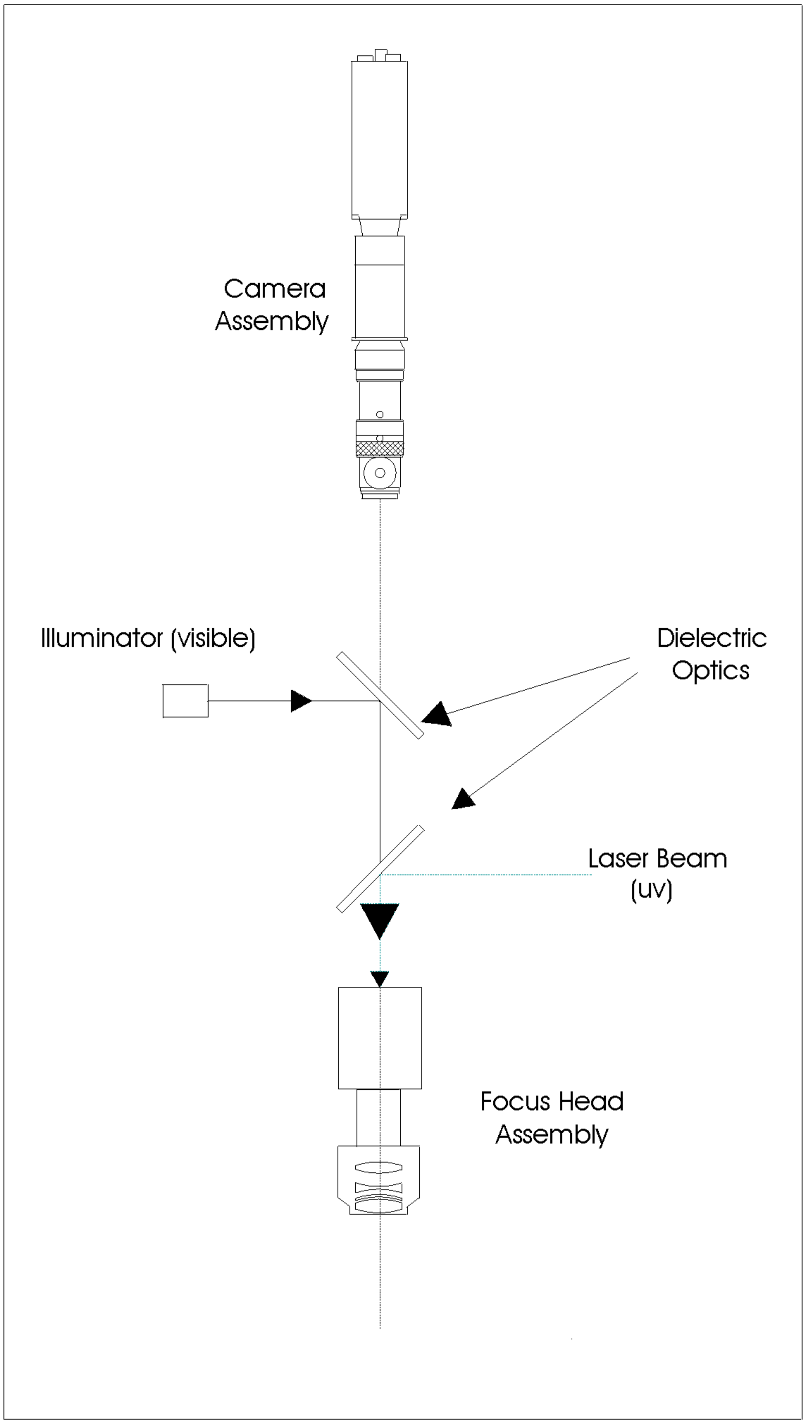


Figure 51- On-axis, on-line viewing setup.

Microscope Imaging Systems

Microscope imaging systems feature the following desirable characteristics:

- High optical demagnification
- Low spherical distortion
- Achromatic lenses permit simultaneous imaging of UV and visible light, allowing on-target viewing during processing

A disadvantage to microscope imaging is the short focal length. Very little space exists between the lens and the workpiece.

Advantages of Microscope Systems	Disadvantages of Microscope Systems
Large Numerical Apertures	Limited Field of View
Short Optical Path Lengths	Short Depth of Field
High Magnification On-Target Viewing	High Cost
Resolution to <1 µm	High Optical Losses
Large Demagnification Factors	Complex Illumination Required

Table 15. Advantages and disadvantages of microscope viewing.

Motion Control

There are three fundamental types of motion systems: stepper motor, servo motor or linear motor. All are used in laser machining processes.

Advantages of stepper motors:

- Low cost
- Rugged and compact
- Simple in design
- No maintenance
- High reliability
- High resolution (<10 μm) when microstepping incorporated into system
- Stiff stationary holding torque
- High operating torque
- Ideal for low speed applications, i.e. micromachining

Some disadvantages of stepper motors include their limitations in positioning accuracy, high operating noise and electric current consumption.

Advantages of servo motors:

- High accuracy when used with encoders
- No electrical current consumption when motor is stationary
- Smooth motion
- Ideal for high speed applications

Disadvantages to servo motion systems are their complexity and high cost.

Advantages of linear motors:

- High accuracy when used with encoders
- Smooth motion
- Extremely fast
- Large stage sizes

Computer control

- Provides easy operator control
- Motion controller card resides in computer expansion slot
- Motion control software required to communicate with controller card
- Provides I/O features to system, or I/O can be controlled by many controller cards
- Touch screen control can be available

Stepper Motor Systems

Motion controller

- Receives high level instructions from the computer
- Computes interpolation profiles and controls drive system
- Output to stepper motor drivers is a step signal and a direction signal for each axis
- Microstepping up to 50,000 steps per motor revolution
- Usually have several velocity profile options
- Open loop or closed loop with encoder feedback

Stepper Motor Drivers

- Control electrical current in windings of each motor
- Adjustable current output

Motors

Rotary motors: lead screw drive for linear positioning

Linear motors: direct drive for reduced torque requirements and greatest accuracy

Servo Systems

Motion controller

- Resides in computer
- Many velocity profile options
- Uses encoder feedback to position motors
- Velocity feedback available
- Output signal is usually a voltage (-10 to +10 volts) proportional to required motor speed

Servo Amplifiers

- Usually compatible with 2 or 4-lead motor hookups
- Adjustable current output

Servo Motors

- 2 or 4-lead
- Current rating based on torque requirements

Encoders

- Linear
- Rotary (physically attached to motor)
- Provide 5 volt square wave pulses directly to motion controller card
- Accuracies < 1 µm

Laser Support Systems

AC Power Distribution System

- 208 vac, three phase power to laser
- 110 vac to control system and laser support equipment
- Electrical safety EMO/interlock circuit

Water cooling system

- Cooling water supply to laser head cooling system
- Temperature and flow control
- Filtration to prevent contamination of laser head

Laser Gas Processing System

- Gas connection between laser and gas processor
- Integration to control system for fault diagnosis
- Provisions for coolant refill

Laser Gas Delivery system

- Certified gas supply; gas cabinet, coaxial gas delivery lines
- Safety valve system for toxic gases
- Optional computer control

Safety

Laser Safety

- High intensity ultraviolet and infrared light hazardous to the eyes (cornea) and skin
- All manufacturers required by law to design and certify compliance with U.S. Code of Federal Regulations, Parts 1040.10 and 1040.11

- CDRH (Center for Devices and Radiological Health), branch of the FDA has oversight
- Class I, II, III and IV based on the level of radiation that is accessible by humans during normal operation of the equipment
- Interlocked protective housing for Class I
- Required safety labels, inspections and recordkeeping
- Reporting to FDA: model change reports and annual reports

Mechanical Safety

- Large motion control systems may pose mechanical hazards to people
- Mechanical guards
- Documented maintenance procedures

Electrical Safety

- Lethal high voltages in the laser head
- Electrical safety covers
- Qualified service personnel only

Materials Safety

- Toxic and corrosive fluorine and chlorine gases
- Compressed gas cylinders need proper handling

Conclusion

1. Laser processing provides a valuable and unique capability in high precision materials processing
2. The complexity of lasers sometimes means that they are best applied to high value added processes, but in many cases they provide very cost effective solutions
3. Contact mask processing, near field imaging, focal point machining and beam conditioning techniques permit novel approaches to developing cost effective solutions
4. Proper integration of motion control and beam delivery can enhance the utility and flexibility of laser systems
5. Successful integration of a laser into a full turnkey system requires multi-disciplinary expertise in the areas of software, control systems, optical and mechanical design
6. Successful use of laser systems includes dedication to the technology, a thorough understanding of the basic principles, always with an eye on safety
7. Reputable laser contract manufacturing centers ("job shops") provide a valuable resource for prototyping, R&D, pilot production runs, and in some cases, large volume production

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Appendix A – Glossary

Average Output Power: The total energy per pulse times the number of pulses per second (Joules/s = Watts)

Beam Delivery System: Optics and hardware used to condition and direct a beam of light to a specific location on target

Beam Diameter: The diameter of the portion of the laser beam that contains 86% of the total beam energy

Beam Divergence: The tendency of a laser beam to expand in diameter as it moves away from the source, measured in milliradians

Beamsplitter: An optical device, frequently a thin piece of glass inserted at an angle, for dividing a beam into two or more beamlets; can be either geometric or dielectric

Coherent Radiation: Light that consists of wave trains traveling in phase with each other

Critical Angle: The angle at which the refracted ray lies tangent to the surface along two media. At angles greater than the critical angle, the refracted ray will not penetrate the second material and there is total reflection

Energy Density: Laser energy per unit area in J/cm^2

Field Lens: A lens, usually of long focal length, used to project the laser beam onto the imaging lens; used for keeping a highly divergent beam collimated

Focal Length: The distance from the lens to the focal point, usually measured in millimeters

F-number: **F# = f/D** , where f is the focal length of the lens and D is the lens aperture diameter, a measure of the amount off light passing through the lens

Focal Plane: The plane at which all light rays converge to a point, perpendicular to the axis of the beam

Focal Point: That point on the optical axis of a lens to which an incident bundle of parallel light rays will converge

Image Plane: The plane perpendicular to the axis of a lens in which an image is formed

Index of Refraction: The ratio of the speed of light in a vacuum to the velocity in a specific material (**$n = c/\nu$**)

Iris Diaphragm: A mechanical device designed to vary the effective diameter of an imaging lens, thereby controlling the amount of light allowed through the lens while screening out diffracted light

Mask: A field stop or aperture located at an object plane of an imaging system that determines the size and shape of an image at a given demagnification

Monochromatic: Light that consists of only one wavelength. An industrial laser beam consists of a very narrow band of wavelengths around a central wavelength

Oscillator: Another word to describe a laser cavity, which is an electromagnetic oscillator

Photon: A particle of light that has energy but no mass or charge. A photon has properties of both a particle and a wave

Plano-convex Lens: A lens that converges an incident bundle of rays to a focus; convex shaped on one side and flat on the other

Population Inversion: A state in which more atoms or molecules of a lasing medium are at a high energy level than are at some lower energy level associated with the lasing transition

Power Density: Laser output per unit area in W/cm^2

Pulsewidth: Also known as pulse length, this is the time or duration of a laser pulse in seconds

Q-Switch: A device that acts as a shutter and moves in and out of the beam path at regular intervals so that a large amount of energy is stored and then released in a burst. As an option on CW (continuous wave) lasers, it provides a means of significantly increasing the peak power of the output

Repetition Rate: The number of pulses per second produced by a pulsed or q-switched laser

TEA Laser: An Acronym for **T**ransversely **E**xcited **A**tmospheric laser. This CO_2 gas laser uses a transverse flow of gas and operates at higher pressures than other gas lasers, generally near atmospheric pressure. The result is a higher energy beam

Wavelength: The length of the light wave, measured from crest to crest. The wavelength determines the color of the light and also influences material interaction

Appendix B - List of Tables

Appendix C – List of Figures